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BOOK OF

FULL TEXT

11. INTERNATIONAL CONGRESS ON CONTEMPORARY SCIENTIFIC RESEARCH

JULY 01-07, 2026

BALTIC STATES & FINLAND

EDITOR

Assoc. Prof. Dr. Ayhan DAĞDEVİREN

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BOOK OF FULL TEXTS

11TH INTERNATIONAL
ISPEC CONGRESS ON CONTEMPORARY SCIENTIFIC RESEARCH

July 01-07, 2026 Baltic States and Finland

EDITOR

Assoc. Prof. Dr. Ayhan DAĞDEVİREN

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ISPEC 11TH INTERNATIONAL CONGRESS ON CONTEMPORARY SCIENTIFIC RESEARCH

July 01-07, 2026
Baltic States & Finland

ORGANIZING INSTITUTION

ISPEC INSTITUTE

CONGRESS ID

CONGRESS TITLE
ISPEC 11TH INTERNATIONAL CONGRESS ON CONTEMPORARY SCIENTIFIC RESEARCH

DATE
July 01-07, 2026

PLACE
Baltic States & Finland
Face-to-face & Online (Zoom)

PARTICIPANT COUNTRIES (21)

Turkey, Morocco, Nigeria, Azerbaijan, India, Pakistan, Algeria, Bangladesh, Turkish Republic of Northern Cyprus, Georgia, Kazakhstan, Poland, Indonesia, Portugal, Albania, Vietnam, Ukraine, United States, Brunei, Romania, Hungary

164	28	79	85
TOTAL ACCEPTED PAPERS	TOTAL REJECTED PAPERS	PAPERS FROM TURKIYE	INTERNATIONAL PARTICIPANTS

EVALUATION PROCESS & PRESENTATION
All applications have undergone a double-blind peer review process · Oral Presentations

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11. INTERNATIONAL CONGRESS ON CONTEMPORARY SCIENTIFIC RESEARCH

JULY 01-07, 2026 / BALTIC STATES & FINLAND

PROGRAMME

SCIENCE • INNOVATION • COLLABORATION • IMPACT

ESTONIA | LATVIA | LITHUANIA | FINLAND

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03.07.2026 / IN-PERSON SESSION-1

Riga Local Time: 09:00-11:30 | Radisson Blu Hotel & Spa, Daugava Riga

HEAD OF SESSION: Dr. DERYA OCAL

Authors	Affiliation	Presentation Title
OSMAN MERT YAZ BAHADIR DEMIREL	Erciyes University	Comparison of the physical and mechanical properties of pellets produced from safflower biomass prepared at different grinding sizes
BAHADIR DEMIREL OSMAN MERT YAZ	Erciyes University	Structural and functional evaluation of a robotic arm developed for an autonomous harvesting robot
SEMRA BENZER RECEP BENZER	Gazi University	Analysis of growth characteristics of invasive Atherina boyeri using artificial intelligence and classical methods
SERVET UZTEMUR ABDURRAHMAN ILGAN AYLIN KIRISCI-SARIKAYA	Anadolu University	Examining teachers' perceptions of school principals' hubristic behaviors by school level and teaching branch
DERYA OCAL	Ataturk University	Transhumanism and the biological limits of humanity: technological intervention, bodily transformation, and ethical debates
MURAT ATESLI	Anadolu University	Catastrophic images in contemporary Turkish painting
YASAR USLU	Anadolu University	An analysis of mayday posters within the framework of postcolonial theory
SERVET UZTEMUR ALI GOKALP MURAT POLAT FEYZA DALAYLI PO CHING HUANG DANIEL KWASI AHORSU CHUNG-YING LIN	Anadolu University	Measuring conspiracy beliefs in social media contexts: development and validation of the social media conspiracy beliefs scale
TURKAN PASALI KILIT IBRAHIM USLU BEYZA ORUC SUDE ORMECI DUYGUCAN KARAOGLAN MUHAMMED EMIN DEMIRCI BEGUM CALISKAN PERIHAN SECIL YACAN HATICE EZGI TURKDONMEZ MUSTAFA YAYLA UFUK ERKURT	Kutahya Health Sciences University	The effect of menopause duration on clinical, biochemical, menopausal symptom, and depression parameters in postmenopausal women: a comparison of early and late postmenopause
ÇAGLAR AKAR	Istanbul Okan University	Normative agent-based framework for policy prioritization under conflict and poverty shocks
OZBIL OZMEN	Istanbul Okan University	Comparative evaluation of 3D printed polymer materials using finite element analysis

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03.07.2026 / IN-PERSON SESSION-2

Riga Local Time: 09:00-11:30 | Radisson Blu Hotel & Spa, Daugava Riga

HEAD OF SESSION: Dr. AYHAN DAGDEVIREN

Authors	Affiliation	Presentation Title
CIHAN YUKSEL	Mersin University	The real erosive effect of inflation on corporate income tax revenues: evidence from Türkiye
AYNUR PALA	Manisa Celal Bayar University	Examining the effects of distance education on values education
SELCUK KILIC	Erzincan Binali Yildirim University	DFT, MEP, Molecular Docking, and ADME-Based In Silico Evaluation of the N-(1,3-Benzodioxol-5-yl)-2,4-dioxo-1H-pyrimidine-5-sulfonamide Compound Against BRAF V600E Mutant Kinase
SELCUK KILIC	Erzincan Binali Yildirim University	Computational Preliminary Insights into TLR7/8-Mediated Immunomodulation: A Schrödinger Glide-Based Molecular Docking Analysis of the Imidazo[4,5-c]quinoline Derivative IT-37 with Human Toll-like Receptor 8
YUSUF SERT	Yozgat Bozok University	DFT studies of 1,3-benzodioxole-5-sulfonamide
YUSUF SERT	Yozgat Bozok University	MEP and docking analysis of 1,3-benzodioxole-5-sulfonamide
AYHAN DAGDEVIREN IBRAHIM MERCIMEK	Cankiri Karatekin University	Latvian culinary culture
IBRAHIM MERCIMEK AYHAN DAGDEVIREN	Cankiri Karatekin University	Health tourism policies and practices in Lithuania
AHMET UNLU	Ministry Of Education	Traces of hunting culture in Satılmış Sen’s poetry

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02.07.2026 / ONLINE SESSION-1 / HALL-1	
Riga Local Time: 10:00-12:00	Ankara Local Time: 10:00-12:00
Zoom Meeting ID: 844 6001 0824 / Zoom Passcode: 123456	

HEAD OF SESSION: Dr. GULLU ABDIYEVA

Authors	Affiliation	Presentation Title
OGUZHAN DANIS	Yozgat Bozok University	The problem of comparability of financial statements in a high-inflation environment: A literature review from the perspective of accounting standards and financial reporting
OGUZHAN DANIS	Yozgat Bozok University	The role of AI-supported management accounting information in strategic decision-making processes
FERHAT ATIK	Girne American University	Simulation of truth: Rethinking the relationships among reality, representation, and faith in post-truth regimes
GULLU ABDIYEVA	Azerbaijan Medical University	Botulinum toxin after hemorrhoidectomy
MUSTAFA MAJID MADLOOL AL_KHAZRAJI IRFAN KURTBAS	Hitit University	Experimental investigation of time-dependent heat and mass transfer behavior under frosting conditions in cryogenic ambient air vaporizers
DOGUKAN UZUNKAYA EBRU ACUNER TURET	Istanbul Technical University	Analysis of energy poverty and gender inequality
MUSTAFA DURSUNLAR	Yozgat Bozok University	Comparative analysis of manual and robotic welding applications in railway vehicle chassis manufacturing
ILHAN CAKIL MEHMET OZER FATIH BALIKOGLU	Balikesir University	Investigation of the quasi-static mechanical behavior of asymmetric inter-ply hybrid double-curved composite structures

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02.07.2026 / ONLINE SESSION-1 / HALL-2

Riga Local Time: 10:00-12:00 | Ankara Local Time: 10:00-12:00

Zoom Meeting ID: 844 6001 0824 / Zoom Passcode: 123456

HEAD OF SESSION: Dr. GAFARLI (QAFAROV) RAMAZAN

Authors	Affiliation	Presentation Title
FIDAN ASKEROVA	Azerbaijan University Of Languages	Opportunities for implementing the Education 4.0 model at the undergraduate level
BOLA CHRISTIE ATULOMAH ORJIME ANN NGUNAN	*Federal University of Technology Ilaro Ogun State*	Repositioning Academic Libraries in the Digital Age: Factors Influencing Low Library Patronage among Students in Nigerian Tertiary Institutions
GAFARLI (QAFAROV) RAMAZAN	Amea Institute Of Folklore	Folklore theories of epic memory: In the context of Turkic and European epics
AYTEN NAHIDE KORKMAZ MUSTAFA OZYESIL	Istanbul Aydin University	Climate policy uncertainty, green bonds, and stock market resilience: Evidence from European listed energy and utility firms
AYTEN NAHIDE KORKMAZ HASAN AGAN KARADUMAN	Istanbul Aydin University	A green approach to the circular bioeconomy, climate change, and the environment
AHMET KÖSE DENIZ ÖZGÜR BERFIN KILINÇ	Kırıkkale University	Comparison of the Effects of Different Inoculation Methods on *Fusarium oxysporum* f. sp. melongenae-Induced Disease Development and Morphological Parameters in Local Hasan Dede and Commercial Eggplant Cultivars
MUHAMMET TALHA ERIKEL ISMAIL ENES PARLAK	Bursa Technical University	A comparative evaluation of YOLOv8, YOLO11, and Faster R-CNN architectures for in-vehicle firearm and knife detection
DENIZ KIZIR MUSA ESIT OSMAN GUNAYDIN ZEYNEB KILIC	Adiyaman University	Multidimensional trend analysis of meteorological changes in the Thrace region, Türkiye (1965–2025)
OSMAN USLU	Afyon Kocatepe University	Demographic predictors of internet usage time and social comparison: A quantitative study

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HEAD OF SESSION: Dr. HUSEYIN OZDEMIR

Authors	Affiliation	Presentation Title
OSMAN USLU	Afyon Kocatepe University	Is cyberloafing always harmful? Reconsidering positive outcomes in digital workplaces
BERKAY KARACOR MELTEM OZKAN	Cukurova University	Finite element analysis of low-bed trailer ramps with different design geometries using two different materials
BERKAY KARACOR MURAT SURKUC	Cukurova University	Investigation of the structural and weight optimization of vehicle roof-rack mounting brackets using finite element analysis
SERAP DUMAN GULUMSER GULTEKIN AKDUMAN	Gazi University	An examination of factors influencing peer relationships among preschool children using CHAID analysis
HUSEYIN OZDEMIR	Cankiri Karatekin University	The effect of entrepreneurship education on the entrepreneurial tendencies of tourism undergraduate students: The case of Cankiri Karatekin University
SEVGI KANSIZ	Samsun University	Theoretical calculations and in silico drug-likeness of a nitrophenyl schiff base
SEVGI KANSIZ	Samsun University	Molecular surface analysis, molecular docking, and adme investigation of a nitrothiophene-containing schiff base
HUSEYIN OZDEMIR	Cankiri Karatekin University	A study on health tourism awareness among tourism undergraduate students: The case of Cankiri Karatekin University
MURAT OLTULU	Ankara University	Bridge terms enabling conceptual transformation in Qur'anic semantics: 'Ilm, tilāwah, idhn, and waḥy
BUKET KAYIŞLI ARKADAŞ	*İnönü* University	The human–nature relationship in the context of sufi cosmic human understanding and modern human philosophy

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02.07.2026 / ONLINE SESSION-1 / HALL-4

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Zoom Meeting ID: 844 6001 0824 / Zoom Passcode: 123456

HEAD OF SESSION: Dr. BUI XUAN VUONG

Authors	Affiliation	Presentation Title
INA ZELA	Mediterranean University of Albania	A comparative assessment of alternative methods for estimating the non-observed economy
ATULOMAH BOLA CHRISTIE KUMOYE DANIEL OLALEKAN	*Federal University of Technology Ilaro*	A review of open-source integrated library systems and sustainable library services in Nigerian universities
BOLA CHRISTIE ATULOMAH ODUMADE ADEPERO OLAJUMOKE	*Federal University of Technology Ilaro*	Information literacy skills and the management of fake news among university students in the post-truth era
BUI XUAN VUONG	*Sai Gon University*	Bleaching of kaolinite mineral to enhance whiteness and reduce iron oxide content
OKAILI OUMAIMA RAFII MOHAMED HATTABI MOHAMED	*Hassan II University*	Aeroelastic design of high-aspect-ratio wings incorporating structural batteries
OUASSILA RIOUCHI KHALID ELKALAY MOURAD BAGHOUR	*Cadi Ayyad University*	Dynamics of small pelagic fish and plastic debris distribution in marine ecosystems
OUASSILA RIOUCHI KHALID ELKALAY MOURAD BAGHOUR	*Cadi Ayyad University*	Ingestion of microplastics by fish
PRITHEERAJ SEN MAINAN RAY CAESAR ROY	*Amity University Kolkata*	Evaluating the effectiveness of Indians regulatory response to single-use plastics: strategies for adaptive capacity building and futuristic trends

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HEAD OF SESSION: Dr. K.R. PADMA

Authors	Affiliation	Presentation Title
SUMON HOSSAIN SADIA ISLAM SHAKIL AHMED TARIQ-AL KASIF	*University of Rajshahi*	Biological traits of glossogobius giuris (hamilton, 1822) in a wetland ecosystem (nw bangladesh): implications for sustainable, fisheries management
I. EL FENGOUCHI N. LAHLOUHI R. HSISSOU L.C. COSTA M. EL HASNAOUI	*Ibn-Tofail University*	Novel pentafunctional epoxy polymer: preparation, structural and optical characterization
SONDE DIMEJI ROTIMI	*Sai Gon University*	Waiting for the truck: an evaluation of the psychological effects of delayed deliveries on customers and supply chain personnel in Nigeria
BUI XUAN VUONG	*Sai Gon University*	Bleaching of kaolinite mineral to enhance whiteness and reduce iron oxide content
OUASSILA RIOUCHI KHALID ELKALAY MOURAD BAGHOUR	*Cadi Ayyad University*	Transfer of microplastics from the marine environment to humans through the food chain
SANIA ABID SYED MOHSAN RAZA SHAH ARSHIA ZIA	*University Of Education*	Role of neem leaf extract in the morpho-anatomical and physiological response of pennisetum glaucum (l.) r. br. under water deficit conditions
OKAILI OUMAIMA RAFII MOHAMED HATTABI MOHAMED	*Hassan Ii University*	Aeroelastic design of high-aspect-ratio wings incorporating structural batteries
HANANE MAHROUG KHALIL OUKEBDANE CHERIFA HAKIMA MEMOU FATIMA ZAHRA BENHACHEM	*University Centre Of Maghnia*	Lignocellulosic sawdust as a low-cost adsorbent for the removal of brilliant green and bemacid blue
K.R. PADMA	*Women's University*	Reconceptualizing herbal knowledge: indigenous plant-derived remedies for covid-19 in India

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02.07.2026 / ONLINE SESSION-1 / HALL-6

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HEAD OF SESSION: Dr. TUHINA SINHA

Authors	Affiliation	Presentation Title
BASHIR AHMAD USMAN YANKUZO ALHASSAN YUNUSA ALKALI MOHAMMED JIBRIL ABUBAKAR A. EJIKO MOHAMMED MAISHERA	*Federal University Of Technology Minna Niger State*	The impact of security challenges on emerging technology in mathematics, engineering, technology, and science (mets) education lecturers in universities
TUHINA SINHA	*Amity University Jharkhand*	Optimizing efficiency in cross-border trade: a transaction cost economics approach to online dispute resolution (odr)
NUNO BAPTISTA MÁRIO ANTÃO FIRMINO ALMEIDA	*Lusíada University*	Uncertainty in business strategy
NUNO BAPTISTA MÁRIO ANTÃO	*Lusíada University*	A social capital approach to study coopetition involving smes
MELIK SAMI KHELIL SARA TALLAL ABDEL KARIM BOUZIR	*Mohamed Khider Biskra University*	Illuminating experience: the role of light in shaping emotional and perceptual responses in architecture
MELIK SAMI KHELIL SARA TALLAL ABDEL KARIM BOUZIR	*Mohamed Khider Biskra University*	Fragmentation and continuity: reconciling cubist aesthetics with spatial coherence in architecture
MELIK SAMI KHELIL SARA TALLAL ABDEL KARIM BOUZIR	*Mohamed Khider Biskra University*	Computational morphogenesis in architecture: parametric strategies for integrating form and structural logic
MELIK SAMI KHELIL SARA TALLAL ABDEL KARIM BOUZIR	*Mohamed Khider Biskra University*	Bridging dimensions: methodologies for converting two-dimensional abstraction into three-dimensional architecture.
MELIK SAMI KHELIL SARA TALLAL ABDEL KARIM BOUZIR	*Mohamed Khider Biskra University*	Reconceptualizing architecture as art: integrating fine art methodologies into spatial design practice

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Riga Local Time: 12:30-14:30	Ankara Local Time: 12:30-14:30
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HEAD OF SESSION: Dr. CEMILE DURSUN

Authors	Affiliation	Presentation Title
SEVIN AKSOY SACIDE PEHLIVAN	Istanbul University	Beyond genetic determinism: A genomic and developmental framework for autism risk assessment
CEMILE DURSUN BEKIR GULER	Bartin University	Artificial intelligence and science education: current trends and a thematic review (2023–2026)
Z. GONUL BALKIR ALTAY ILTAN AKTURK ECEM KOCAOGLAN	Cyprus Aydin University	Communicative rationality and the problem of legal legitimacy in Habermas
Z. GONUL BALKIR ALTAY ILTAN AKTURK ECEM KOCAOGLAN	Cyprus Aydin University	Analysis of the impact of international law on the protection of marine ecosystems in Cyprus
GULSAH BALABAN AHMET SAIM GULSOY AZRA TOPCU KUBRA ISIK	Istanbul Sabahattin Zaim University	Childhood traumas and dream themes: The mediating role of belief in paranormal events
Mehmet Doğan Mehmet Zeki Acar	*Mardin Artuklu University*	Future professions: artificial intelligence and smart agriculture technologies in agriculture
SUHEDA GOKDAS MUSA ESIT ZEYNEB KILIC	Adiyaman University	The impact of climate change on hydro-meteorological parameters: Integration of classical tests with ITA and IPTA methods

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HEAD OF SESSION: Dr. NIHAL KILIC

Authors	Affiliation	Presentation Title
KUBRA KOC NIHAL KILIC	Tekirdag Namik Kemal University	Obligate ectoparasites of human skin: biology and ecology of demodex mites
NIHAL KILIC KUBRA KOC HAVVA GOKTEPE FATMA BETUL TIRPAN	Tekirdag Namik Kemal University	Effects of different doses of a locally produced diatomaceous earth (detech wp90) on *tetranychus urticae* koch (acari: tetranychidae) and the predatory mite phytoseiulus persimilis athias-henriot (acari: phytoseiidae) under laboratory conditions
MUSTAFA DEMIR ALI CAN TELLIOGLU AYLUT DANA MURAT SEN	Vehicle Systems Chief	Integrated evaluation of forklift fork design, analysis, and testing processes
AYSE GUL AKCA ASLI ERGENEKON ARSLAN	Bilecik Seyh Edebali University	Evaluation of teachers' psychological preparedness levels for disaster threats: the case of Eskişehir
YILMAZ ISIK MUSA ESIT MEHMET FATIH SAHAN	Adiyaman University	Statistical trend analysis of precipitation and temperature parameters in Türkiye's mediterranean region
ISMAIL YILDIRIM MUSA ESIT YALCIN YILMAZ	Adiyaman University	Long-term climate trends in Türkiye's southeastern Anatolia region using classical and innovative statistical methods
PETEK GOKCE OZUN OZAN ERCAN EMRE BICER	Sivas University of Science and Technology	Electrochemical modeling of li-ion batteries using comsol multiphysics

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HEAD OF SESSION: Dr. MEHMET FATIH CAN

Authors	Affiliation	Presentation Title
MEHMET FATIH CAN	Iskenderun Technical University	Fisheries management risk assessment under climate change: a conceptual framework for climate-resilient fisheries
HILAL AKCIL GOKHAN RIFAT KOCYIGIT ONDREJ HOJDA	Mimar Sinan Fine Arts University	Institutional challenges in architectural design competitions: a comparative analysis of Türkiye and European countries (2016–2024)
ABDURRAHMAN CELIK MUSA ESIT MEHMET FATIH SAHAN	Adiyaman University	Long-term trend analysis of annual precipitation and temperature data in Türkiye's eastern black sea region
ISMET ASIM ASLANGOZ MUSA ESIT MEHMET FATIH SAHAN	Adiyaman University	Multi-method trend analysis of temperature and precipitation trends in Türkiye's eastern Anatolia region: the cases of Ardahan, Erzurum, and Kars
DURSU KAZIM	Unec, Economy, Economic Policy	The impact of creating green jobs on social welfare
GULSAH BALABAN CHARISSA SERAVINNA AZZAHRA HANEEN HAMMADI	Istanbul Sabahattin Zaim University	Human–ai relationships: associations with personality, attachment, and psychological symptoms
ALZAKI ZAKARIA SULIMAN SALIH HASAN TERZI	*Karabuk University*	The effect of international experience and global orientation on business performance with mediating role of global market orientation: case study of Turkish food companies.

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HEAD OF SESSION: Dr. TUHINA SINHA

Authors	Affiliation	Presentation Title
MANAR ABID AMINA BENABDALLAH KHAOULA BOUDJABER GHANIA BOURZAMA LUIGI DEBELLIS	*Chadli Bendjedid University*	Chemical composition and antifungal properties of laurel leaves from El Tarff, Algeria
YOUSSEF TLEMSANI MOHAMED EBN TOUHAMI	*İbn Tofail University*	Evaluating the efficacy of ict-based interventions in physics education
TSIIREGZEN ANDARAI ENDRE DOMOKOS	*University Of Pannonia*	Gis-based spatial assessment of physicochemical and radiological characteristics of groundwater in darkhan-uul province, Mongolia
ELEMEHDI MAJDI HAMZA MAROUANI ALLOUN FOUAD SOUFIANE ZERRAF SAID BELAAOUAD	*Hassan II University Of Casablanca*	Crystal structure elucidation of a novel organic–inorganic hybrid material, 2-ethyl-n-phenylmethanaminium dihydrogen phosphite: an experimental and theoretical approach
MOHAMMED ALIYU SULEIMAN	*School Of Secondary Education*	Parental socio-economic status as a correlate of secondary school student's mathematical ability and academic achievement in quantitative economics in minna, Niger State
FATIMA MOUTAKIF SOUKAINA AMEUR ABDELLAH ZEROUAL HABIB EL ALAOUI EL ABDALLAOUI	*Chouaib Doukkali University*	DFT study of the regio- and chemo selective 1,3-dipolar cycloaddition between azomethine
TUHINA SINHA	*Amity University Jharkhand*	Subsidizing the green transition: reconciling climate-smart agriculture regulations with wto non-discrimination principles
ELMEHDI MAJDI HAMZA MAROUANI ALLOUN FOUAD SOUFIANE ZERRAF SAID BELAAOUAD	*Hassan Ii University Of Casablanca*	Synthesis, crystallographic characterization, and theoretical study of a novel $(C_7H_8NO_2)_2H_2P_2O_7$ single crystal
GIVI DUCHIDZE	*East European University*	Geopolitical competition and its impact on the global agenda for sustainable economic development
YUSUF AHMED TIJJANI ZAINAB IDRIS MOHAMMED NASIRU SADA	*Ahmadu Bello University*	Impact of customer awareness and perceived religious compatibility on the adoption of Islamic banking services in Nigeria

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HEAD OF SESSION: Dr. YEGANA AHMADOVA

Authors	Affiliation	Presentation Title
NODAR SULASHVILI MAGDA DAVITASHVILI EKATERINE LOMIA LALI PATSIA TAMAR OKROPIRIDZE DAVID APHKHAZAVA	*Georgian National University*	Translational assessment of epigenomic determinants of aging: large-scale
HAYAT MALGHI	*Sultan Moulay Slimane University*	Mild solutions for hybrid fractional differential equations
SAMIHA ISLAM BORSHA ALVI ISLAM SIFAT	*Daffodil Institute of It*	Human-ai collaboration in modern education: a review of emerging trends.
CHAIMAE EL YAACOUBI NIHADE BENSITEL PHUONG NGUYEN TRI ACHARF EL KASMI	*Abdelmalek Essaadi University*	Life cycle assessment of a wastewater treatment plant
KAWTHAR EL AHMADI KHADIJA HABOUBI PHUONG NGUYEN-TRI	*Abdelmalek Essaâdi University*	Green extraction of cannabis sativa l. using supercritical co_2: process optimization and evaluation of the antimicrobial potential of extracts and by- products
YEGANA AHMADOVA	*Azerbaijan State Pedagogical University*	Methods of implementing practical and independent activities in geography teaching
SAIDI MOHAMED	*Oran Graduate School of Economics*	Artificial intelligence and the economic efficiency of urban waste management
ANCA GATA	*University Of Galati*	Representations of linguistic constructions in teaching Romanian as a foreign language
PRAISE ENENCHE AGADA CHARLES YAKUBU MAKUN	*Federal University of Technology*	Impact of climate-responsive design strategies on thermal comfort in community civic centers in Abuja, Nigeria

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HEAD OF SESSION: Dr. SUPOM ROY

Authors	Affiliation	Presentation Title
YUSUF AHMED TIJJANI ABDULKADIR AHMAD	*Ahmadu Bello University*	Does strategic alignment impact on operational efficiency of commercial banks in Nigeria?
SITI ZASKIA PELANGI PUTRI ALIYA FAZILA EFFENDI NALA NINDISA QANITAH IRAWAN	*Lampung University*	Social media as a tax education tool: it's impact among young people in Indonesia
FARRUKH MAHFOOX RIAZ AHMED	*Bahria University*	Importance of sustainability in seaports: evidence from Pakistan
SUMON HOSSAIN SADIA ISLAM SHAKIL AHMED TARIQ-AL KASIF	*University Of Rajshahi*	Biological traits of glossogobius giuris (hamilton, 1822) in a wetland ecosystem (nw bangladesh): implications for sustainable fisheries management
SUPOM ROY	*Trine University*	Ethical hacking and penetration testing: how organizations use ethical hackers to strengthen security
ARCHANA DIXIT	*Gurugram University*	Analysis of the $\lambda_s $cdm model with latest observational data sets
YEGANA AHMADOVA	*Azerbaijan State Pedagogical University*	Children and environmental education for a sustainable future
MOHAMMED DENZIRA MOHAMMED EL IDRISSI ABDELMALEK MATINE SAID ESSKALLI	*Sultan Moulay Slimane University*	DFT elucidation of the mechanism and stereoselectivity of the hydroboration–oxidation reaction of α′-trans-himachalene: molecular docking and admet assessment of the resulting derivatives
SOUMAYA TALBI AMAL EL KHANCHAOUI SALHA HAMRI ABDERRAFIA HAFID MOSTAFA KHOUILI SOUAD RABI ABDELLATIF ESSOUMHI	*Sultan Moulay Slimane University*	Enhanced adsorption of Congo red by multi-metal layered double hydroxides (ldhs).

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HEAD OF SESSION: Dr. HATICE KANBUR CAVUS

Authors	Affiliation	Presentation Title
HATICE KANBUR CAVUS MURAT CAVUS	Yozgat Bozok University	Comprehensive analysis of low-frequency dielectric properties and charge-carrier dynamics in Schottky barrier heterostructures
HATICE KANBUR CAVUS MURAT CAVUS	Yozgat Bozok University	Dielectric response and charge-carrier dynamics in InGaAs Schottky barrier heterostructures
BIRCAN SAYAR RECEP SAHINGOZ MEHMET YAKAN	Yozgat Bozok University	Determination of changes in the optical properties of bacteria exposed to a magnetic field using ultraviolet–visible spectroscopy
METIN AKIZ HURMET FULYA AKIZ	Yozgat Bozok University	A homotopic model for historical cryptographic processes
HURMET FULYA AKIZ	Yozgat Bozok University	On convergence via δ-open sets in ideal topological spaces
ALI PEHLIVANLI RECEP SAHINGOZ	Yozgat Bozok University	The effect of heat-treatment duration on Vickers hardness and selected magnetic properties of $Fe_{39}Ni_{39}Mo_4Si_6B_{12}$ metallic glass alloy
EMINE TUGCE SARAC CEBECI FATIH TASTAN HATICE BAS	Yozgat Bozok University	Investigation of the effects of Medicago sativa L. methanol extract on mortality, acetylcholinesterase activity, and oxidative stress parameters in Galleria mellonella

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HEAD OF SESSION: Dr. BERNA YAVUZ PEHLIVANLI

Authors	Affiliation	Presentation Title
FATIH TASTAN EMINE TUGCE SARAC CEBECI HATICE BAS	Yozgat Bozok University	Evaluation of the inhibitory effects of trifolium campestre on selected enzymes
BERNA YAVUZ PEHLIVANLI	Yozgat Bozok University	From geological resources to advanced technology: nanotechnological applications of rare earth elements
MUSTAFA BATUHAN ERTEKIN BERNA YAVUZ PEHLIVANLI	Yozgat Bozok University	Investigation of the Neogene succession in the Niğde–Ulukışla basin: general geology, stratigraphy, and the evolution of bituminous shales within the Katrandedetepe formation
LEVENT YAZICI MEDINE COPUR DOGRUSOZ	Yozgat Bozok University	Evaluation of agro-industrial plant by-products as alternative feed sources in animal production
MEDINE COPUR DOGRUSOZ LEVENT YAZICI	Yozgat Bozok University	Potential utilization of hemp (cannabis sativa l.) plant residues as an alternative feed resource in animal production
ALI ONUR KAYA MERT CAN EMRE	Akdeniz University	Investigation of the effect of synthesis method on the magnetic properties of $COFe_2O_4$ nanoparticles
ALI ONUR KAYA MERT CAN EMRE	Akdeniz University	Machine learning applications in modern drug discovery: current advances, challenges, and future perspectives

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HEAD OF SESSION: Sadais Amjad

Authors	Affiliation	Presentation Title
Alexzender Anak Stapa Junaid M. Shaikh	Universiti Teknologi Brunei	Macroeconomic Determinants of Economic Growth: A Comparative Analysis of Brunei, Malaysia, and Singapore (2010–2023)
Yen Shin Chze@Amy Yen Junaid M. Shaikh	Universiti Teknologi Brunei	How Accounting Competencies Drive Audit Quality and IFRS Usefulness in Brunei and Malaysia
Abdul Wazeef A.M. Abdul Junaid M. Shaikh	Universiti Teknologi Brunei	Budgetary Practices and Financial Performance of Small and Medium Enterprises (SMEs) in Brunei Darussalam
Nurul Khairina binti Kamal Junaid M. Shaikh	Universiti Teknologi Brunei	Artificial Intelligence in Accounting Information Systems for ESG Reporting: Managerial and Economic Evidence from ASEAN
Anuar Gulshat Bekkozhanova Gulnar Manapova Gulzhan	Al-Farabi Kazakh National University	A Conceptual Analysis of the Binary Opposition "TRUTH/LIE" in English Literature: From Metaphysical Absolute to Postmodern Deconstruction
Aisha A. Ohieku Salisu Alhaji Nuhu	University of Abuja	Bridging nursing and engineering: advancing healthcare through innovation, ai, and human-centered design – a systematic review
Sadid Shahriyar	Sher-e-Bangla Agricultural University	Dendro-ecological zoning for semi-arid restoration: a data-driven species selection framework for the barind tract, bangladesh
Vyacheslav PRYLYUK	Taras Shevchenko University of Kyiv,	Hr management – key factor of competitiveness in modern business
Addra Noah Agbo	University Of Abuja,	Upholding Nursing Ethics: Maintaining Professional Boundaries in Practice. A study conducted in selected health Institutions in Nasarawa State, Nigeria
Sadais Amjad	The Islamia University of Bahawalpur,	Quantum-Enhanced AI: A Comparative Study of Classical and Quantum Machine Learning Models in Financial Applications
Palanisamy A. Deepak S. Muthuramalingam R.	Bharath institute of higher education and research Chennai	3D Printing of Medicines: Custom-Made Dosage Forms

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HEAD OF SESSION: Anna Kopiczko

Authors	Affiliation	Presentation Title
Anna Kopiczko Patrycja Widłak Joanna Cieplińska	*Józef Piłsudski University of Physical Education in Warsaw*	Determinants of skeletal health in elite athletes: associations among bone mineral density, lean mass, and bone stress injuries
Patrycja Widłak Anna Kopiczko Dariusz Boguszewski Aspasia Dania Piotr Bartnicki	*Józef Piłsudski University of Physical Education in Warsaw*	Multifactorial injury risk assessment in team sport athletes: integrating functional, morphological, and biochemical indicators
Anna Kopiczko Joanna Cieplińska Patrycja Widłak Artur Kruszewski	*Józef Piłsudski University of Physical Education in Warsaw*	Predictors of bone stress fractures in professional athletes: role of bone mineral density and muscle mass
Patrycja WIDŁAK Anna KOPICZKO Bartłomiej MICHALAK Marzena MALARA Joanna CIEPLIŃSKA	*Józef Piłsudski University of Physical Education in Warsaw*	Assessment of sports injury risk in professional karate athletes using fms and y-balance tests
Kamila Żarska Patrycja Widłak	*Józef Piłsudski University of Physical Education in Warsaw*	Eating disorders and body image in young female athletes: the impact of sports environment and type of discipline
Przemysław Kowalski Patrycja Widłak	*Józef Piłsudski University of Physical Education in Warsaw*	Lower limb injuries among male volleyball players in lower leagues: the scale of the problem and potential risk factors
Ayesha Batool Farkhanda Anjum Sobia Maqsood Shafiq-ur-Rehman Zia	University of Agriculture	Silent witnesses, hidden victims: examining the impact of domestic violence on children in punjab, Pakistan
N.K. Udaya Prakash Y. Gunashree S. Bhuvaneswari N. Preethi	Vels Institute of Science	Bio functional evaluation the biosoot of indian traditional medicine, vetiver
Fatima Mustapha Bindawa Abubakar Sani	Umaru Musa Yar'adua University	A Literature Review on Bauhinia rufescence leaves used for Anti-malarial activity
Inyang, B. U., Ekpo, E.I.	*Akwa Ibom State Polytechnic*	Mangrove-Inspired Design Strategies for Flood-Resilient Housing in the Niger Delta region of Nigeria

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Authors	Affiliation	Presentation Title
Lawal N.A. Omisande L.A.	*Federal Polytechnic Ilaro Ogun State*	The effectiveness of crystalline waterproofing admixture in hydrophobic concrete
Samira ZERBIB Khalid HILAL Ahmed KAJOUNI	*University Sultan Moulay Slimane*	Existence of Solutions for Nonlinear \(\psi\)-Hilfer Complex-Order Fractional Systems: An Integral Equation Approach
Khadija ELKHALLOUFY Manal MENCHIH Khalid HILAL Ahmed KAJOUNI	*University Sultan Moulay Slimane*	Linear Chaos and Strong Stability in the Conformable Von Foerster-Lasota Equation
Ozcan Mammadov, İsmail Karakaş, Fatma Aykut Tonk	*Ege University*	Characterization of some morphological characteristics and biological performance of Maize F3 Population under water stress condition
Mehmet Fatih YILMAZ Mahmut KAPLAN	*Malatya Turgut Özel University*	Seed Oil Quality of Hungarian Vetch (*Vicia pannonica* Crantz) Cultivars: Crude Oil Content and Fatty Acid Composition
Mehmet Fatih YILMAZ Mahmut KAPLAN Abdullah Yasin DALKILIÇ	*Malatya Turgut Özel University*	Characterization of Narrow-Leaved Vetch (*Vicia sativa* subsp. *nigra* (L.) Ehrh.) Genotypes Collected from Kahramanmaraş Natural Flora in Terms of Some Morphological and Seed Characteristics
Mesut TEKELİ İsmail KARAKAŞ Fatma AYKUT TONK	*Ege University*	A Study on the Agricultural and Technological Characteristics of Cotton F_2 Populations

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DFT, MEP AND MOLECULAR DOCKING ANALYSIS
1,3-BENZODIOXOLE-5-SULFONAMIDE
Geometry optimization • Theoretical IR/PED • FMO • MEP • hCA II docking
Dr. Yusuf SERT
Yozgat Bozok University, Yozgat, Türkiye

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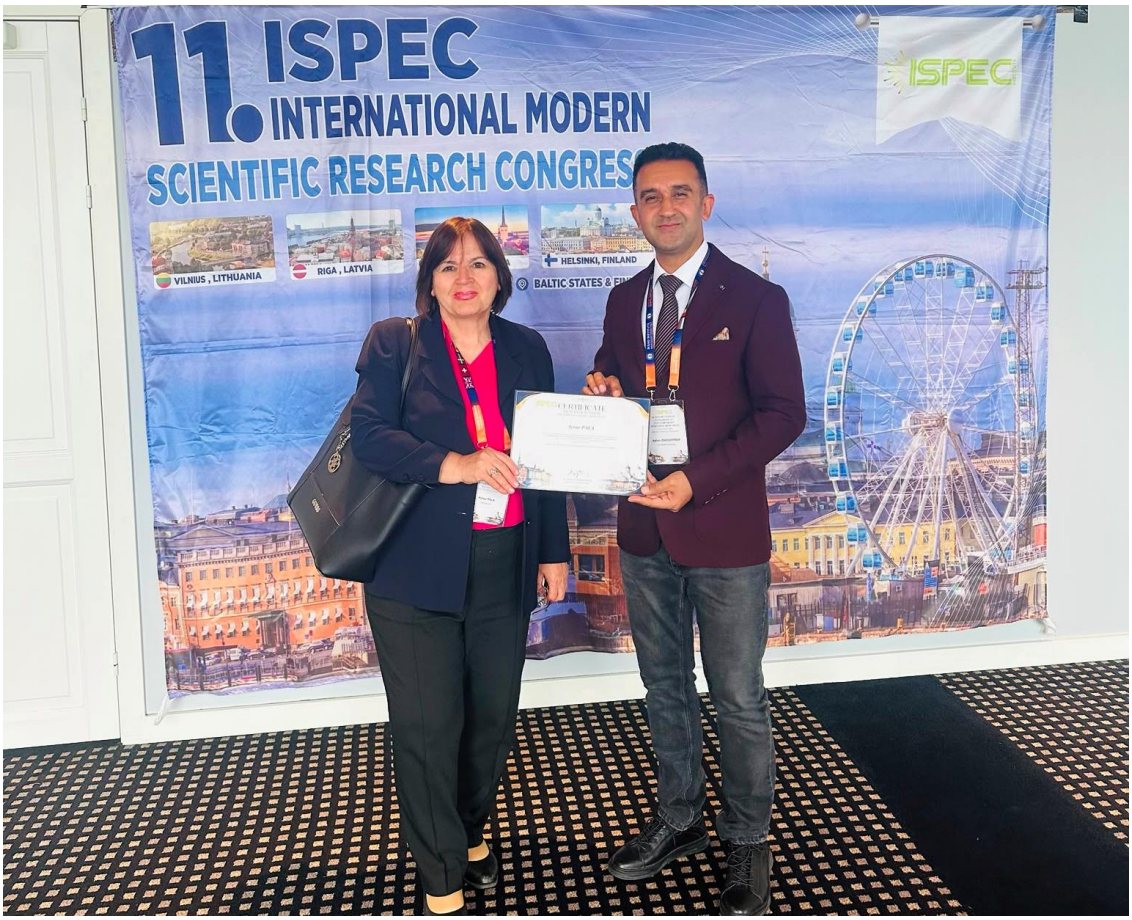
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COMPARISON OF THE PHYSICAL AND MECHANICAL PROPERTIES OF PELLETS PRODUCED FROM SAFFLOWER BIOMASS PREPARED AT DIFFERENT GRINDING SIZES

FARKLI ÖĞÜTME BOYUTLARINDA HAZIRLANAN ASPİR BİYOKÜTLESİNDEN ÜRETİLEN PELETLERİN FİZİKSEL VE MEKANİK ÖZELLİKLERİNİN KARŞILAŞTIRILMASI

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ÖZET

Aspir bitkisi, yağ ekstraksiyonundan sonra geriye kalan lignoselülozik biyokütle kullanılarak enerji üretimi için değerlendirilebilen önemli bir tarımsal kaynaktır. Bu biyokütlenin peletleştirme yoluyla yoğunlaştırılması, hem enerji yoğunluğunu artırma hem de depolama ve taşınabilirliği iyileştirme açısından avantajlar sunar. Bu çalışmada, öğütme inceliğinin ayçiçeği biyokütlesinden üretilen peletlerin kalite özellikleri üzerindeki etkisi araştırılmıştır. Çalışma kapsamında, ayçiçeği materyali, 10 mm, 14 mm ve 18 mm'lik elek açıklıklarına sahip bıçaklı bir değirmende öğütülerek üç farklı parçacık boyutu hazırlanmıştır. Elde edilen hammaddeler kullanılarak 6 mm çapında peletler üretilmiştir. Üretilen peletlerin kalite özelliklerini belirlemek amacıyla çap, uzunluk, ağırlık, parçacık yoğunluğu, kırılma mukavemeti, mekanik dayanıklılık ve diğer fiziko-mekanik özellikler gibi parametreler analiz edilmiştir. Bulgular, öğütme inceliğinin peletlerin fiziksel bütünlüğünü ve mekanik mukavemetini önemli ölçüde etkilediğini göstermektedir. Daha ince öğütülmüş malzemelerden üretilen peletlerin daha homojen bir yapı ve daha yüksek yoğunluk değerleri sergilediği gözlemlenmiştir. Buna karşın, daha iri taneli malzemelerden üretilen peletler, daha fazla yapısal düzensizlik ve daha düşük mekanik mukavemet sergilemiştir. Ayrıca, öğütme inceliğinin peletlerin boyut ve ağırlık dağılımını da etkilediği tespit edilmiştir. Bu sonuçlar, pelet üretiminde hammaddenin parçacık boyutunun optimize edilmesinin kalite parametreleri açısından kritik bir rol oynadığını göstermektedir. Çalışma, pelet yakıtı olarak kavak biyokütlesinin potansiyelini vurgulamakta ve uygun öğütme koşullarının belirlenmesine ilişkin önemli bilgiler sunmaktadır. Bulguların, enerji üretiminde tarımsal atıkların daha verimli kullanımına katkıda bulunacağı öngörülmektedir.

Anahtar kelimeler: Yenilenebilir enerji, biyokütle, tarımsal atık, pelet yakıtı, aspir, öğütme inceliği

ABSTRACT

The safflower plant is an important agricultural resource that can be utilized for energy production using the lignocellulosic biomass remaining after oil extraction. Concentrating this biomass through pelletization offers advantages in terms of both increasing energy density and improving storage and transportability. In this study, the effect of grinding fineness on the quality characteristics of pellets produced from sunflower biomass was investigated. As part of the study, sunflower material was ground in a knife-type mill with screen apertures of 10 mm, 14 mm, and 18 mm to prepare three different particle sizes. Using the resulting raw materials, pellets with a diameter of 6 mm were produced. To determine the quality characteristics of the produced pellets, parameters such as diameter, length, weight, particle density, breaking strength, mechanical durability, and other physico-mechanical properties were analyzed. The findings indicate that the fineness of grinding significantly affects the physical integrity and mechanical strength of the pellets. It was observed that pellets produced from finer-ground materials exhibited a more homogeneous structure and higher density values. In contrast, pellets produced from coarser particle materials exhibited greater structural irregularities and lower mechanical strength. Additionally, it was found that grinding fineness also affects the size and weight distribution of the pellets.

These results demonstrate that optimizing the particle size of the raw material in pellet production plays a critical role in terms of quality parameters. The study highlights the potential of aspen biomass as a pellet fuel and provides important insights into determining appropriate grinding conditions. It is anticipated that the findings will contribute to the more efficient use of agricultural waste in energy production.
Keywords: Renewable energy, biomass, agricultural waste, pellet fuel, safflower, grinding fineness

INTRODUCTION

Limitations in fossil energy resources, fluctuations in energy prices, and the environmental impacts of production and consumption processes have accelerated studies on renewable energy sources. In this context, plant residues generated as a result of agricultural production are an important biomass resource because they are locally accessible and contain organic matter that can be utilized for energy production. The uncontrolled disposal of agricultural residues in fields, their burning, or their storage under unsuitable conditions may cause environmental and economic losses. In contrast, converting these residues into solid biofuel provides an applicable approach that combines waste management with energy production (Yaman, 2012; Miranda et al., 2015). Biomass materials may naturally have low bulk density, irregular geometric structure, and variable moisture properties. These characteristics create significant difficulties in transportation, storage, feeding, and combustion systems. Pelletization reduces a substantial part of these limitations by converting ground biomass into a cylindrical and denser form under pressure. As a result of pelletization, a fuel with more homogeneous dimensions, higher volumetric energy density, and better flow properties can be obtained. However, pellet quality is shaped not only by the pressing process but also by the combined effects of numerous variables, including the type and chemical composition of the raw material, moisture content, particle size, die geometry, pressing pressure, and temperature (Miranda et al., 2015; Mostafa et al., 2019).

The grinding process in pellet production is one of the main preparation stages that directly affects the feeding of the raw material into the die and the contact area formed between particles. Smaller particles can fill the voids within the die more effectively, increase the contact surface between particles, and enable the pellet to acquire a more homogeneous structure. In contrast, excessively fine grinding may increase energy consumption and may also limit production capacity by increasing die friction in some biomass materials. Coarser particles may require less energy for grinding; however, they may cause void formation within the pellet, an irregular surface structure, and low mechanical durability. Therefore, determining an appropriate particle size is one of the main elements in establishing a balance between pellet quality and production energy (Mostafa et al., 2019; Williams et al., 2018). Pellet density expresses the volume occupied by the biomass mass within the pellet and indicates the extent to which the pelletization process provides successful compaction. High pellet density is generally advantageous because more fuel can be stored and transported per unit volume. Nevertheless, density alone is not sufficient to explain pellet quality. The ability of pellets to maintain their integrity without disintegration during transportation and use requires the evaluation of properties such as mechanical durability and breaking strength. The formation of fine material increases in pellets with low mechanical durability; this may cause storage losses, blockages in fuel-feeding systems, and dust-related safety risks (Williams et al., 2018; Rupasinghe et al., 2023). The bulk behavior of the ground raw material is also an important indicator of the pelletization process. Material density shows the extent to which ground biomass can be packed within a specific volume. Particle shape, size, and size distribution determine this value. Although more voids may remain between coarse and fibrous particles, the presence of particles of different sizes in appropriate proportions can allow smaller particles to fill the spaces between larger particles and contribute to an increase in bulk density. Therefore, the finest grinding level should not always be expected to produce the highest material density. Studies on biomass pellets have shown that the effect of particle size may vary depending on the material type and particle-size distribution (Gendek et al., 2023; Rupasinghe et al., 2023).

Safflower (*Carthamus tinctorius L.*) is an annual plant grown for its oil-rich seeds and is capable of adapting to arid and semi-arid conditions. Stems, branches, and other lignocellulosic components generated after oil production or harvesting often remain as residues with low economic value. The utilization of these residues in pellet-fuel production may contribute to increasing the added value obtained from the safflower production chain and to the more efficient use of agricultural biomass.

However, merely obtaining pellets is not sufficient for evaluating the usability of a new biomass resource in pellet production. Quality indicators such as the dimensional properties, density, breaking strength, and mechanical durability of the produced pellets must be examined together.

Studies on the pelletization of agricultural and industrial residues have demonstrated that different raw materials may exhibit substantially different physical and mechanical properties. Research conducted on tea factory wastes, pistachio shells, olive pomace, woody residues, and different biomass mixtures has reported that raw-material structure, moisture, and particle size are determining factors for pellet density and durability (Bilgin et al., 2016; Develi et al., 2021; Artemio et al., 2018; Gendek et al., 2023). This indicates that suitable preparation and pelletization conditions must be determined separately for each biomass source.

The aim of this study was to compare the physical and mechanical properties of 6 mm diameter pellets produced from safflower biomass ground through screen apertures of 10, 14, and 18 mm. For this purpose, ground-material density, pellet diameter, pellet length, pellet weight, pellet density, breaking strength, and mechanical durability were determined. The effect of grinding size on pellet quality was evaluated using the obtained results, and the potential of safflower agricultural residues for pellet-fuel production was discussed.

MATERIAL AND METHOD

The material of the study consisted of lignocellulosic agricultural residues obtained after the harvest of safflower (*Carthamus tinctorius L.*). Safflower plants were cultivated in the experimental field of the Faculty of Agriculture at Erciyes University, and the plant material obtained after harvest was transported to the laboratories of the Department of Biosystems Engineering, Faculty of Agriculture, Erciyes University. Foreign materials were removed, and the material was sun-dried under natural conditions to reduce its initial moisture content. The dried safflower material was ground in a knife-type mill. Screen apertures of 10, 14, and 18 mm were used during grinding, thereby forming three different grinding groups. Grinding sizes refer to the screen apertures used in the mill. The resulting ground materials were stored separately to prevent mixing, and the pelletization process was carried out under the same operating conditions. A laboratory-scale pellet mill was used for pellet production. The material obtained from each grinding group was fed continuously and uniformly into the machine, and pellets with a nominal diameter of 6 mm were produced in all groups. Thus, grinding size constituted the independent variable of the study, whereas pellet diameter and other production conditions were kept constant among the groups. The experimental design was established as a single-factor structure consisting of 10, 14, and 18 mm grinding sizes. Three replications were used for each grinding group in the statistical evaluation of the physical and mechanical properties.

Determination of ground-material density

A container with a known volume was used to determine the mass of ground safflower biomass per unit volume. The empty container was first weighed using a balance with a sensitivity of 0.01 g, after which the materials prepared at grinding sizes of 10, 14, and 18 mm were freely filled into the container. No additional compaction was applied during filling; the top surface of the container was leveled, and the mass of the filled container was recorded. Material density was calculated in kg m^{-3} by dividing the net mass of the material in the container by the container volume. Measurements were performed in three replications for each grinding size.

Determination of the dimensional properties and weight of pellets

The diameters and lengths of pellets randomly selected from each grinding group were measured using a digital caliper. Pellet diameter and length were recorded in meters, and the values were converted to millimeters for presentation of the findings. Pellet mass was determined using a balance with a sensitivity of 0.01 g. Mean measurement values from three replications for each grinding size were used in the statistical analysis.

Determination of pellet density

Pellet density was determined based on estimating the volume of uniformly cylindrical solid biofuels using the stereometric method. Pellet volume was calculated from the measured diameter and length values using the following equation:

$V_p = \pi D^2 L / 4$

In this equation, V_p represents pellet volume (m^3), D represents pellet diameter (m), and L represents pellet length (m). Pellet density was then determined by dividing pellet mass by the calculated volume:

$\rho_p = m_p / V_p$

In the equation, ρ_p represents pellet density (kg m^{-3}), m_p represents pellet mass (kg), and V_p represents pellet volume (m^3). The calculation approach was based on the stereometric method used to determine the particle density of uniformly shaped pellets.

Determination of mechanical durability

A 50 g pellet sample was used for each grinding group in the mechanical durability test. Pellet samples were rotated in a tumbler test apparatus for 10 minutes and, after completion of the test, were passed through a sieve with a 3.15 mm aperture. The mass of the pellets retained on the sieve was measured using a balance with a sensitivity of 0.01 g. Mechanical durability was calculated by dividing the mass retained on the sieve after the test by the sample mass before the test:

$MD = (m_s / m_i) \times 100$

In the equation, MD represents mechanical durability (%), m_s represents the pellet mass retained on the sieve after the test (g), and m_i represents the pellet mass before the test (g). The test was performed in three replications for each grinding size. Mechanical durability was evaluated as an indicator of the ability of pellets to maintain their integrity against abrasion and impacts during transportation and use.

Determination of breaking strength

To determine breaking strength, pellets randomly selected from each grinding group were subjected to compression between two parallel plates. Loading was continued until fracture occurred in the pellet structure, and the maximum resistance at the moment of fracture was recorded. The results were evaluated in MPa. Values from three replications for each grinding size were included in the statistical analysis. This test represents the capacity of an individual pellet to maintain its structural integrity under compressive loading.

Statistical analysis

The data were evaluated using one-way analysis of variance to determine the effect of grinding size on pellet properties. A 95% confidence level was used to determine differences among the groups, and Duncan's multiple comparison test was applied to the properties for which significant differences were found. The statistical significance level was accepted as $p<0.05$. The results were presented as mean ± standard deviation. Multiple-comparison groups for mechanical durability were reported according to the experimental analysis results, whereas ground-material density was evaluated descriptively using the available mean values.

RESULTS AND DISCUSSION

Ground-material density

The material density values of safflower biomass ground through different screen apertures are presented in Table 1. Material density varied between 192.04 and 217.64 kg m^{-3}. The highest value was obtained at the 14 mm grinding size, with 217.64 kg m^{-3}, whereas the lowest value was obtained at the 18 mm grinding size, with 192.04 kg m^{-3}. The material density at the 10 mm grinding size was determined as 197.94 kg m^{-3}.

Table 1. Density of safflower material at different grinding sizes

Grinding size	Material density (kg m^{-3})
10 mm	197.94
14 mm	217.64
18 mm	192.04

The higher material density in the 14 mm grinding group suggests that the particles in this group formed a more suitable packing arrangement within the bulk. Although finer particles would be expected in the 10 mm group, in which the smallest screen aperture was used, the fact that material density did not reach its highest value indicates that not only mean particle size but also particle shape and size distribution affect bulk behavior. The coexistence of particles of different sizes may increase bulk density by allowing smaller particles to fill the voids between larger particles. In contrast, the coarser and more fibrous structure in the 18 mm grinding group may have caused more voids to remain between particles. The grinding and densification behavior of biomass may vary considerably depending on the fibrous structure of the raw material and particle geometry. Gendek et al. (2023) reported that particle arrangement affected the physico-mechanical properties of pellets produced from different lignocellulosic materials. Rupasinghe et al. (2023) also emphasized that particle size and distribution, together with the material used and pelletization conditions, are among the main variables determining pellet quality. The high material density obtained at the 14 mm grinding size in this study indicates that an intermediate grinding size may be advantageous for the bulk packing of safflower biomass.

Physical and mechanical properties of the pellets

The diameter, length, weight, pellet density, breaking strength, and mechanical durability values of pellets produced from different grinding sizes are presented in Table 2. Although a die with a nominal diameter of 6 mm was used in all groups, the measured diameter values varied between 5.93 and 6.23 mm. No statistically significant difference was determined among the grinding groups in terms of pellet diameter ($p=0.109$). This result indicates that pellet diameter was primarily determined by die geometry and that changes in grinding size within the range of 10-18 mm had a limited effect on the final diameter.

Table 2. Physical and mechanical properties of safflower pellets produced at different grinding sizes

Grinding size	Pellet diameter (mm)	Pellet length (mm)	Pellet weight (g)	Pellet density (kg m^{-3})	Breaking strength (MPa)	Mechanical durability (%)
10 mm	5.93 ± 0.24	20.42 ± 1.17	0.517 ± 0.066	914.46 ± 68.89^{a}	1.16 ± 0.11^{a}	99.13^{b}
14 mm	6.23 ± 0.11	19.33 ± 3.27	0.737 ± 0.126	626.14 ± 16.74^{b}	0.85 ± 0.10^{ab}	99.70^{a}
18 mm	5.93 ± 0.09	18.09 ± 0.97	0.660 ± 0.066	662.17 ± 81.94^{b}	0.56 ± 0.26^{b}	96.59^{c}

Note: Values are presented as mean ± standard deviation. Means indicated by different superscript letters within the same column are significantly different according to Duncan's test ($p<0.05$).

Pellet length varied between 18.09 and 20.42 mm; the highest mean was obtained in the 10 mm grinding group and the lowest mean in the 18 mm grinding group. However, the difference among the groups was not statistically significant ($p=0.443$). Although a numerical decrease in pellet length was observed as grinding size increased, particularly the high variability in the 14 mm group prevented this trend from being statistically confirmed. Pellet length does not depend solely on grinding size because it is affected by the fracture behavior of the compacted material leaving the die. The feeding pattern, friction at the die outlet, and the mechanical effects to which pellets are exposed during cooling may also alter the length distribution.

Pellet weight was determined as 0.517 ± 0.066 g in the 10 mm grinding group, 0.737 ± 0.126 g in the 14 mm group, and 0.660 ± 0.066 g in the 18 mm group. Although the effect of grinding size on pellet weight was not significant at the 5% significance level, the p value of 0.063 indicates that there was a clear numerical trend among the groups. The highest pellet weight obtained in the 14 mm group demonstrates that the pellets in this group could reach higher mass values even though their mean length was lower. This indicates that pellet weight is affected not only by geometric dimensions but also by the degree of compaction within the pellet and by structural differences among individual pellets.

Pellet density

The effect of grinding size on pellet density was statistically significant (F=18.919; p=0.003). The highest pellet density was obtained in the 10 mm grinding group, with 914.46 ± 68.89 kg m^{-3}. Pellet densities in the 14 and 18 mm groups were determined as 626.14 ± 16.74 and 662.17 ± 81.94 kg m^{-3}, respectively, and these two groups were included in the same statistical group. Accordingly, pellets produced at the 10 mm grinding size had a substantially denser structure than those produced from coarser grinding groups.

The increase in pellet density obtained from the material prepared through a 10 mm screen aperture can be explained by the ability of smaller particles to fill the voids within the die more effectively. As particle size decreases, the total contact surface increases and particles can approach one another more easily under pressure. Consequently, the void volume within the pellet decreases and the mass per unit volume increases. Williams et al. (2018) stated that a small particle size can improve the mechanical properties of pellets, whereas Mostafa et al. (2019) indicated that grinding level and pelletization conditions jointly affect density and mechanical strength. The results obtained in the present study are consistent with this general approach, indicating that more finely prepared safflower biomass forms a more compact pellet structure.

Another noteworthy result was that the 14 mm group, which had the highest ground-material density, produced the lowest mean pellet density. This finding demonstrates that the packing behavior of the raw material in a freely formed bulk and its compaction behavior under pressure during pelletization are not identical. The 14 mm material exhibited a high bulk density when freely filled into the container; however, it did not bind within the die as effectively as the smaller particles. Therefore, high material density alone does not guarantee high pellet density. The deformability of particles, contact area, and activation of natural binding components under pressure may be more decisive for pellet density.

Pellet density is known to provide an important advantage for fuel logistics. High density allows a greater amount of biomass to be stored within the same transportation and storage volume. Miranda et al. (2015) stated that densification reduces problems arising from the low volumetric density of biomass. Rupasinghe et al. (2023) demonstrated that pellet density and bulk density vary depending on raw-material composition, particle distribution, and production conditions. In this respect, the pellet density of 914.46 kg m^{-3} obtained in the 10 mm grinding group indicates that safflower residues can be converted into a dense solid-biofuel form.

Breaking strength

A statistically significant difference was determined among grinding groups in terms of breaking strength (F=9.125; p=0.015). The highest breaking strength was obtained in the 10 mm group, with 1.16 ± 0.11 MPa, whereas the lowest value was obtained in the 18 mm group, with 0.56 ± 0.26 MPa. According to Duncan's multiple comparison test, the 10 mm group was included in group a and the 18 mm group in group b, whereas the 14 mm grinding group, with a value of 0.85 ± 0.10 MPa, was included in the intermediate ab group shared with both groups.

As grinding size increased from 10 to 18 mm, breaking strength decreased by approximately half. This trend suggests that coarse particles may form larger voids and weak contact regions within the pellet cross-section. The greater contact surface of finer particles may have created a more homogeneous internal structure under pelletization pressure and increased pellet resistance to compression. The intermediate value obtained in the 14 mm group supports the generally inverse relationship between grinding size and breaking strength.

The similar ranking of the breaking-strength and pellet-density results is important.

The 10 mm pellets, which had the highest density, also exhibited the highest breaking strength, whereas breaking strength decreased in the lower-density 14 and 18 mm pellets. This indicates that a reduction in voids within the pellet and an increase in interparticle bonding improve compressive resistance. Nevertheless, the relationship between density and mechanical resistance may not be the same for every biomass type. Variables such as raw-material composition, fiber orientation, and pelletization temperature may also affect fracture behavior (Williams et al., 2018).

Williams et al. (2018) stated that the mechanical properties of biomass pellets are important for evaluating their behavior during transportation, storage, and grinding processes; however, different mechanical tests represent different loading conditions of the pellet. Therefore, the breaking strength determined in this study reflects the behavior of an individual pellet under compression and should be evaluated together with the mechanical durability test. The high density and high breaking strength of the 10 mm group demonstrate that this grinding size is advantageous in terms of individual-pellet integrity.

Mechanical durability

Mechanical durability values were above 96% in all grinding groups. The highest mechanical durability was determined in the 14 mm grinding group, with 99.70%, followed by the 10 mm group with 99.13%. The lowest value was obtained at the 18 mm grinding size, with 96.59%. The three grinding groups were represented by different letters in the multiple-comparison results, and grinding size was determined to have a significant effect on mechanical durability.

Mechanical durability indicates the resistance of pellets to disintegration under repeated impact and friction. Unlike the breaking test applied to an individual pellet, this parameter represents the behavior of a group of pellets under collective transportation and handling conditions. Therefore, the highest mechanical durability observed in the 14 mm group demonstrates that these pellets were highly stable under the abrasion and impact conditions of the tumbler test, although they did not constitute the group with the highest individual-pellet breaking strength.

Although the mechanical durability of the 10 mm group was also very high, it was lower than that of the 14 mm group. Fine grinding increased pellet density and compressive resistance, whereas the highest durability in the tumbler test occurred at the intermediate grinding size. This may be related to an excessively fine structure forming brittle regions on the pellet surface or to differences in pellet response to surface abrasion during testing. On the other hand, in the 14 mm group, particles may have been sufficiently small to provide adequate bonding while remaining sufficiently coarse to support the pellet framework, thereby increasing mechanical durability. This interpretation is consistent with the approach that particles of different sizes can form an appropriate structural framework.

The decrease in mechanical durability to 96.59% in the 18 mm grinding group suggests that coarse particles formed weak bonding regions within the pellet structure. Williams et al. (2018) reported that pellets with low durability produce more fine material during transportation and processing. Rupasinghe et al. (2023) emphasized that mechanical durability is determined by the combined effects of raw-material properties, particle size, moisture, and pelletization conditions. Although the high values obtained in all groups in this study indicate that safflower biomass can be converted into durable pellets without the addition of a binder, the results also demonstrate that 18 mm grinding produced a lower-quality outcome.

The fact that the highest pellet density and mechanical durability values were obtained in different grinding groups clearly demonstrates that pellet quality should not be evaluated using a single parameter. Grinding at 10 mm provided superiority in terms of pellet density and breaking strength, whereas grinding at 14 mm produced the best results for material density and mechanical durability. In contrast, 18 mm grinding produced the lowest values for both breaking strength and mechanical durability. Therefore, the selection of the optimum grinding size should be based on the intended use and the priority quality criterion.

Evaluation of the overall effect of grinding size

When all results of the study are evaluated together, grinding size appears to have substantially changed the quality profile of safflower pellets. No statistical difference occurred in dimensional properties, particularly pellet diameter and length.

This indicates that pellet geometry was largely determined by die diameter and outlet conditions. Although the 14 mm group produced a higher mean pellet weight, the fact that the difference was not significant at $p<0.05$ demonstrates that this property alone is insufficient to explain the effect of grinding.

The most evident quality differences occurred in pellet density, breaking strength, and mechanical durability. High pellet density and breaking strength were obtained in the 10 mm grinding group as a result of the tight packing of small particles. In the 14 mm grinding group, freely formed material density and mechanical durability reached their highest levels. These results indicate that intermediate-size particles may positively affect the collective impact and abrasion behavior of pellets. The lower mechanical properties observed in the 18 mm group suggest that pelletizing safflower biomass with coarser particles may weaken internal structural integrity.

Grinding energy and product quality should be evaluated together in pellet production. Finer grinding generally consumes more energy, although it may form denser and more resistant pellets. In this study, the 10 mm grinding size provided the highest density and breaking strength; however, the 14 mm group produced a better result in terms of mechanical durability. In industrial applications, not only laboratory quality parameters but also mill energy consumption, pelletization capacity, die wear, and unit product cost should be considered. Mostafa et al. (2019) stated that pelletization conditions affect energy consumption together with physical and mechanical properties. Therefore, it would be beneficial to measure grinding and pelletization energy requirements within the same experimental design in future studies.

The high mechanical durability values obtained for safflower biomass are a positive indicator that this material can be used in the production of agricultural-residue-based pellet fuel. Nevertheless, for a comprehensive evaluation of pellets as fuel, calorific value, ash content, volatile matter, fixed carbon, elemental composition, and combustion emissions should also be determined. Miranda et al. (2015) emphasized that ash content and elemental composition, as well as physical quality, determine the utilization class of pellets obtained from different agricultural sources. Therefore, the present results demonstrate the physical and mechanical suitability of safflower pellets, while also indicating that complementary analyses are required for final fuel classification.

CONCLUSION

In this study, pellets with a diameter of 6 mm were produced from safflower biomass ground through screen apertures of 10, 14, and 18 mm, and the effect of grinding size on physical and mechanical quality properties was investigated. Ground-material density varied between 192.04 and 217.64 kg m^{-3}, and the highest value was obtained at the 14 mm grinding size. This result demonstrated that the intermediate grinding size provided more effective packing of safflower material in a freely formed bulk.

No statistically significant difference was determined among grinding groups in terms of pellet diameter and length. The 14 mm group produced the highest mean pellet weight; however, the difference was not significant. In contrast, pellet density and breaking strength were significantly affected by grinding size. The highest pellet density, 914.46 kg m^{-3}, and the highest breaking strength, 1.16 MPa, were obtained in the 10 mm grinding group. This group demonstrated that more finely prepared safflower material can form a more compact structure within the die.

Mechanical durability was high in all groups. The highest mechanical durability was determined at the 14 mm grinding size, with 99.70%, whereas the lowest mechanical durability was obtained at the 18 mm grinding size, with 96.59%. Thus, the 10 mm grinding size was prominent in terms of density and breaking strength, whereas the 14 mm grinding size was prominent in terms of material density and mechanical durability. The 18 mm grinding size showed lower performance, particularly in terms of breaking strength and mechanical durability.

The results demonstrate that an optimum grinding size for safflower-pellet production cannot be selected based on a single quality criterion. A 10 mm grinding size appears more appropriate for applications in which high pellet density and individual-pellet compressive strength are prioritized, whereas a 14 mm grinding size appears more appropriate when abrasion resistance during transportation and storage is prioritized. Considering the overall quality balance, grinding within the range of 10-14 mm was concluded to constitute a suitable processing range for safflower biomass, whereas 18 mm grinding may reduce mechanical quality.

Future studies should evaluate wider particle-size ranges, different moisture contents, pelletization temperature, and die pressure together. It is recommended that the energy consumed during grinding and pelletization be measured and that the quality improvement be examined together with its energy cost. In addition, the calorific value, ash content, combustion behavior, flue-gas emissions, and long-term storage stability of the pellets should be determined. These analyses will enable a more comprehensive assessment of the usability of safflower agricultural residues as commercial pellet fuel.

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STRUCTURAL AND FUNCTIONAL EVALUATION OF A ROBOTIC ARM DEVELOPED FOR AN AUTONOMOUS HARVESTING ROBOT

OTONOM BİR HASAT ROBOTU İÇİN GELİŞTİRİLEN ROBOTİK KOLUN YAPISAL VE İŞLEVSEL DEĞERLENDİRİLMESİ

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ÖZET

Modern tarım uygulamalarında otomasyonun yaygınlaşması, bitki üretiminde tekrarlayan ve hassas görevleri yerine getirmek üzere robotik sistemlerin kullanımına yönelik araştırmaları hızlandırmıştır. Bu sistemlerde, bitkiyi sadece tespit etmek yeterli değildir; bitkiye fiziksel olarak ulaşmak ve ona zarar vermeden hasat etmek de büyük önem taşımaktadır. Bu nedenle, robotik kol tasarımı, hasat robotlarının performansını doğrudan belirleyen temel faktörlerden biridir. Bu çalışma, ekibimiz tarafından geliştirilen otonom hasat robotunun robotik kol yapısını ve bunun sistemle entegrasyonuna yönelik yaklaşımı ele almaktadır. Robotik kolun tasarım sürecinde, sera ortamlarındaki çalışma koşulları, bitki yapısı ve hasat senaryoları dikkate alınarak uygun hareket kabiliyeti ve erişim aralığı sağlanmıştır. Hedef mahsulün hassas bir şekilde işlenebilmesini sağlamak için eklem yapısı, bağlantı elemanları ve uç efektör uyumluluğu değerlendirilmiştir. Ayrıca, robot kolunun görüntü işleme biriminden gelen konum verileriyle senkronize çalışabilmesini sağlamak amacıyla algılama ve hareket kontrol alt sistemleri arasındaki veri akışı incelenmiştir. Bu bağlamda, algılanan ürünün koordinat bilgilerinin robot koluna aktarılması ve uygun hareket komutlarının üretilmesi süreci ele alınmıştır. Bulgular, robot kolun yalnızca mekanik bir yapı olarak değil, algılama ve kontrol sistemleriyle birlikte çalışan entegre bir bileşen olarak değerlendirilmesi gerektiğini göstermektedir. Bu yaklaşım, hasat robotlarının daha istikrarlı ve hassas çalışmasına katkıda bulunmaktadır. Bu çalışmanın, sera koşullarında kullanıma uygun otonom hasat sistemleri geliştirmeyi amaçlayan tasarım ve uyarlama süreçleri için bir kılavuz görevi göreceğine inanılmaktadır.

Anahtar kelimeler: Akıllı tarım, tarım robotları, robotik kol, kinematik yapı, hareket kontrolü
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ABSTRACT

The spread of automation in modern agricultural practices has accelerated research into the use of robotic systems to perform repetitive and precise tasks in crop production. In these systems, it is not sufficient merely to detect the crop; physically accessing it and harvesting it without causing damage is also of great importance. For this reason, robotic arm design is one of the key factors that directly determines the performance of harvesting robots. This study addresses the robotic arm structure for the autonomous harvesting robot developed by our team, as well as the approach to its integration with the system. During the robotic arm's design process, appropriate mobility and access range were ensured by considering the working conditions in greenhouse environments, plant structure, and harvesting scenarios. The joint structure, connection elements, and end-effector compatibility were evaluated to enable precise manipulation of the target crop. Additionally, the data flow between the sensing and motion control subsystems was examined to ensure the robotic arm could operate in sync with the position data from the image processing unit. In this context, the process of transferring the detected product's coordinate information to the robotic arm and generating appropriate motion commands was addressed. The findings indicate that the robotic arm should be considered not merely as a mechanical structure, but as an integrated component that works in conjunction with sensing and control systems.

This approach contributes to more stable, precise operation of harvesting robots. It is believed that this study serves as a guide for the design and adaptation processes aimed at developing autonomous harvesting systems suitable for use in greenhouse conditions.
Keywords: Smart agriculture, agricultural robots, robotic arm, kinematic structure, motion control
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INTRODUCTION

The aging of the agricultural workforce, the movement of the young population away from rural areas, and the increasing difficulty of finding qualified workers during harvesting periods increase the need for automation technologies. Harvesting is a critical production stage that must be carried out at the right time according to the maturity level of the crop, requires intensive labor, and directly affects product quality. In harvesting based on human labor, processing time and product quality may vary due to fatigue, time pressure, working conditions, and worker experience. Agricultural robots provide an alternative to these problems through their ability to perform repetitive tasks according to specified standards, operate continuously for long periods, and use sensor data in decision-making processes (Bechar and Vigneault, 2016; Droukas et al., 2023).

The successful performance of agricultural robots does not depend solely on the development of a platform with autonomous mobility. The crop must be detected under environmental conditions, its maturity status must be determined, its three-dimensional position must be calculated, it must be approached through a safe trajectory, and it must be detached from the plant using an appropriate end-effector. Each of these tasks requires the coordinated operation of different sensing, computational, and mechanical subsystems. Bac et al. (2014) stated that detection, accessibility, cycle time, and product damage are the main performance criteria in harvesting robots for high-value crops. Current reviews also emphasize that the success of robotic harvesting systems depends on the combined consideration of image processing, depth sensing, manipulator design, motion planning, and end-effector technologies (Droukas et al., 2023; Miao et al., 2023).

Although greenhouse environments are considered controlled production areas for robotic harvesting, they contain important structural difficulties in practice. The limited passage area between plant rows, partial occlusion of the crop by leaves and branches, reflections caused by sunlight and artificial lighting, the presence of crops of different sizes within the same field of view, and the natural movement of the plant complicate the decision-making process of the robotic system. In addition, factors such as humidity, temperature, dust, and irrigation water inside the greenhouse require the protection of mechanical and electronic components. Therefore, unlike fixed and orderly working areas on industrial production lines, an agricultural robotic arm should be designed to adapt to variable environmental conditions. There are two basic approaches in robotic harvesting applications: bulk harvesting and selective harvesting. In bulk harvesting, the crops on the plant are removed during the same operation without maturity discrimination, whereas in selective harvesting only crops at the desired maturity or quality level are targeted. Although selective harvesting enables the preservation of product quality and the separate collection of fruits that ripen at different times, it requires a more complex structure in terms of sensing and manipulation. Studies conducted on crops such as strawberries, tomatoes, and apples have shown that precise three-dimensional positioning and crop-specific end-effector design are critical for selective harvesting (Feng et al., 2014; Feng et al., 2018; Benavides et al., 2020; Miao et al., 2023).

The robotic arm is the main subsystem that performs the physical interaction between the mobile platform and the crop. The degrees of freedom of the arm, link lengths, joint arrangement, payload capacity, structural rigidity, and controllability directly affect the workspace and harvesting success. An insufficient number of degrees of freedom may prevent the formation of an appropriate approach angle, particularly when the crop is located behind leaves or branches. Conversely, an unnecessarily complex joint structure may increase system cost, weight, and control load. Therefore, a balance must be established between accessibility and mechanical simplicity during the design process. The end-effector attached to the endpoint of the robotic arm in harvesting robots is of particular importance for product integrity because it comes into direct contact with the crop. The end-effector must grasp the crop with sufficient force without applying excessive pressure that may cause crushing, scratching, or surface damage. While pulling and twisting movements are sufficient for some crops, the stem must be cut for

others. Therefore, structures in which grasping and cutting functions are combined in a single module may provide adaptability to different harvesting scenarios. The modular attachment of the end-effector to the robotic arm allows components intended for different crops to be replaced easily. A coordinate transformation must be performed between detection of the crop by the image processing system and access to the crop by the robotic arm. The pixel position and depth information obtained from the camera are first transformed into a three-dimensional point in the camera coordinate system. This point is then transferred to the base reference system of the robotic arm. Calibration errors in the transformation chain may cause the arm to approach the target from an incorrect point. Günen (2022) demonstrated that three-dimensional point cloud data can be used to determine fruit position. Ruybalid et al. (2025) reported that a dual-camera depth-sensing approach can improve precision in positioning clustered crops.

The aim of this study is to evaluate the structural and functional characteristics of the six-degree-of-freedom robotic arm belonging to an autonomous harvesting robot developed for use under greenhouse conditions. The mechanical structure, joint arrangement, end-effector compatibility, approach to working with coordinates received from the sensing unit, inverse-kinematics-based motion generation, and control architecture of the robotic arm were considered together. Rather than presenting a completed field performance experiment, the study focuses on examining the developed design in terms of system requirements and defining the criteria to be used in subsequent prototype validations.

MATERIAL AND METHOD

The study is based on the structural and functional evaluation of the robotic arm developed for use in an autonomous harvesting robot and the sensing-control chain connected to this arm. The system was considered as consisting of a mobile robot platform, a six-degree-of-freedom robotic arm, an end-effector, an RGB-D imaging unit, embedded control boards, a minicomputer, motor drivers, and a portable power unit. When determining the evaluation criteria, narrow working areas inside the greenhouse, the irregular geometry of plants, the presence of the crop at different heights and angles, leaf cover, and the requirement to harvest without damaging the crop were taken into account.

The functional evaluation of the robotic arm was carried out through a five-stage operating cycle: detection of the crop, calculation of its three-dimensional position, planning of the motion path toward the target, approaching the crop and performing the harvesting operation, and subsequently retracting the arm to place the crop in the collection bin. The required input information, control outputs, and possible sources of error were defined at each stage. This approach enabled the mechanical design to be evaluated not only in terms of workspace but also in terms of the data relationship it establishes with the sensor and control systems.

Evaluation of the mechanical structure of the robotic arm

The robotic arm was designed as a six-degree-of-freedom structure consisting of a rotating base, shoulder, elbow, and wrist joints. The rotating base enables the arm to be directed toward the horizontal workspace around the robot platform. The shoulder and elbow joints determine the reach distance and height to the target, while the wrist joints regulate the angle at which the end-effector approaches the crop. This joint arrangement provides motion flexibility when the crop is not located directly in front of the robot or when it must be approached through the leaves at a specific angle.

The use of ABS and similar lightweight materials in the arm body is advantageous in terms of reducing the moving mass and the load on the motors. However, lightness alone is not sufficient for agricultural use. The arm links must not deflect under repeated loads, joint clearances must be maintained at a level that does not impair target accuracy, and vibration must be limited when the end-effector contacts the crop. Therefore, the rigidity of the connection points, the bearing arrangement, and the motor-reduction matching should also be examined during prototype tests.

Because of the possibility of exposure to moisture and irrigation water under greenhouse conditions, the use of protective housings, cable ducts, and connection seals in the joint regions has been envisaged. Cable routes must be arranged in accordance with the joint axes to prevent the cables from being tensioned or becoming entangled in the joints during arm motion. The modular wrist connection allows the end-effector to be changed for different crops or harvesting methods. This feature is important so that the system does not remain dependent on a single crop and can be used with different end tools in the future.

The six degrees of freedom enable the orientation of the end-effector to be controlled in addition to its position. However, increasing the number of degrees of freedom may result in multiple joint configurations in the inverse kinematics solution. Some configurations may exceed mechanical limits, cause collision with the robot body, or approach the crop from an unsuitable direction. Therefore, motion generation should consider not only reaching the target point but also joint limits, collision risk, and approach direction.

Evaluation of the end-effector design

The end-effector, which comes into direct contact with the crop during harvesting, was considered as a modular structure in which a two-finger gripper and a stem-cutting mechanism operate together. Covering the gripper fingers with soft contact elements that can conform to the crop surface distributes the contact pressure over a wider area and reduces the risk of crushing. Adjusting the gripping force according to crop size is particularly important for crops that are sensitive to mechanical damage, such as strawberries and tomatoes.

Integrating the scissor mechanism with the gripper allows the stem to be cut in a controlled manner after the crop has been held. Performing the cutting operation before grasping may cause the crop to fall, whereas performing it too late may create unnecessary pulling force on the plant. Therefore, grasping, cutting, and retraction commands must be executed in a specific sequence. The use of sensors in the end-effector to detect the grasping state or contact force may contribute to verifying that the crop is held securely.

The geometry of the end-effector should be compact enough to enter narrow gaps between the crop and other parts of the plant. Conversely, a mechanism that is too small may not provide sufficient gripping force and cutting capacity. A balance was established between these two requirements in the design. The modular connection makes it possible to change the gripper fingers, cutting tip, or entire end-effector unit according to the target crop.

Sensing, coordinate transformation, and data flow

The color image and depth map obtained from the RGB-D camera are used together to direct the robotic arm toward the correct target. The image processing algorithm first identifies the target crop in the image and then extracts the pixel coordinate of the crop center or stem region. Using the depth value, this pixel is transformed into a three-dimensional point in the camera coordinate system. Benavides et al. (2020) demonstrated that identifying the tomato and stem region together is important for correctly selecting the cutting point in robotic harvesting.

The target point obtained in the camera coordinate system cannot be used directly by the robotic arm. The position of the camera relative to the robot platform and the arm base must be determined through calibration, and the target coordinate must be transferred to the arm base reference system using appropriate transformation matrices. Camera calibration, measurement error of the depth sensor, and mounting tolerances of the arm base on the platform contribute to the total positioning error. Therefore, camera-arm calibration must be verified regularly when the system is commissioned.

Partial occlusion of the crop by a leaf or glare on its surface may reduce detection confidence. In such cases, it would be safer for the system to acquire images again from different angles or postpone targets with a low confidence score rather than relying on a single image. Sending only coordinates from the image processing unit to the robotic arm is not sufficient; information related to target size, orientation, maturity confidence, and surrounding obstacles should also be transferred to the motion planning stage.

Kinematic model and motion control

The joint angles required for the robotic arm to reach the target coordinate are determined through inverse kinematics calculations. Forward kinematics calculates the position and orientation of the end-effector using known joint angles, whereas inverse kinematics produces appropriate joint angles from the desired endpoint position. In an agricultural environment, it is possible to reach the target point with more than one joint solution. Among these solutions, the one that does not exceed joint limits, provides the shortest and safest motion relative to the current position, and reduces the risk of collision with the plant must be selected.

The motion planning process is more comprehensive than moving linearly and directly to the target point. The arm must move from its initial position to an approach point near the crop, proceed toward the crop at low speed in the final section, and follow a safe retraction trajectory after harvesting. Abrupt speed and acceleration transitions may create vibration at the arm tip and adversely affect target accuracy and product integrity. Therefore, joint speeds should be limited using smooth profiles, and low speed with controlled acceleration should be used particularly near the crop.
In the control architecture, position and speed references are transmitted to the motor drivers, and joint positions are monitored using encoder or step information. Limit switches are used as a safety layer to prevent mechanical limits from being exceeded. In the event of communication loss, motor overcurrent, an unexpected obstacle, or a position-tracking error, the arm must be stopped safely. In agricultural robots, safety is a fundamental requirement not only to protect the user but also to prevent damage to the plant and the robotic system.

Evaluation of the functional operating cycle
The basic sequence of operations applied by the robotic arm to harvest a crop is summarized in Table 1. Each stage of the cycle contains conditions that must be verified before proceeding to the next stage. This structure increases system reliability by preventing an error in sensing from being converted directly into mechanical motion.

Table 1. Stages of the robotic harvesting cycle and control requirements

Stage	Operation performed	Validation or safety condition
1. Detection	Identification of the target crop and, if possible, the stem region in the camera image	Detection confidence must be above the threshold value and the target must be considered mature
2. Positioning	Calculation of the three-dimensional target coordinate from color and depth information	The depth data must be valid and the camera-arm transformation must be applied
3. Path planning	Generation of the approach point, joint solution, and collision-free trajectory	Joint limits must not be exceeded and no plant/robot collision must be predicted
4. Approach and harvesting	The end-effector approaches the crop at low speed, followed by grasping and stem cutting	Grasping of the crop must be verified and the cutting command must be applied in the correct sequence
5. Retraction and release	The arm carries the crop to the collection bin and releases it	The crop must be held securely, the path must be clear, and the release must be completed

The most critical part of this operating cycle in terms of design is the transition between the sensing result and mechanical motion. A small error in the target coordinate may cause the end-effector to move toward a leaf, branch, or empty space instead of the fruit. Therefore, the initial position at which the crop is detected should be compared with current images acquired during arm motion, and the target coordinate should be updated when the crop moves. A visual-feedback-based approach may provide greater adaptability than moving only to a fixed position calculated at the beginning.

Structural and functional findings
The structural evaluation showed that the six-degree-of-freedom arm architecture provides a suitable basis for reaching crops at different positions within the greenhouse and adjusting end-effector orientation. While the rotating base, shoulder, and elbow links create the workspace, the wrist joints make it possible to approach the target from different angles. This structure provides a functional advantage particularly when the crop cannot be accessed directly from the front and a lateral or inclined approach is required because of leaves or branches.

The modular end connection of the robotic arm was evaluated positively in terms of adaptability to different harvesting scenarios. The presence of the two-finger gripper and the cutting mechanism in the same unit provides a controlled operating sequence in which soft crops are first held and then detached from the stem. However, to prevent product damage, the gripping force must be adjustable and the contact surfaces must be covered with soft material. The pressure distribution and cutting reliability of the end-effector on real crops should be verified through field tests.

The functional evaluation revealed that robotic arm performance cannot be considered independently of the mechanical workspace. Camera calibration, transfer of the target coordinate to the arm reference system, selection of the inverse kinematics solution, and timing of motor motions are parts of the same processing chain. An error at any stage of this chain may increase at the endpoint and affect harvesting success. Therefore, mechanical precision, sensing accuracy, and control software must be improved together.

The lightweight body, cable protection, and joint housings were identified as positive design features in terms of the suitability of the system for greenhouse use. However, because lightweight materials may deflect in long links, the displacement of the robotic arm in the fully extended position and its vibration behavior under load should be measured. Similarly, the long-term effects of humidity, temperature, and dust on motors, drivers, and connection elements cannot be fully explained by short-term laboratory tests.

For the robotic arm to form a successful harvesting system, it is not sufficient simply to increase the motion speed to its maximum value. High speed should be used in motions away from the crop, whereas low speed should be used during the approach and grasping stages. In this way, cycle time can be reduced while target accuracy and product safety are maintained. Droukas et al. (2023) emphasized that cycle time is one of the main limitations of commercial applicability in robotic harvesting systems. Therefore, reducing unnecessary pauses and excessive joint movements along the trajectory should be a priority in subsequent development stages.

Design targets and validation criteria

Target performance criteria were determined for evaluating the developed robotic arm in subsequent prototype and greenhouse trials. The values presented in Table 2 are not measured final results but targets intended to be achieved during the design and validation process of the system. Each criterion should be tested through repeated experiments involving different lighting conditions, crop positions, and leaf-cover conditions.

Table 2. Basic design targets determined for the prototype

Performance criterion	Design target	Validation approach
Harvesting success	Successful harvesting of approximately 90% of mature targets	Determination of the number of successful grasping and detachment operations in repeated greenhouse trials involving at least 50 targets
Positioning accuracy	Maintaining the end-effector target-position error at approximately ±5 mm or below	Measurement of camera-arm coordinate error and endpoint deviation at known reference points
Product integrity	No evident crushing or surface damage in at least 93% of harvested crops	Classification of product damage through visual inspection before and after harvesting
Cycle time	Approximately 12 seconds per crop, including detection, approach, grasping-cutting, and release	Separate timing of the operating stages and identification of the steps requiring the most time

Performance criterion	Design target	Validation approach
Continuous operation	Approximately two hours of operation with the selected battery and drive system	Monitoring of energy consumption, temperature, and error records under different loads and motion frequencies

The success rates and cycle times reported in the literature for robotic harvesting systems vary widely depending on crop type, imaging conditions, and system architecture. Feng et al. (2014) and Feng et al. (2018) demonstrated the importance of coordination between image processing and the robotic arm in systems developed for tomato harvesting. Yuanshen et al. (2016) evaluated the potential of a dual-arm structure to reduce operating time. Although these studies indicate that the specified targets may be technically achievable, the success of the developed system can only be demonstrated through repeated tests under its own operating conditions.

DISCUSSION

Developing mechanical design and sensing and control systems separately in robotic harvesting systems may cause significant incompatibilities during the integration stage. Even if the camera determines crop position with high accuracy, mechanical backlash in the arm, link deflection, or calibration error may prevent access to the target. Similarly, a high-precision arm cannot be successful when it is directed toward a target that has been incorrectly identified because of leaf cover. Therefore, the integrated evaluation approach adopted in this study enables subsystem performance to be examined through a common harvesting task.

While the six-degree-of-freedom structure provides access flexibility, it increases control complexity. The occurrence of multiple inverse kinematics solutions for each target requires the most appropriate solution to be selected. The selection criteria should not be limited solely to the amount of joint motion; the approach angle of the end-effector, the possibility of collision with the plant, motor torques, and ease of transition to the next target should also be evaluated. In multi-target harvesting scenarios, appropriate determination of target order may reduce total motion time and energy consumption.

In image-based positioning, the accuracy of the depth sensor may vary depending on target distance and surface characteristics. Gaps may occur in depth data on bright or small crop surfaces. Therefore, multiple images, point cloud filtering, or additional proximity sensors may be used when RGB-D camera data alone are insufficient. The dual-camera depth approach discussed by Ruybalid et al. (2025) may provide additional information for separating crop clusters. However, increasing the number of sensors also increases the calibration and processing load.

For commercial use of the robotic arm, cycle time, success rate, and product damage should be evaluated together. Performing all motions at low speed to increase safety may reduce product damage, but it decreases system efficiency. Increasing speed alone increases the risk of positioning error and mechanical vibration. The most appropriate approach is to use a motion profile that is fast away from the crop, slow in the contact region, and supported by visual feedback. This strategy may help establish a balance between safety and efficiency.

Economic feasibility is as important as technical performance. Components such as the RGB-D camera, precision motors, minicomputer, and specialized end-effector increase prototype cost. At the initial stage, the system may be expected to be more advantageous in large-scale greenhouse enterprises or those with high labor costs. The modular design may allow the same robot platform to be used for different crops, thereby spreading the investment cost over a wider range of applications. Locally manufactured connection elements and an open-source control infrastructure may also be effective in reducing cost.

The main limitation of the study is that the structural and functional evaluations have not yet been supported by comprehensive greenhouse performance data. Experiments should be conducted with different crop sizes, positions, and lighting conditions to validate the specified targets. In addition, the workspace of the arm, repeatability, endpoint error, energy consumption, motor temperature, product damage, and cycle time should be measured separately. The data to be obtained will enable the mechanical design and control parameters to be improved iteratively.

CONCLUSION

In this study, the mechanical structure, end-effector design, data exchange with the sensing unit, and motion control approach of the robotic arm belonging to an autonomous harvesting robot developed for use under greenhouse conditions were evaluated together. It was determined that the six-degree-of-freedom arm structure provides suitable motion flexibility for reaching crops at different heights and angles, and that the rotating base, shoulder, elbow, and wrist joints jointly regulate the workspace and end-effector orientation.

Combining the two-finger gripper and the stem-cutting mechanism in the same module provides a functional solution for holding soft crops and detaching them from the plant. However, the gripping force, contact surface, and cutting sequence should be experimentally optimized to preserve product integrity. The modular end connection provides an important advantage in adapting the system to different crops.

It was concluded that the success of the robotic arm does not depend solely on its mechanical structure. Detection of the crop with an RGB-D camera, correct transformation of the coordinate from the camera reference to the arm base, selection of the appropriate inverse kinematics solution, and driving the motors with safe motion profiles form a common control chain. Any error in this chain may directly affect the ability of the end-effector to reach the target and the harvesting success.

The values specified for harvesting success, positioning accuracy, product integrity, cycle time, and continuous operating time are design targets. Repeated laboratory and greenhouse trials must be conducted before these values can be accepted as actual system performance. In subsequent studies, the workspace and repeatability of the robotic arm should be measured, collision-free motion planning algorithms should be tested under different crop and plant arrangements, and the end-effector should be supported with force feedback.

In general, the developed robotic arm architecture provides a modular and improvable foundation that can be integrated into an autonomous harvesting system. Addressing sensing, motion planning, and mechanical manipulation within a single system approach will contribute to the development of more stable and precise harvesting robots suitable for greenhouse conditions.

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SIR BARAJ GÖLÜ'NDEKİ İSTILACI *ATHERINA BOYERI*'NİN BÜYÜME ÖZELLİKLERİNİN GELENEKSEL VE YAPAY ZEKÂ TABANLI YAKLAŞIMLARLA MODELLENMESİ

ANALYSIS OF GROWTH CHARACTERISTICS OF INVASIVE ATHERINA BOYERI USING ARTIFICIAL INTELLIGENCE AND CLASSICAL METHODS

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ÖZET
İstilacı türler, yer aldıkları ekosistemlerde biyolojik çeşitlilik üzerinde baskı oluşturarak ekolojik dengeyi olumsuz yönde etkileyen önemli faktörler arasında bulunmaktadır. Türkiye iç sularında yayılım gösteren *Atherina boyeri*, yüksek adaptasyon yeteneği ve hızlı populasyon artışı ile öne çıkan istilacı balık türlerinden biridir. Bu çalışmada, Sır Baraj Gölü'nde bulunan *Atherina boyeri* bireylerinin büyüme özellikleri farklı modelleme yaklaşımları kullanılarak incelenmiştir. Araştırma kapsamında toplam boy, standart boy, çatal boy, ağırlık ve cinsiyet gibi biyometrik veriler değerlendirilmiştir. Geleneksel yaklaşımlar çerçevesinde büyüme parametreleri klasik istatistiksel modeller ile analiz edilirken, yapay zekâ temelli yöntem olarak çok katmanlı yapay sinir ağları algoritması Weka yazılımı kullanılarak değerlendirilmiştir. Elde edilen model sonuçları; doğruluk, hata oranı ve tahmin performansı açısından karşılaştırılmıştır. Çalışma sonuçlarının, istilacı türlerin populasyon dinamiklerinin daha iyi anlaşılmasına katkı sağlayacağı, büyüme modellemelerinde alternatif yöntemlerin kullanımına yönelik bilimsel bir çerçeve sunacağı ve sürdürülebilir balıkçılık yönetimine veri temelli katkılar sağlayacağı öngörülmektedir. Bunun yanında, yapay zekâ tabanlı yaklaşımın bu alanda alternatif ve etkili bir modelleme aracı olarak değerlendirilebileceği belirlenmiştir.
Anahtar Kelimeler: istilacı tür, *Atherina boyeri*, geleneksel yaklaşım, yapay zekâ yaklaşım, büyüme,

ABSTRACT
Invasive species are among the major factors that negatively affect ecological balance by exerting pressure on biodiversity within the ecosystems they invade. *Atherina boyeri*, which has spread throughout Turkish inland waters, is one of the most prominent invasive fish species due to its high adaptability and rapid population growth. In this study, the growth characteristics of *Atherina boyeri* individuals inhabiting Sır Dam Lake were investigated using different modeling approaches. Biometric variables, including total length, standard length, fork length, body weight, and sex, were evaluated. Within the framework of conventional approaches, growth parameters were analyzed using classical statistical models, while a multilayer artificial neural network (ANN) algorithm implemented in the WEKA software was employed as the artificial intelligence-based approach. The performance of the developed models was compared in terms of prediction accuracy, error rates, and overall predictive capability. The findings are expected to contribute to a better understanding of the population dynamics of invasive species, provide a scientific framework for the application of alternative modeling approaches in growth prediction, and support sustainable fisheries management through data-driven decision-making. Furthermore, the results demonstrate that the artificial intelligence-based approach can serve as an effective and reliable alternative tool for growth modeling.
Keywords: invasive species; *Atherina boyeri*; conventional approach; artificial intelligence approach; growth modeling.

1. GİRİŞ

Biyolojik istilalar, günümüzde habitat kaybı ve iklim değişikliği ile birlikte biyolojik çeşitliliği tehdit eden en önemli çevresel sorunlardan biri olarak kabul edilmektedir (Simberloff et al., 2013). Özellikle iç su ekosistemleri, istilacı türlerin yerleşmesi ve yayılması açısından oldukça hassas sistemlerdir. Doğal yayılış alanları dışına taşınan türler, yerel türlerle besin ve yaşam alanı rekabetine girebilmekte, ekosistemin mevcut yapısını değiştirebilmekte ve zamanla baskın tür haline gelebilmektedir (Cucherousset ve Olden, 2011). Bu nedenle istilacı türlerin biyolojik özelliklerinin ve populasyon dinamiklerinin belirlenmesi, su kaynaklarının sürdürülebilir yönetimi açısından önemli bir gereklilik olarak görülmektedir.

Atherina boyeri Risso, 1810, geniş çevresel toleransı ve yüksek uyum yeteneği sayesinde farklı habitatlarda yaşayabilen küçük pelajik bir balık türüdür (Kottelat ve Freyhof, 2009). Türün doğal dağılımı Avrupa ve Akdeniz havzasını kapsamakla birlikte, son yıllarda birçok göl ve baraj gölünde başarılı populasyonlar oluşturduğu bildirilmektedir (Leonardos, 2001). Türkiye'de de farklı iç su ekosistemlerinde yayılım gösteren *A. boyeri*, bazı bölgelerde yüksek populasyon yoğunluklarına ulaşarak ekolojik açıdan dikkat çeken türlerden biri haline gelmiştir. Türün kısa yaşam döngüsü, hızlı büyümesi ve yüksek üreme kapasitesi, yeni ortamlara uyum sağlamasını kolaylaştıran temel özellikler arasında gösterilmektedir.

Bir türün yeni bir ekosistemdeki başarısının anlaşılabilmesi için büyüme özelliklerinin ortaya konulması büyük önem taşımaktadır. Balıkçılık biyolojisinde büyümenin değerlendirilmesinde en yaygın kullanılan yöntemlerden biri boy-ağırlık ilişkilerinin incelenmesidir. Boy ve ağırlık arasındaki ilişkinin belirlenmesi, yalnızca bireylerin büyüme karakteristikleri hakkında bilgi vermekle kalmamakta, aynı zamanda populasyonların sağlık durumlarının ve çevresel koşullara verdikleri tepkilerin değerlendirilmesine de katkı sağlamaktadır (Ricker, 1975; Froese, 2006).

Türkiye'de *A. boyeri* üzerine gerçekleştirilen araştırmaların büyük bölümü türün populasyon yapısı, büyüme özellikleri ve boy-ağırlık ilişkileri üzerine yoğunlaşmıştır. Farklı göl ve baraj göllerinde yürütülen çalışmalar, türün bulunduğu habitatın özelliklerine bağlı olarak farklı büyüme performansları gösterebildiğini ortaya koymuştur (İlhan ve Sarı, 2015). Bununla birlikte, bu çalışmaların önemli bir kısmında büyüme değerlendirmeleri geleneksel istatistiksel yöntemlerle gerçekleştirilmiştir.

Son yıllarda yapay zekâ uygulamalarının çevre bilimleri ve biyolojik araştırmalarda kullanımında önemli bir artış yaşanmaktadır. Özellikle yapay sinir ağları, değişkenler arasındaki karmaşık ilişkileri ortaya koyabilme ve yüksek doğrulukta tahminler üretebilme özellikleri nedeniyle farklı araştırma alanlarında yaygın olarak kullanılmaktadır (Lek ve ark., 1996; Olden ve ark., 2008). Su ürünleri alanında gerçekleştirilen çalışmalar da yapay zekâ yöntemlerinin büyüme tahminleri, çevresel modellemeler ve biyolojik veri analizlerinde başarılı sonuçlar verebildiğini göstermektedir. Son yıllarda gerçekleştirilen araştırmalar, yapay zekâ temelli yaklaşımların geleneksel yöntemlerle birlikte kullanıldığında biyolojik süreçlerin daha kapsamlı değerlendirilmesine katkı sağlayabileceğini ortaya koymaktadır (Benzer ve Benzer, 2023).

Buna karşın, *A. boyeri* üzerine gerçekleştirilen çalışmalarda yapay zekâ tabanlı modelleme yaklaşımlarının kullanımına ilişkin araştırmalar oldukça sınırlıdır. Özellikle Türkiye iç sularındaki populasyonlar üzerinde geleneksel büyüme analizleri ile yapay sinir ağı modellerinin birlikte değerlendirildiği çalışmaların yetersiz olduğu görülmektedir. Bu durum, farklı modelleme yaklaşımlarının aynı veri seti üzerinde karşılaştırılmasını gerekli kılmaktadır.

Bu çalışmada, Sır Baraj Gölü'nde yaşayan istilacı *A. boyeri* bireylerinin büyüme özelliklerinin belirlenmesi amaçlanmıştır. Bu kapsamda toplam boy, çatal boy, standart boy, ağırlık ve cinsiyet verileri kullanılarak geleneksel istatistiksel analizler gerçekleştirilmiş, ardından aynı veri seti kullanılarak çok katmanlı yapay sinir ağı modeli oluşturulmuştur. Elde edilen sonuçlar karşılaştırılarak yapay zekâ tabanlı yaklaşımın büyüme modellemelerindeki uygulanabilirliği değerlendirilmiştir.

2. MATERYAL VE YÖNTEM

Bu çalışmanın materyalini, Kahramanmaraş ili sınırları içerisinde yer alan Sır Baraj Gölü'nden elde edilen 249 adet *Atherina boyeri* bireyleri oluşturmaktadır. Yakalanan örnekler laboratuvar ortamına getirilerek biyometrik ölçümleri yapılmıştır.

Her birey için toplam boy (TL), çatal boy (FL), standart boy (SL), ağırlık (W) ve cinsiyet bilgileri kaydedilmiştir. Boy ölçümleri 0,1 cm hassasiyetle, ağırlık ölçümleri ise 0,01 g hassasiyetli dijital terazi kullanılarak gerçekleştirilmiştir.

Elde edilen verilerin değerlendirilmesinde öncelikle tanımlayıcı istatistikler hesaplanmış ve tüm değişkenler için minimum, maksimum, ortalama ve standart sapma değerleri belirlenmiştir. Toplam boy, çatal boy, standart boy ve ağırlık değişkenlerine ait frekans dağılımları incelenerek örneklenen populasyonun biyometrik yapısı ortaya konulmuştur.

Boy-ağırlık ilişkilerinin belirlenmesinde balıkçılık biyolojisi çalışmalarında yaygın olarak kullanılan $W=aL^b$ modeli kullanılmıştır (Ricker, 1975; Froese, 2006). Bu denklemde W ağırlığı (g), L boyu (cm), a regresyon sabitini ve b büyüme katsayısını ifade etmektedir. Parametre tahminleri regresyon analizi ile hesaplanmış ve elde edilen b katsayısına göre büyüme tipi değerlendirilmiştir. Buna göre b=3 izometrik büyümeyi, b>3 pozitif allometrik büyümeyi ve b<3 negatif allometrik büyümeyi göstermektedir (Froese, 2006). Ayrıca toplam boy, çatal boy ve standart boy arasındaki ilişkiler doğrusal regresyon analizleri kullanılarak incelenmiştir.

Geleneksel istatistiksel analizlere ek olarak, biyometrik değişkenler ile ağırlık arasındaki ilişkinin modellenmesinde yapay sinir ağı yaklaşımından yararlanılmıştır. Yapay sinir ağları, biyolojik sistemlerden esinlenerek geliştirilen ve değişkenler arasındaki karmaşık doğrusal olmayan ilişkileri modelleyebilen veri işleme yöntemleri olarak tanımlanmaktadır (Lek et al., 1996; Olden et al., 2008). Bu kapsamda analizlerde Weka veri madenciliği yazılımının çok katmanlı algılayıcı (Multilayer Perceptron) algoritması kullanılmıştır (Hall et al., 2009). Modelin giriş değişkenleri toplam boy, çatal boy, standart boy ve cinsiyet olarak belirlenirken, çıkış değişkeni ağırlık olarak tanımlanmıştır. Ağın eğitimi hata geri yayılımı (backpropagation) algoritması kullanılarak gerçekleştirilmiştir (Rumelhart et al., 1986).

Oluşturulan modelin performansının değerlendirilmesinde belirleme katsayısı (R^2), ortalama mutlak hata (MAE) ve hata kareler ortalamasının karekökü (RMSE) kullanılmıştır. R^2 değeri modelin açıklayıcılık düzeyini gösterirken, MAE ve RMSE değerleri tahmin hatalarının büyüklüğünü değerlendirmek amacıyla kullanılmıştır (Willmott and Matsuura, 2005). Geleneksel regresyon modeli ile yapay sinir ağı modelinden elde edilen sonuçlar karşılaştırılarak modellerin tahmin performansları değerlendirilmiştir. Tüm istatistiksel analizler IBM SPSS Statistics ve Weka yazılımları kullanılarak gerçekleştirilmiş olup istatistiksel anlamlılık düzeyi $p<0,05$ olarak kabul edilmiştir.

3. BULGULAR

Araştırma kapsamında incelenen 249 adet *A. boyeri* bireyinin 106'sı dişi ve 143'ü erkek olarak belirlenmiştir. Bireylere ait biyometrik özellikler Tablo 1'de verilmiştir. Dişi bireylerin ortalama toplam boyu 79.55±13.01 mm, ortalama ağırlığı ise 3.92±1.59 g olarak hesaplanmıştır. Erkek bireylerde ortalama toplam boy ve ağırlık değerleri sırasıyla 77.33±11.70 mm ve 3.41±1.28 g olarak belirlenmiştir. Tüm bireyler birlikte değerlendirildiğinde ortalama toplam boy 78.28±12.30 mm, ortalama çatal boy 82.70±12.19 mm, ortalama standart boy 72.57±11.44 mm ve ortalama ağırlık 3.62±1.44 g olarak hesaplanmıştır.

Tablo 1. Sır Baraj Gölü'ndeki Atherina boyeri bireylerine ait biyometrik özellikler.

Grup	n	Standart Boy (mm)	Toplam Boy (mm)	Çatal Boy (mm)	Ağırlık W (g)
Dişi	106	73.59 ± 12.17	79.55 ± 13.01	84.14 ± 13.09	3.92 ± 1.59
Erkek	143	71.81 ± 10.85	77.33 ± 11.70	81.62 ± 11.41	3.41 ± 1.28
Toplam	249	72.57 ± 11.44	78.28 ± 12.30	82.70 ± 12.19	3.62 ± 1.44

Toplam boy, çatal boy ve standart boy arasındaki ilişkiler incelendiğinde tüm boy parametreleri arasında yüksek düzeyde doğrusal ilişkiler olduğu belirlenmiştir (Tablo 2). En yüksek determinasyon katsayısı çatal boy ile standart boy arasındaki ilişkide elde edilmiş (R^2=0.979), bunu toplam boy-çatal boy (R^2=0.961) ve toplam boy-standart boy (R^2=0.960) ilişkileri izlemiştir. Elde edilen sonuçlar, çalışmada kullanılan boy parametrelerinin birbirleriyle güçlü bir ilişki içerisinde olduğunu göstermektedir.

Tablo 2. Atherina boyeri bireylerine ait boy-boy ilişkileri

İlişki	**Regresyon Denklemi**	**R^2**
TB-ÇB	ÇB = 6.681 + 0.971(TB)	0.961
TB-SB	SB = 1.243 + 0.911(TB)	0.960
ÇB-SB	SB = -4.227 + 0.929(ÇB)	0.979

Balıkçılık biyolojisinde büyüme özelliklerinin belirlenmesinde yaygın olarak kullanılan boy-ağırlık ilişkileri incelendiğinde, dişi bireyler için büyüme denklemi $W = 0.00001005 \cdot CB^{2.8894}$ (R^2=0.950), erkek bireyler için $W = 0.00000796 \cdot CB^{2.9328}$ (R^2=0.964) ve tüm bireyler için $W = 0.00000844 \cdot CB^{2.9234}$ (R^2=0.956) olarak hesaplanmıştır (Tablo 3). Elde edilen b değerlerinin tamamının 3'ten küçük olması nedeniyle populasyonun negatif allometrik büyüme eğilimi gösterdiği belirlenmiştir. Bununla birlikte b katsayılarının 3 değerine oldukça yakın olması, büyümenin izometrik modele yakın bir karakter sergilediğini göstermektedir.

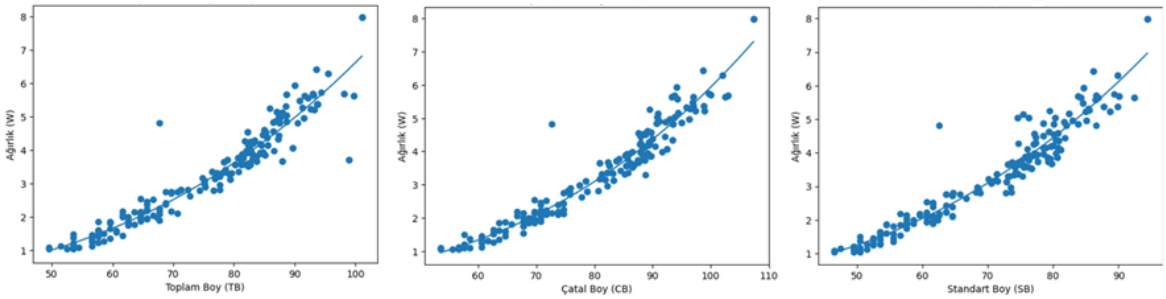
Tablo 3. Atherina boyeri bireylerine ait boy-ağırlık ilişkileri.

Grup	**n**	**Boy-Ağırlık İlişkisi**	**R^2**
Dişi	106	$W = 0.00001005 \times CB^{2.8894}$	0.950
Erkek	143	$W = 0.00000796 \times CB^{2.9328}$	0.964
Dişi + Erkek	249	$W = 0.00000844 \times CB^{2.9234}$	0.956

Cinsiyetlere göre büyüme parametreleri karşılaştırıldığında dişi bireylerin ortalama boy ve ağırlık değerlerinin erkek bireylerden daha yüksek olduğu görülmüştür (Tablo 4). Erkek bireylerde elde edilen regresyon modelinin determinasyon katsayısı daha yüksek olduğu (R^2=0.964) belirlenmiştir. Her iki cinsiyette de negatif allometrik büyüme gözlenmiş olmakla birlikte, erkek bireylerde hesaplanan b katsayısının izometrik büyüme değerine daha yakın olduğu tespit edilmiştir.

Tablo 4. Cinsiyetlere göre büyüme parametrelerinin karşılaştırılması.

Parametre	**Dişi**	**Erkek**
Birey Sayısı (n)	106	143
Ortalama Toplam Boy (mm)	79.55 ± 13.01	77.33 ± 11.70
Ortalama Çatal Boy (mm)	84.14 ± 13.09	81.62 ± 11.41
Ortalama Standart Boy (mm)	73.59 ± 12.17	71.81 ± 10.85
Ortalama Ağırlık (g)	3.92 ± 1.59	3.41 ± 1.28
b katsayısı	2.8894	2.9328
R^2	0.950	0.964
Büyüme Tipi	Negatif allometrik	Negatif allometrik



Şekil 1. Sır Baraj Gölü'nden elde edilen A. boyeri bireylerinde toplam boy–ağırlık, çatal boy–ağırlık ve standart boy–ağırlık ilişkileri ve logaritmik regresyon eğrileri.

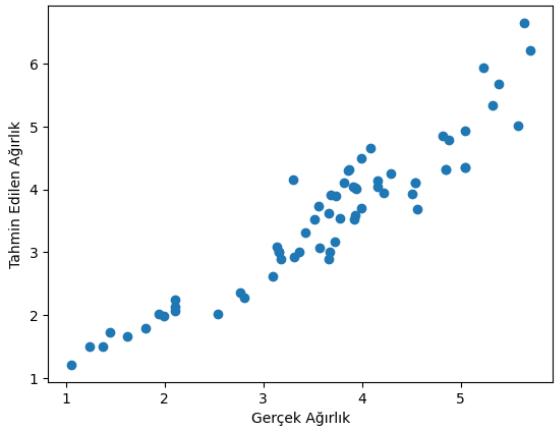
Çalışmada toplam boy, çatal boy ve standart boy ile ağırlık arasındaki ilişkiler tek bir şekil içerisinde sunulmuştur (Şekil 1). Tüm morfometrik değişkenler ile ağırlık arasında güçlü pozitif ilişkiler belirlenmiş olup, özellikle çatal boy değişkeninde daha dar dağılım ve daha güçlü model uyumu gözlenmiştir. Bu durum çatal boyun ağırlık tahmininde en açıklayıcı morfometrik değişken olduğunu göstermektedir.

Geleneksel regresyon modelleri ile yapay sinir ağı modellerinin performansları karşılaştırıldığında her iki yaklaşımın da ağırlık tahmininde yüksek doğruluk sağladığı görülmüştür (Tablo 5). Toplam boy kullanılarak oluşturulan ANN modeli R^2=0.947 değeri ile aynı değişken kullanılarak oluşturulan regresyon modelinden (R^2=0.939) daha yüksek performans göstermiştir. Buna karşılık çatal boy ve standart boy kullanılarak oluşturulan regresyon modelleri, ilgili ANN modellerine göre daha yüksek determinasyon katsayısına ulaşmıştır. Çatal boy kullanılarak oluşturulan regresyon modeli tüm modeller arasında en yüksek performansı göstermiş ve R^2 değeri 0.956 olarak hesaplanmıştır.

Tablo 5. Geleneksel regresyon ve yapay sinir ağı modellerinin performans karşılaştırması.

Model	**Girdi Değişkenleri**	**Çıktı Değişkeni**	**Regresyon R^2**	**ANN R^2**
TB-W	Toplam Boy (TB)	Ağırlık	0.939	0.947
CB-W	Çatal Boy (CB)	Ağırlık	0.956	0.941
SB-W	Standart Boy (SB)	Ağırlık	0.942	0.934

Gerçek ağırlık değerleri ile model tarafından tahmin edilen ağırlık değerleri arasındaki ilişki incelendiğinde, gözlenen ve tahmin edilen değerlerin genel olarak yüksek uyum gösterdiği belirlenmiştir (Şekil 2). Noktaların diyagonal doğrultuya yakın bir dağılım sergilemesi, modelin veri seti üzerindeki tahmin performansının yüksek olduğunu ortaya koymaktadır. Bununla birlikte, bazı bireylerde gözlenen sapmaların bulunması modelin küçük varyasyonları tam olarak yansıtamadığını göstermekle birlikte, genel eğilimin güçlü bir korelasyon yapısına sahip olduğu görülmektedir (Şekil 2).



Şekil 2. Gerçek ve tahmin edilen ağırlık değerleri arasındaki ilişki

4. SONUÇ

Bu çalışmada Sır Baraj Gölü'nde yaşayan istilacı *A. boyeri* bireylerinin büyüme özellikleri geleneksel istatistiksel yöntemler ve yapay sinir ağı modeli kullanılarak incelenmiştir. Elde edilen bulgular, türün biyometrik özelliklerinin farklı modelleme yaklaşımları ile başarılı bir şekilde açıklanabildiğini göstermiştir.

Geleneksel analizler sonucunda, çatal boy değişkeninin ağırlık üzerindeki determinasyon katsayısı diğer boy değişkenlerine göre daha yüksek olduğu belirlenmiş ve en yüksek determinasyon katsayısı CB-W modelinde elde edilmiştir (R^2=0.956). Tüm boy değişkenlerinde b değerinin 3'ten küçük olması nedeniyle populasyonun negatif allometrik büyüme eğilimi gösterdiği tespit edilmiştir.

Yapay sinir ağı modeli ile yapılan analizlerde ise biyometrik değişkenler kullanılarak ağırlık tahmini gerçekleştirilmiş ve yüksek performans değerleri elde edilmiştir.

ANN modeli içerisinde en yüksek performans toplam boy girdisi ile elde edilmiş (R^2=0.947), diğer modellerde ise benzer düzeyde ancak daha düşük performans değerleri gözlenmiştir.
Genel olarak değerlendirildiğinde, hem geleneksel regresyon modellerinin hem de yapay sinir ağı yaklaşımının *A. boyeri* bireylerinde ağırlık tahmininde başarılı sonuçlar verdiği belirlenmiştir. Bununla birlikte, tek değişkenli regresyon modellerinin bazı durumlarda çok değişkenli yapay sinir ağı modeline kıyasla daha yüksek açıklayıcılık sağlayabildiği görülmüştür.
Elde edilen sonuçlar, istilacı türlerin büyüme özelliklerinin değerlendirilmesinde geleneksel yöntemlerin güçlü ve güvenilir bir temel sunduğunu, yapay zekâ tabanlı yaklaşımların ise bu analizleri destekleyici ve tamamlayıcı bir araç olarak kullanılabileceğini göstermektedir.

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TRANSHÜMANİZM VE İNSANLIĞIN BİYOLOJİK SINIRLARI: TEKNOLOJİK MÜDAHALE, BEDENSEL DÖNÜŞÜM VE ETİK TARTIŞMALAR
TRANSHUMANISM AND THE BIOLOGICAL LIMITS OF HUMANITY: TECHNOLOGICAL INTERVENTION, BODILY TRANSFORMATION, AND ETHICAL DEBATES

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ABSTRACT
Transhumanism, as a philosophical and scientific approach aiming to transcend the biological limits of the human being and enhance human capacity through technology, points to a mode of thinking whose roots extend as far back as human history itself. According to this perspective, humans are not entirely independent from natural limitations such as disease, aging, death, cognitive constraints, and physical inadequacies; however, these boundaries are expected to be overcome through fields such as biotechnology, artificial intelligence, genetic engineering, neurotechnology, and cybernetics. Within the scope of transhumanism, controversial topics such as the prevention of hereditary diseases through gene-editing technologies (CRISPR), mind-controlled device interaction via brain–computer interfaces, life extension through artificial organs and bioengineering, and AI-supported cognitive enhancement are actively being explored. Transhumanist thought does not regard humans as fixed biological entities but rather as continuously improvable beings. However, this approach also raises debates concerning the transformation of human nature, the deepening of inequalities, the ambiguity of ethical boundaries, and the redefinition of what it means to be "human."
This study examines transhumanism in the context of attempts to transcend human biological limitations and questions the transformative effects of technological developments on the human body. From this perspective, the human being is redefined not as a fixed biological entity but as a continuously improvable "project." The study highlights the ethical, social, and ontological consequences of this transformation of humanity. While the alteration of human nature blurs the boundaries of the concept of "human," it also introduces new areas of debate such as increasing inequalities, issues of access justice, and identity problems. Furthermore, the question of whether technological enhancements should be limited solely to medical purposes or considered a broader field of human empowerment gains significance. In this framework, transhumanism's claim to liberate humans from biological constraints is critically evaluated as both a promising and a risk-bearing paradigm. Consequently, it becomes essential to reconsider ethical principles, social equality, and philosophical boundaries related to the definition of humanity in the process of technologically redesigning the human being.
Keywords: Transhumanism, Human Nature, Biotechnology, Human Enhancement, Ethic.

ÖZET
İnsanın biyolojik sınırlarını aşmak ve kapasitesini teknoloji aracılığıyla geliştirmek amacı taşıyan felsefi ve bilimsel bir yaklaşım olarak "transhümanizm", kökleri insanlık tarihi kadar eski bir düşünüş biçimine işaret etmektedir.
Bu düşünceye göre insan; hastalık, yaşlanma, ölüm, bilişsel sınırlılıklar ve fiziksel yetersizlikler gibi doğal sınırlardan tamamen bağımsız değildir, ancak biyoteknoloji, yapay zekâ, genetik mühendisliği, nöroteknoloji ve sibernetik gibi alanlar sayesinde bu sınırlar ortadan kalkacaktır. Transhümanizm kapsamında günümüzde gen düzenleme teknolojileri (CRISPR) ile kalıtsal hastalıkların önlenmesi, beyin-bilgisayar arayüzleri ile düşünceyle cihaz kontrolü, yapay organlar ve biyomühendislik ile yaşam süresinin uzatılması ve yapay zekâ destekli bilişsel artırımlar gibi tartışmaya açık konular üzerinde çalışılmaktadır. Transhümanist düşünce, insanı "değişmez biyolojik bir varlık" olarak değil, sürekli geliştirilebilir bir varlık olarak görür. Ancak bu yaklaşım; insan doğasının değişmesi, eşitsizliklerin artması, etik sınırların belirsizleşmesi ve "insan olma" tanımının yeniden yapılması gibi tartışmaları da beraberinde getirmektedir.

Bu çalışma, transhümanizm düşüncesini insanın biyolojik sınırlarını aşma girişimi bağlamında ele almakta ve teknolojik gelişmelerin insan bedeni üzerindeki dönüştürücü etkilerini sorgulamaktadır.
Bu düşünce tarzına göre insan, sabit bir biyolojik varlık olmaktan ziyade sürekli geliştirilebilir bir "proje" olarak yeniden tanımlanmaktadır. Çalışma, insana dair bu dönüşümün etik, toplumsal ve ontolojik sonuçlarına dikkat çekmektedir. İnsan doğasının değiştirilmesi, "insan" kavramının sınırlarını belirsizleştirirken, eşitsizliklerin derinleşmesi, erişim adaleti ve kimlik sorunları gibi yeni tartışma alanlarını da ortaya çıkarmaktadır. Ayrıca teknolojik iyileştirmelerin yalnızca tıbbi amaçlarla mı sınırlandırılması gerektiği yoksa insan kapasitesini artırmaya yönelik genişletici bir özgürlük alanı mı olarak değerlendirilmesi gerektiği sorusu önem kazanmaktadır. Bu çerçevede transhümanizmin insanı biyolojik sınırlardan kurtarma iddiasının hem umut verici hem de risk barındıran bir paradigma olduğu yönünde bir sorgulama önem kazanmaktadır. Sonuç olarak, insanın teknolojik olarak yeniden tasarlanması sürecinde etik ilkeler, toplumsal eşitlik ve insanlık tanımına ilişkin felsefi sınırların yeniden düşünülmesi gerektiği üzerine düşünmek zaruridir.
Anahtar Kavramlar: Transhümanizm, İnsan Doğası, Biyoteknoloji, İnsan Artırımı, Etik.

INTRODUCTİON

Humanity's desire to transcend itself does not belong exclusively to the contemporary era. Across a broad intellectual tradition extending from mythological narratives to modern science, human history has been marked by accounts and ideas that exemplify the ideal of exceeding human limitations. hether consciously or unconsciously, humanity has imagined the possibility of becoming an overhuman." In mythology, the figures of gods and demigods embody this ideal. "In Ancient Greece, Zeus, as the king of gods, was considered the supreme being, while Eros, the god of love, as half-god and half-human, also presents us with an example of the overhuman. Although transhumanism is a relatively new concept, its traces can be found as far back as the Epic of Gilgamesh. The Epic of Gilgamesh, which also includes one of the earliest accounts of the Flood narrative, tells the story of a king searching for immortality" (Demir, 2018, p. 98). Today, this ideal can be discussed through concrete developments in fields such as biotechnology, artificial intelligence, genetic engineering, neurotechnology, and cybernetics. As Harari (2016) emphasizes, humanity is entering an era in which biological structures can be redesigned. This transformation reopens classical philosophical assumptions regarding human nature to critical reconsideration. Throughout history, humankind has sought the path to "immortality." In this context, the desire for a healthy and resilient body has coexisted with an aspiration toward disembodiment, both of which have persisted in intellectual traditions up to the present day. While advances in medicine extend human lifespan, humanity still struggles to confront the reality of death. In this regard, machines -particularly computer-based systems- have begun to offer potential solutions. "Just as the First Industrial Revolution was powered by the invention of the loom, the Second by the steam engine, and the Third by the assembly line, the Fourth will be powered by machines that appear to think -'intelligent systems'" (Frank, Roehrig, & Pring, 2019, p. 17).

As an extension of human thought, computer technologies developed through artificial neural network systems have placed humanity on an irreversible historical trajectory. Operating through algorithms, these systems function by organizing information according to semantic proximity, frequency of occurrence, and relevance of use. This structure reveals a system composed of powerful organizations, dominant mechanisms, and the maximization of profit. "Powerful organizations are engaged in a major race toward the future of humanity, and their goal is—to win at any cost! Because the future of humanity depends on it! Soon, it will not be the most hardworking individuals, but the organizations that use the most successful algorithms that will thrive! Because algorithms will determine how to invest best and generate maximum profit" (Volland, 2022, p. 19).

Transhumanism, which argues that human biological limits can be transcended through technology and seeks to redefine human existential capacity, is based on the assumption that humans are not merely biologically constrained beings but are also entities that can be reshaped through scientific and technological advancement. Within this framework, humans are conceptualized as potential "objects of enhancement" capable of surpassing natural constraints such as disease, aging, death, and cognitive limitations (Bostrom, 2005). Rather than being confined to extending human lifespan alone, transhumanism aims to go beyond contemporary scientific and technological progress, striving toward a "Humanity+" or "H+" era in which human physical and cognitive abilities are significantly enhanced.

"At this stage, in the age of artificial intelligence and technology, the entity that emerges -part human, part machine- and reached at the end of the transhumanist process is called the 'posthuman.' We can define the transhuman as the transitional state between Homo sapiens and the posthuman, while the posthuman refers to the being reached at the end of this transformation process" (Çelebi, 2025, p. 20).
Tracing the roots of a thought system as old as human history and grounded in techno-scientific progress, this movement is not solely concerned with improving existing human capabilities or addressing health-related issues. Rather, it aims to endow human existence with new attributes and capacities. Such posthumanist developments directly involve bodily modification -that is, the transformation of the human into a post-human condition. Technologies developed within the framework of transhumanism target not only the treatment of diseases but also the enhancement of human capacities. Gene-editing technologies such as CRISPR make it possible to eliminate hereditary diseases, while brain–computer interfaces enable direct interaction between human thought and digital systems. In addition, artificial organs and bioengineering applications hold the potential to extend human lifespan. These developments have placed the concept of "human enhancement" at the center of scientific and ethical debates. In this context, the human body is no longer considered a fixed and immutable structure but rather a system that can be intervened in, optimized, and redesigned. However, this transformation represents not only a technical advancement but also a philosophical rupture requiring a redefinition of human nature, identity, and subjectivity. Fukuyama (2002) draws attention to the transformative potential of such technological interventions on human nature, emphasizing that their social and political consequences may be profound.
One of the most significant debates raised by the transhumanist approach is the increasing ambiguity of ethical boundaries. The use of technology for human enhancement blurs the line between medical necessity and voluntary "improvement." This situation gives rise to new social problems such as access inequality, technological privilege, and emerging "biological class distinctions." Thus, transhumanism becomes not only an individual development project but also a paradigm that encompasses broader issues of social justice. In many respects, transhumanism presents a dual-edged transformation: it simultaneously offers hope and risk through its claim to transcend human biological limitations. On the one hand, it holds the potential to extend human life, eliminate diseases, and enhance cognitive capacities; on the other hand, it fundamentally reopens the question of what it means to be human. For this reason, transhumanist developments must be addressed not only in technical terms but also through their ethical, social, and ontological dimensions.

Transhumanism: Conceptual and Theoretical Framework

In the contemporary century we inhabit, the concept of "homo digitalicus" is widely used to emphasize the interaction between humans and digital technologies. This concept refers to the digitized human being -that is, the subject of the digital age- whose mind is now understood as a hybrid formation composed of both biological and digital systems (Köktürk, 2021, p. 106). The designation of the human being as "transhuman" within a biotechnological context is worth examining, as it provides insights into how humanity positions itself existentially in the world. From this perspective, transhumanism emerges as an attempt to transcend the biological and cognitive limitations of the human being through technological means. It is based on the assumption that the current natural structure of humanity is not an ultimate boundary but rather a process that can be improved and transformed. According to Bostrom (2005), transhumanism is "an intellectual movement that advocates the use of reason to transcend the limits of the human condition." In this framework, the human is not considered a fixed subject but a continuously reconfigurable entity shaped through technological interventions. Transhumanism refers to an approach that seeks to transcend human biological limits by using technologies -particularly nanotechnology operating at atomic and molecular levels- to enhance physical, mental, and emotional capacities. This intersection is significant both ethically and scientifically (Demir, 2018, p. 96).
The concept of transhumanism is derived from the Latin roots "trans" (beyond) and "humanism." The prefix "trans" denotes "beyond" or "across." In this sense, the term can be interpreted as "beyond-humanism" or "enhancement-humanism." Transhumanism is defined as "a grand project aimed at repairing the biological body, enhancing and elevating the human being, and ultimately guiding humanity toward a higher model" (Ferry, 2023, p. 1), as well as "a comprehensive program emerging

from scientific and technological progress that seeks the physical, mental, emotional, and moral elevation of humanity at all levels" (Ferry, 2023, p. 157). The transhumanist approach developed under the leadership of Nick Bostrom at the Future of Humanity Institute at the University of Oxford combines the humanist belief in perfection through scientific rationality with a human enhancement program. "Such interventions on the human are presented as if they are consistent with Enlightenment humanist rationality. The humanist belief in perfectibility through scientific rationality is combined with a highly industrialized and powerful robotics and AI-driven human enhancement program" (Braidotti, 2019, p. 82). Within this framework, the term "post-human" refers to a new stage reached by humanity with the assistance of technology.

The concept of transhumanism was first used by Julian Huxley in his 1968 article of the same name to denote "social progress." Arguing that the geographical exploration of the Earth had largely been completed, Huxley claimed that the exploration of human nature and human possibilities had only just begun. He further suggested that humanity would reach a new existential threshold when a sufficient number of people sincerely declare, "I believe in transhumanism" (as cited in Gacar, 2024, p. 85). Transhumanism, which views the human mind as the most advanced and complex cognitive structure, is grounded in the assumption that humans can imagine realities far beyond their physical capabilities - possibly unreal or never-to-be-realized scenarios- questioning reality itself and constructing alternative realities. From this perspective, it emphasizes overcoming biological death. At its core, this approach seeks to enhance humans both physically and mentally, thereby expanding the boundaries of existence toward a more advanced condition. This, in turn, is indirectly associated with the idea of human happiness.

Historically, happiness has been a central aim in Ancient Greek and Hellenistic philosophy. In the Middle Ages, happiness was equated with reaching God. In the 17th and 18th centuries, it was understood as a state of well-being. In the 19th century, it became associated with individual happiness within utilitarian thought (Demir, 2018, p. 96). Bentham based his moral and political philosophy on the principle of "the greatest happiness for the greatest number" (1996, pp. 36–37). Transhumanist thought, however, can be seen as an expanded version of the 19th-century hedonistic conception of happiness. As Hansell and Grassie (2010, p. 38) argue, "because they focus on personal satisfaction, transhumanists do not take into account the pre-modern connection between happiness and virtue."

The theoretical foundations of transhumanism are rooted in the humanist tradition. While Renaissance humanism placed human reason and potential at the center, transhumanism expands this perspective through technological progress. According to More (1990), transhumanism is "a rational and technological extension of the desire to go beyond humanity." In this context, transhumanism can be seen as a continuation of humanism; however, it diverges from it by aiming to transcend the biological limits of human nature. On a philosophical level, transhumanism rejects the idea of an immutable human essence. Within this approach, the human is not a "finished being" but a process that requires continuous enhancement. In transhumanist theory, the concept of "human enhancement" is central. This refers to the improvement of human capacities beyond medical necessity. Neurotechnological implants, gene-editing techniques, and AI-supported cognitive systems are considered key tools of this enhancement process. These technologies make it possible not only to cure diseases but also to move beyond what is considered "normal." In this framework, the notion of the "technological human" emerges as a key concept in the transformation proposed by transhumanism (Demir, 2018, p. 95). Transhumanism, in this sense, seeks to radically transform the current understanding of humanity through technological and biotechnological evolutionary possibilities (Francesca, 2013, p. 27). Aiming at the "improvement" of the human condition, transhumanism instrumentalizes various scientific domains—including nanotechnology, biotechnology, information technology, and cognitive science—as well as human rationality. Operating under the promise of equal opportunity, quality of life, and happiness for all conscious beings, transhumanism can be described as a project of "human self-transcendence" (Şengel, 2024, p. 9). In this approach, the coding and control of the human mind and body, as well as the replacement of existing organs with technologically advanced artificial ones, serve its core objectives. The idea of achieving immortality, enhancing intelligence, improving life processes, and extending lifespan reflects a pursuit of "higher levels of existence," with the creation of a "technological human" as its primary goal.

"The technological human is a being in which meaning is generated through technologically produced artificial extensions that replace the biological human organism" (Demir, 2018, p. 97).

The main doctrines of transhumanism (Schneider, 2022, pp. 157–158) include: (a) the radical transformation of humanity through technology in the future; (b) the possibility of understanding long-term consequences through systematic research; (c) openness to and support for emerging technologies; (d) the protection of the moral rights of individuals who wish to use technology to expand their mental and physical capacities and increase control over their lives; (e) consideration of dramatic future technological advances in planning; (f) the establishment of a social order that enables rational public deliberation and responsible decision-making; and (g) the advocacy of the well-being of all sentient beings -whether artificial intelligences, humans, posthumans, or non-human animals. Neurotechnology and artificial intelligence integration constitute one of the most critical dimensions of transhumanist thought. Brain-computer interfaces (BCIs) aim to expand cognitive capacities by enabling direct interaction between the human mind and digital systems. In this context, the human mind is no longer merely a biological structure but becomes a hybrid system integrated into digital networks. As Harari (2016) states, humanity is entering an era in which "biological algorithms can be rewritten." Genetic engineering represents another fundamental component of transhumanist theory. Gene-editing technologies such as CRISPR-Cas9 allow for the redesign of the human genome. This development not only enables the elimination of genetic diseases but also opens the possibility of selectively enhancing physical and cognitive traits. Consequently, the human being is transformed from a biologically contingent entity into a designable system.

Transhumanism is also closely related to posthumanist debates. Posthumanism challenges anthropocentric thinking and positions the human as part of a broader technological and ecological network. In this sense, the human is no longer the center of the universe but one component of a multi-agent system. This perspective represents a significant ontological shift that questions human exceptionalism. At the ethical level, transhumanism raises significant concerns. In particular, the question of who will have access to enhancement technologies introduces the risk of deepening social inequality. If such technologies become accessible only to certain economic groups, the emergence of "biological class differences" has been suggested as a possible outcome. Fukuyama (2002) criticizes this development by emphasizing that the political and social consequences of transforming human nature should not be overlooked. He argues that the effects of biotechnological interventions on human nature must be carefully considered in terms of their broader social and political implications. In light of all these discussions, transhumanism presents a multilayered theoretical framework that proposes a profound transformation of human nature, its boundaries, and its future. This framework emerges at the intersection of biotechnology, artificial intelligence, and neurotechnology, redefining the human as both a biological and technological being. Therefore, transhumanism should be regarded not only as a scientific field of development but also as a comprehensive paradigm with philosophical, ethical, and social dimensions.

Human Biological Limits and Technological Intervention

Human biological limits have historically been one of the fundamental determinants of human existence. These limits consist of natural processes that are traditionally assumed to be unchangeable, such as aging, disease, death, and cognitive capacity. However, modern science and technology increasingly demonstrate that these boundaries are not absolute; rather, they are structures that can be intervened in and transformed. In this context, the human body is being redefined as a system open to technological intervention rather than a fixed biological structure.The idea that biological limits can be overcome has become concrete, particularly through advances in biotechnology and genetic engineering. Gene-editing technologies such as CRISPR-Cas9 make it possible to restructure the human genome and offer significant potential for eliminating hereditary diseases. These technologies suggest that the so-called "natural" boundaries of human biology can be altered through engineering intervention. Technology also offers the possibility of extending human lifespan, as well as the freedom to modify one's own body -or choose not to do so- and even the possibility of resisting time and remaining biologically unchanged. Although Baudrillard (2011, p. 292) argues that "as living beings live longer and steal from death, they lose their symbolic value," technological attempts to halt aging and extend human life continue to generate opposing perspectives.

Technological intervention is not limited to the genetic level; it also expands the functional capacity of the human body through neurotechnology and cybernetic systems. Brain–computer interfaces (BCIs) establish a direct connection between the human mind and digital systems, enabling the integration of cognitive processes with the external digital environment. This transformation points to a hybrid structure in which the human mind transcends its biological limitations and becomes integrated with digital systems. In this process, the human body is increasingly conceptualized not merely as a "repairable" structure but as an "enhanceable" one. According to Bostrom (2005), human enhancement refers not only to the treatment of diseases but also to the extension of human capacities beyond the normal range. This approach goes beyond the therapeutic boundaries of medicine and introduces the idea of redesigning human nature. Another significant dimension of technological intervention is the extension of lifespan and the control of biological aging. Anti-aging research encompasses scientific studies aimed at slowing down or reversing cellular aging. These efforts strengthen the idea that death may no longer be an inevitable biological condition but rather a technically manageable process. As Harari (2016) states, humanity is now on the threshold of "an era in which biological algorithms can be rewritten." This expression indicates that the human body is increasingly understood as a system that can be reprogrammed at genetic, neurological, and physiological levels. Thus, biological limits are transformed from fixed natural structures into variables open to scientific manipulation.

Technological intervention also raises critical questions regarding "human identity" and subjectivity. The transformation of the human body into a modifiable structure implies a corresponding transformation in the perception of the self. Within this framework, a new tension emerges between biological continuity and technological variability. As Dağ (2020, p. 43) states, "the idea of delaying death or achieving immortality is a central problem transhumanism seeks to overcome. Genetic engineering can prevent diseases affecting the human body and delay aging, ensuring bodily preservation. Another approach is to search for ways to upload human consciousness, including the brain, into computers." Genetic engineering and biotechnological developments constitute one of the most critical fields of contemporary scientific transformation due to their capacity to directly intervene in human biological structure. In particular, the development of CRISPR-Cas9 gene-editing technology has opened a wide range of applications, from treating hereditary diseases to enhancing biological capacities. Doudna and Charpentier (2014) describe CRISPR technology as "a revolutionary tool that enables precise and programmable editing of genetic material." This development has intensified debates regarding the possibility of using the human genome not only for therapeutic purposes but also for redesigning physical and cognitive traits. From a transhumanist perspective, biotechnology becomes a fundamental tool for transcending human biological limitations (Bostrom, 2005). However, genetic interventions also have significant social consequences. Fukuyama (2002) emphasizes that the transformation of human nature through biotechnological interventions poses serious risks in terms of social equality, ethical responsibility, and human rights. At the same time, biotechnological developments offer promising outcomes in areas such as lifespan extension, artificial organ production, and personalized medicine. According to Harari (2016), humanity is approaching a "designed human" era by pushing evolutionary processes beyond natural selection through biotechnology. Therefore, genetic engineering should be understood not only as a scientific advancement but also as a multidimensional transformation that redefines humanity's ontological position.

a) CRISPR and Gene Editing Technologies

Genetic engineering has reached one of its most significant turning points with the development of CRISPR-Cas9 technology. This system has radically expanded the intervention capacity of genetic science by enabling targeted modifications in DNA sequences. Thanks to this technology, the genetic structure of living organisms can be redesigned with a precision that was previously impossible. CRISPR technology, inspired by the natural immune mechanisms of bacteria, operates on a "cut-and-paste" principle at the genomic level. This method carries a revolutionary potential in the treatment of genetic diseases. In particular, the elimination of hereditary disorders strengthens the transhumanist idea that human biology can be redesigned. According to Bostrom (2005), human enhancement technologies are "tools that make it possible to go beyond the natural limits of human capacity." In this regard, CRISPR is considered not only a therapeutic tool but also an enhancement-oriented technology. This situation blurs the boundary in medical ethics between "treatment" and "enhancement.

” Gene-editing technologies are not limited to eliminating diseases; they also include the potential for selectively enhancing physical and cognitive traits. This has brought the debate on the “designed human” to the forefront. Thus, genetic intervention becomes not only a biological process but also one with profound social consequences. As Harari (2016) argues, modern biotechnology is transforming humans into beings in which “biological algorithms can be rewritten” (Harari, 2016). This statement indicates that genetic structure is no longer seen as a fixed destiny but as an editable information system. Accordingly, human nature is increasingly defined in terms of flexibility rather than immutability. The widespread use of CRISPR technology also raises significant ethical debates. In particular, the limits of genetic intervention, its impact on future generations, and the redefinition of what is considered “natural” constitute the main areas of discussion.

b) Artificial Organs and Life Extension

Another important field of biotechnological development is artificial organ production and tissue engineering. Artificial organs developed for patients awaiting transplantation offer a solution to one of the most critical problems in medicine: organ shortage. These advancements demonstrate that parts of the human body are becoming technically producible. Artificial organ technologies are realized through the use of 3D bioprinting and cellular engineering techniques. In this way, the laboratory production of organs such as the heart, kidneys, and liver has become possible. This process encourages the rethinking of the human body as a sustainable system composed of replaceable parts. From a transhumanist perspective, these developments are directly related to the goal of extending human life. The extension of lifespan is not merely a medical objective but is also considered an ontological transformation, since the postponement of death fundamentally alters human perception of existence. Harari (2016) interprets this process within the framework of humanity’s “quest for immortality,” arguing that technology blurs the boundaries between life and death. In this context, artificial organs represent not only a biological innovation but also a development that redefines the existential limits of the human being. According to Bostrom (2005), human enhancement technologies make it possible to radically expand human experience through lifespan extension. This leads to a transformation in both the quantity and quality of life. The human being is no longer a limited life-cycle entity but becomes a potentially extendable existence. However, these developments also raise significant ethical concerns. In particular, the potential of lifespan extension to increase social inequality is a major point of debate, as access to such technologies may depend on economic and social factors.

c) Brain-Computer Interfaces and Neurotechnology

One of the most significant developments in the field of neurotechnology is brain–computer interfaces (BCIs). These systems enable the direct transfer of the brain’s electrical signals to digital devices, allowing control through thought alone. This technology increasingly blurs the boundaries between the human mind and machines. BCI technologies represent an important medical breakthrough, particularly for individuals with paralysis, enabling communication and control of prosthetic devices. However, these systems are not limited to therapeutic purposes; they also occupy a central place in transhumanist debates due to their potential to enhance cognitive capacity. According to Harari (2016), humanity is “moving toward a new form of existence where biological and digital systems are integrated.” This statement suggests that the human mind is no longer conceived solely as a biological structure but as a network integrated with digital systems. Neurotechnological developments also raise fundamental questions regarding the nature of consciousness. The technological restructuring of the mind–body relationship leads to a transformation of the concept of the “self.” This indicates that human identity becomes increasingly open to technological intervention. Bostrom (2005) argues that cognitive enhancement technologies could significantly increase human capacities and fundamentally transform social structures. In this sense, BCI technologies have the potential to generate not only individual but also societal transformations. From an ethical perspective, neurotechnology raises new concerns such as privacy and mental autonomy. The transfer of brain data into digital environments makes the concept of “mental privacy” highly problematic. This situation introduces the risk that even human thought may become technologically accessible.

Human Enhancement and AI-Powered Transformation

Human beings have historically engaged in efforts not only to dominate nature but also to understand and analyze their own development. As humanity has gained self-knowledge and achieved progress in intelligence-related domains, it has also persistently reflected on its ultimate aspiration: "immortality." Through technologies developed by humankind, civilization has experienced a significant leap forward. "Increasing human lifespan, preventing poverty, providing resources for a growing population, and creating a healthy environment are among the primary concerns. In addition to these, the way to improve ourselves lies in intelligent technologies capable of solving complexity in order to cope with challenges" (Kurzweil, 2015, p. 239).

First introduced as a scientific concept in 1955, artificial intelligence emerged as part of a project led by John McCarthy, who aimed to define both its possibilities and limitations. "McCarthy's purpose in this project was to enable machines to use language, form abstractions and concepts, solve types of problems typically solved by humans, and improve themselves" (Reese, 2020, p. 75). Artificial intelligence, fundamentally understood as software and computational systems capable of learning, represents an extension of attempts to analyze human learning mechanisms. These developments also raise the possibility that "the development and adaptation of artificial intelligence may create both new opportunities and challenges in all areas concerning human life" (Rouhiainen, 2020, p. 3). Human augmentation, powered by AI technologies, is one of the core components of transhumanist thought, referring to the enhancement of individuals' physical, cognitive, and sensory capacities through technological tools. This concept defines a transformation process that is not limited to treating diseases but aims to surpass normal biological limits. In this sense, the human is no longer considered a fixed entity but a continuously improvable system. Unlike traditional medicine, human enhancement blurs the boundary between "treatment" and "improvement," aiming to transcend the notion of normality itself. This shift opens the way for redefining the human body as an object of engineering.

According to Bostrom (2005), human enhancement technologies are "a set of tools that make it possible to transcend the natural limits of human capacity." This approach is grounded in the idea that human nature is not fixed and can be reshaped through technological intervention. AI-based systems are among the most important components of human augmentation processes. Artificial intelligence expands human cognitive capacity through big data analysis, learning algorithms, and decision-support systems. This demonstrates that the boundaries between human and machine cognition are becoming increasingly porous. According to Harari (2016), in the age of artificial intelligence, humanity has entered "a transformation process in which biological algorithms merge with digital algorithms." This statement indicates that human cognition is no longer purely biological but a hybrid structure shaped through interaction with digital systems.

AI-assisted augmentation is not limited to cognition; it also affects decision-making, learning, and perception processes. In particular, AI-based assistants restructure human decision-making mechanisms by reducing cognitive load and supporting analytical processes. This development leads to a redefinition of human autonomy in relation to technology. The integration of neurotechnological advances with artificial intelligence enables direct interaction between the human brain and digital systems. Brain–computer interfaces facilitate the direct transfer of thought into machines, advancing human–machine integration to a higher level. This process can also be interpreted as the externalization of the human mind. From a transhumanist perspective, these developments indicate a stage in which human evolution is consciously directed. More (1990) defines transhumanism as "the project of consciously directing human evolution." In this sense, AI-supported human augmentation represents a transition in which natural evolution is replaced by technological evolution. The concept of posthumanism involves transcending human nature, expanding human potential, and transforming the human through technological means. Similarly, in transhumanism, the human is not considered a completed entity, and the final stage of this process is referred to as the "posthuman." "Although the posthuman is not clearly defined in terms of its ontological boundaries in transhumanist literature, we can describe the transhuman as the transitional state between Homo sapiens and the posthuman, and the posthuman as the being reached at the end of this transformation process" (Başak, 2020, p. 25). Posthumanism decentralizes the human and positions technological systems as replacements within the technological age (Doğan, 2024, p. 189).

However, human augmentation processes also raise significant ethical concerns. In particular, inequalities in technological access may lead to new forms of social stratification. The distinction between "enhanced humans" and "non-enhanced humans" introduces a new type of biologically based inequality. Fukuyama (2002) highlights that biotechnological and technological interventions have the potential to alter human nature, emphasizing that this may have serious consequences for social order. The transformation of human nature thus becomes not only an individual choice but also a political issue. The expansion of human enhancement technologies deepens philosophical debates regarding the meaning of human life. While improving quality of life and expanding cognitive capacities may yield positive outcomes, the erosion of "natural" human limits also increases existential uncertainty.

Ethical and Social Dimensions of Transhumanism

One of the most significant ethical areas of debate surrounding transhumanist technologies is the problem of inequality in access to these technologies. Since human enhancement, genetic engineering, and AI-supported systems are highly costly technologies, access to them has the potential to create substantial disparities between societies. This situation raises the risk that biological differences may become embedded within social inequalities. The distribution of technological advancements has never been equal. In particular, the technological gap between developed and developing countries also determines access to transhumanist tools. In this context, technology may function not as an equalizing instrument but rather as a mechanism that reproduces existing social hierarchies. Bostrom (2005) states that if human enhancement technologies are distributed improperly, "a new kind of biological class division may emerge." Fukuyama (2002) similarly emphasizes the societal implications of biotechnological developments, arguing that the uncontrolled diffusion of such technologies may weaken the principle of democratic equality. According to Harari (2016), humanity may in the future face biologically and technologically differentiated "human species."

At the core of transhumanist thought lies the assumption that "human nature is malleable." While traditional philosophical perspectives regard human nature as fixed and universal, transhumanism argues that it can be reshaped through technological intervention. The transformation of human nature has become particularly tangible with advances in genetic engineering, neurotechnology, and artificial intelligence. These technologies possess the capacity to modify human physical and cognitive characteristics. In this sense, humans are transformed from beings defined by nature into systems that can be designed. Harari (2016) describes this transformation as the process through which Homo sapiens becomes Homo deus, emphasizing that biotechnological progress accelerates this transition. As Volland (2022, p. 26) states, "Human culture is the DNA of society. This DNA is now being artificially constructed."

One of the deepest philosophical problems of transhumanism emerges in the domains of identity and ontology. The technologization of the human body and mind renders the continuity of the concept of "self" increasingly problematic. While identity has traditionally been defined through biological continuity and consciousness unity, transhumanist technologies fragment and destabilize this continuity. In particular, neurotechnology and digital consciousness systems blur the boundaries of human identity. Harari (2016) argues that this transformation shifts humanity "from a biological entity to a data-based existence." This indicates that identity is now defined not only by the body but also by flows of information and data. According to Bostrom (2005), consciousness transfer and digital mind technologies may make it possible for human identity to extend beyond biological limits. This development reopens the philosophical question of "personal identity persistence." Fukuyama (2002) further argues that the loss of identity may generate not only individual but also societal crises. Posthumanism considers the human together with all forms of existence constructed as "the other." This suggests that humanity is never purely "human," but always already involves an "other-than-human" dimension. As Gacar (2024, p. 83) states, "since existence is possible only within multiple ontological relations in space and time, this relationality does not support the distinction between 'human' and 'non-human'." From an ontological perspective, transhumanism defines the human not as a fixed entity but as a continuously transforming process. This approach fundamentally transforms the classical metaphysical understanding of the human. The human is no longer regarded as a being that "is," but rather as a being that is constantly "becoming."

Transhumanism is a multi-layered conceptual framework shaped by the claim that humans can transcend their biological limits through technology and is increasingly becoming more visible alongside contemporary scientific developments. The genetic engineering, artificial intelligence, neurotechnology, and biotechnological advancements examined within the scope of this study demonstrate that humanity is undergoing not only a biological transformation but also an ontological one. As this study reveals, transhumanism does not regard the human being as a fixed entity but rather as a continuously improvable process. This approach challenges classical philosophical assumptions about human nature and places the question of what it means to be human at the center of contemporary debate.

Biotechnological developments, particularly CRISPR, artificial organ production, and brain-computer interfaces, indicate that the human body has become a modifiable structure. This suggests that biological limits are not absolute but are continuously redefined through technological progress. As Harari (2016) argues, the modern era can be understood as a period in which "biological algorithms can be rewritten." This implies that humans are no longer solely nature-determined beings but are increasingly integrated into technical systems. According to Bostrom (2005), human enhancement technologies are considered tools capable of increasing human capacity. However, this enhancement does not merely represent a technical improvement; it also signifies a redefinition of existential boundaries.

The transformation of human nature is not only an individual process but also a social one. The redefinition of the concept of the "normal human" necessitates a restructuring of ethical norms as well. In terms of identity and ontological discussions, transhumanism also challenges notions of continuity and sameness. In particular, developments in digital consciousness and neurotechnology transform the sense of self into a fragmented and fluid construct. In this context, transhumanism represents not only technological progress but also a profound philosophical rupture. The human is no longer considered a fixed subject but rather an entity that is continuously reproduced and redefined.

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ÇAĞDAŞ TÜRK RESMİNDE KATASTROFİK İMGELER

CATASTROPHIC IMAGES IN CONTEMPORARY TURKISH PAINTING

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ÖZET

Resim sanatında sanatçıların önemli bir kısmı güzellik kavramını ve estetik bakış açışıyla ilişkili temaları ele almasına karşın bazı sanatçılar da toplumsal kırılma anlarını, siyasi ve iktisadi dönüşümlere sebep olan tarihsel olayları katastrofik imgeler biçiminde betimlemişlerdir. Katastrofik imgeler büyük yangınlar, depremler gibi önemli ekolojik yıkımlar ile savaşlar, kıtlık ve salgın hastalıklar gibi toplumsal çöküşler olarak tasvir edilir. Bununla beraber kuramsal açıdan sanat alanında katastrofi kavramı, salt bir yıkım tasvirinin ötesine geçerek; temsili sistemlerin, aşina olunan biçimlerin ve toplumsal-mekânsal düzenin beklenmedik bir zamanda bozulması olarak da tanımlanır. Fransız düşünür Gilles Deleuze'ün resim düzleminde "klişelerin yerle bir olduğu kaos anı" olarak kavramsallaştırdığı katastrofik imge, Türkiye'nin tarihsel süreçte karşılaştığı, savaşlar, modernleşme sancıları, düzensiz kentleşme politikaları ve doğal felaketlerin yarattığı travmalarıyla birleşerek çağdaş Türk resminde özgün bir dille betimlenmiş olup; Erken dönem Türk resminde yangın, savaş ve göç gibi temalarla "tarihsel bir hüzün ve belge" seviyesinde kalan felaket olgusunun, çağdaş dönemde felsefi ve plastik bir biçimsel anlatıya dönüşmüştür. Türk sanatçılarının yapıtlarında felaketi görselleştirirken ya mesafeli bir çevre-kent analizi ürettikleri ya da travmanın tinsel yasını tuttukları fark edilir. Görsel kültür veri incelemesiyle yapıt okumaları üzerinden oluşturulmuş nitel bir araştırma olan bu çalışmanın amacı, Türk resminde sanatçıların çevresel felaketler, ekolojik yıkımlar ve deprem gibi katastrofik unsurların plastik açıdan ele alınış biçimlerini ortaya çıkarmaktır. Araştırma, katastrofik imge kavramını içeren çağdaş Türk sanatçıların yapıtlarıyla sınırlandırılmıştır.

Anahtar Kelimeler: Çağdaş Türk Resmi, Felaketler, İmge, Katastrofi.

ABSTRACT

While a significant number of artists in the painting art address the concept of beauty and themes related to an aesthetic perspective, some artists have depicted moments of social upheaval and historical events that have led to political and economic transformations through catastrophic imagery. Catastrophic images are depicted as major ecological disasters such as large-scale fires and earthquakes, as well as social collapses such as wars, famines, and epidemics. However, from a theoretical perspective in the field of art, the concept of catastrophe goes beyond a mere depiction of destruction; it is also defined as the disruption of representational systems, familiar forms, and the socio-spatial order at an unexpected moment.

The catastrophic image, conceptualized by the French philosopher Gilles Deleuze as "the moment of chaos when clichés are shattered" within the pictorial plane, has been depicted in contemporary Turkish painting with a unique language, merging with the traumas created by wars, the pains of modernization, chaotic urbanization policies, and natural disasters that Türkiye has faced throughout its historical process; In early Turkish painting, the phenomenon of catastrophe -which remained at the level of "historical sorrow and documentation" through themes such as fire, war, and migration- has transformed into a philosophical and plastic formal narrative in the contemporary period. It is evident that when Turkish artists visualize disaster in their works, they either produce a detached analysis of the environment and the city or observe a spiritual mourning for the trauma.

This qualitative study, which is based on visual culture data analysis and artwork interpretations, aims to reveal how artists in Turkish painting address catastrophic elements such as environmental disasters, ecological destruction, and earthquakes from a plastic arts perspective. The research is limited to the works of contemporary Turkish artists that incorporate the concept of the catastrophic image.

Keywords: Contemporary Turkish Painting, Disasters, Image, Catastrophe.

GİRİŞ

Tarihsel süreçte resim sanatında sanatçıların büyük bir kısmı güzellik kavramını ve estetik bakış açısıyla ilişkili temaları merkeze almış; uyumu, dengeyi ve görsel hazzı önceleyen bir üretim biçimini sürdürmüştür. Ancak bu yaklaşımı benimseyen sanatçıların yanında, sanat tarihinin her döneminde, toplumsal kırılma anlarını, siyasi ve iktisadi dönüşümlere sebep olan tarihsel olayları doğrudan resmin konusu hâline getiren bir damar da daima var olmuştur. Büyük yangınlar, depremler gibi ekolojik yıkımlarla; savaşlar, kıtlık ve salgın hastalıklar gibi toplumsal çöküşler, sanatçıların tuvallerinde katastrofik imgeler biçiminde karşılık bulmuştur (Görsel 1). Sözlük anlamıyla büyük felaket, yıkım veya çöküş anlamına gelen katastrofi (Harper, t.y.), sanat ve felsefe düzlemine taşındığında salt fiziki bir tahribat tasvirinin çok ötesine geçer. Bu kavram; temsili sistemlerin, aşina olunan biçimlerin, kurumsal yapıların ve toplumsal-mekânsal düzenin beklenmedik bir zamanda, ani ve radikal bir biçimde bozulması olarak tanımlanır (Foster, 1996).

Dolayısıyla katastrofik imge, sadece yanan bir evi, yıkılan bir binayı veya savaş meydanındaki kayıpları gösteren bir illüstrasyon değildir. O imge, izleyicinin tanıdık olduğu görsel kodları sarsan, algılama biçimlerini sekteye uğratan ve insanı kendi varoluşsal tekinsizliğiyle "unheimlich" (bkz. Jentsch ve Freud, 2023) baş başa bırakan resimsel bir çığlıktır. Bununla beraber, Deleuze, özellikle Francis Bacon üzerine kaleme aldığı Duyumsamanın Mantığı adlı eserinde ve resim derslerinde geliştirdiği düşüncede, katastrofik imgeyi "klişelerin yerle bir olduğu kaos anı" olarak tarif etmektedir (Görsel 2.) (Deleuze, 2009).

Görsel 1. Yaşlı Pieter Bruegel, Ölümün Zaferi (The Triumph of Death), 1562, Panel Üzerine Yağlıboya, 117x162 cm, Prado Müzesi, Madrid.

Katastrofik imge; organik yapının çözüldüğü, figürlerin deforme olduğu, mekânın parçalandığı ve renklerin kendi özerkliğini ilan ettiği bir kaosu anıdır. Bu kaos anı, yıkıcı olduğu kadar oluşturcu yapıdadır aynı zamanda; çünkü eski algı biçimlerini yıkarak yeni bir plastik dilin, yeni bir duyum mantığının doğmasını sağlar (Deleuze, 2009). Bu bağlamda katastrofi, sadece dış dünyadaki bir felaketin -bir depremin, bir yangının- tuvale mekanik olarak aktarılması değildir; tuvalin kendisinin bir felaket alanına, bir çatışma yüzeyine dönüşmesidir. Çağdaş Türk resminde de felaket olgusu ele alınırken, sanatçıların sadece konuyu değil, boyama eylemini, form oluşturma tekniklerini ve kompozisyon kurgularını da birer "biçimsel kriz" olarak düzenledikleri görülür.Klasik perspektifin kırılması, figürlerin dağılması ve lekeci soyutlamaların öne çıkması, Deleuze'cü anlamda klişelerin yıkılması ve felaketin tinsel ve plastik boyutunun eşzamanlı olarak inşa edilmesi anlamına gelmektedir (Lyotard, 1988).

Görsel 2. Francis Bacon, 'Resim (Painting)', 1946, Tuval Üzerine Yağlıboya ve Pastel, 97.8x132.1 cm, MoMA Modern Sanatlar Müzesi, New York.

GEÇ OSMANLI VE ERKEN CUMHURİYET DÖNEMİ RESSAMLARINDA FELAKET BETİMLEMELERİ

Türkiye'nin tarihsel deneyimi, katastrofik imgenin neden bu denli zengin bir damar olarak ortaya çıktığını anlamamız için önemli bir arka plan sunar. Osmanlı İmparatorluğu'nun çözülüş sürecinden Cumhuriyet'in kuruluşuna uzanan dönem; Balkan Savaşları, Birinci Dünya Savaşı, Kurtuluş Savaşı gibi büyük çaplı çatışmaları, bu çatışmaların doğurduğu kitlesel göç ve mübadele hareketlerini, hızlı ve sancılı bir modernleşme projesini içerir. Bu dönem sanatçıları olan Mıgırdiç Civanyan, İbrahim Çallı, Namık İsmail'in yapıtlarında felaket betimlemesi, büyük oranda "tarihsel bir hüzün" ve "belgeleme" arzusu ile sınırlı kaldığı söylenebilir (Renda, 1977). Bu yapıtlarda felaket, dışsal bir olay olarak, izleyiciyle belirli bir mesafe korunarak aktarılır. Kompozisyonlar büyük oranda akademik-figüratif kurallara bağlıdır; perspektif korunur, form bütünlüğü bozulmaz. Örneğin, İstanbul'un ahşap mahallelerini yok eden o meşhur yangınlar resmedilirken, dumanlar yükselir, insanlar panik halinde kaçışır ancak resmin plastik yapısı hala akademik bir çerçevenin içindedir. Sanatçı, yangının yarattığı dehşeti bir manzara (peyzaj) estetiği ve pitoresk bir anlatı içinde, adeta bir kronikçi gibi kaydeder (Görsel 3 ve 4) (Ateşli, 2016).

Görsel 3. Mıgırdiç Civanyan, "Deniz Kenarında Yangın", metal plaka üzerine yağlıboya, 35,7x55,2 cm, Atatürk Kitaplığı, İstanbul.

Görsel 4. Mıgırdiç Civanyan, "Yangın", metal plaka üzerine yağlıboya, 36x51,5 cm, Atatürk Kitaplığı, İstanbul.

Balkan Savaşları, Birinci Dünya Savaşı'nın dramatik sonuçlarıyla birlikte Şişli Atölyesi (1917) sanatçıları İbrahim Çallı'nın savaş temalı resimlerinde de amaç, toplumsal dayanışmayı artırmak, milli

mücadeleyi destansılaştırmak ya da Namık İsmail'in resminde olduğu gibi yaşanan acıyı ve karamsarlığı tarihe not düşmektir (Bkz. Görünür, 2010). Bu eserlerdeki hüzün, plastik bir deneysellikten ziyade konunun trajik doğasından kaynaklanmaktadır (Görsel 5 ve 6).

Görsel 5. Namık İsmail, "Savaşın Yankıları-Tifüs", 1917, tuval üzerine yağlıboya, 130x170 cm, Ankara Resim Heykel Müzesi, Ankara.

Görsel 6. İbrahim Çallı, "Gece Baskını", 1916, tuval üzerine yağlıboya, 175x225 cm, İstanbul Askeri Müze, İstanbul.

O dönemin koşullarına bakıldığında: yeni kurulan ulus-devletin sanat politikası, büyük ölçüde resmî tarih anlayışının görselleştirilmesi üzerine kuruluydu. Savaş, göç ve yıkım sahneleri, genellikle kahramanlık anlatısının veya milletin direnişinin bir parçası olarak resmedildi; bu da felaketin kendisinin değil, felaket karşısındaki insan iradesinin ön plana çıkarılmasına yol açtı. Böylece felaket, resmin asıl konusu olmaktan çok, kahramanlık anlatısının arka fonu hâline geldi. Ancak Hüseyin Avni Lifij'in savaş temalı resimlerinde yaşanan trajik acının tasviri simgeselci şekilde tasvir edildiği görülür. (Görsel 7 ve 8).

Görsel 7. Hüseyin Avni Lifij, "Kara Gün", 1932, tuval üzerine yağlıboya, 93x119 cm, Ankara Resim Heykel Müzesi, Ankara.

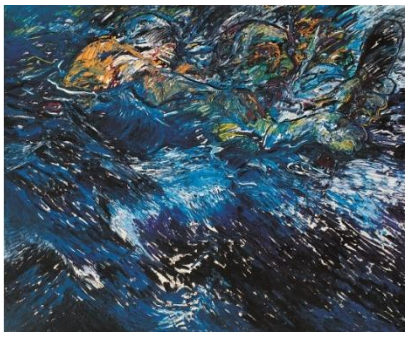
Görsel 8. Hüseyin Avni Lifij, "Savaş ve Alegori", 1917, tuval üzerine yağlıboya, 160x200 cm, İstanbul Resim Heykel Müzesi, İstanbul.

1960 SONRASI ÇAĞDAŞ TÜRK RESMİNDE FELAKET BETİMLEMELERİ

20. yüzyılın ikinci yarısından itibaren ve özellikle 1980'ler sonrasında, Türkiye'nin geçirdiği radikal yapısal dönüşümler, modernleşme sancıları, düzensiz kentleşme politikaları, endüstriyel kirlilik ve ardı ardına yaşanan büyük doğal afetler, çağdaş Türk sanatçılarının felaket olgusuna bakışını kökten değiştirmiştir. Çağdaş dönemde felaket, "belgeleme" seviyesinden kurtularak derinlikli bir felsefi ve plastik biçimsel anlatıya dönüşmüştür. Bu dönüşümün arkasında hem küresel sanat akımlarının -Dışavurumculuk, Yeni Dışavurumculuk, Kavramsal Sanat- etkisi hem de Türkiye'nin kendi tarihsel süreçte karşılaştığı travmaların birikimi yatmaktadır (Antmen, 2008).

Çağdaş Türk sanatçısı, felaketi artık sadece dışarıda gerçekleşen ve kayda geçirilmesi gereken bir olay olarak görmez. Felaket, Frankfurt Okulu düşünürlerinin de vurguladığı gibi, modernitenin ve aydınlanmanın kendi içsel krizlerinin bir sonucu, bireyin ve toplumun içselleştirdiği varoluşsal bir durumdur (Adorno ve Horkheimer, 2010). Plastik açıdan bu durum, figürün ve mekânın parçalanmasıyla kendini gösterir. Çağdaş resimde katastrofik imge; a) katmanlı boya dokularıyla b) gözü rahatsız eden, tekinsiz renk kontrastlarıyla, c) klasik mekân algısını yok eden çoklu perspektiflerle ve amorf formlarla, d) figürlerin adeta çözünerek, eriyerek ya da parçalanarak mekâna karıştığı kompozisyonlarla inşa edilir. Katastrofinin betimlenmesindeki biçimsel yaklaşımlar, resmin konusundan ibaret değildir; boyanın tuvale vuruluş biçimi, tuvalin yırtılması, yüzeyin tahrip edilmesi gibi eylemlerle plastik dilin bizzat kendisi katastrofik bir karakter kazanır. Sanatçılar, felaketi anlatmaz; felaketin yarattığı sarsıntıyı boya, çizgi ve leke gibi biçimsel öğelerle yeniden üretir.

Bu bağlamda Mehmet Güleryüz'ün 1980 tarihli *Stamboli Şehre Doğru* adlı yapıtı (Görsel 9), Türkiye'nin 1980 askerî darbesiyle ve eş zamanlı olarak neoliberal kentleşme dalgasıyla yüzleştiği bir dönemin katastrofik panoramasıdır. Güleryüz, Türk resminde Yeni Dışavurumculuğun en güçlü temsilcilerinden biri olarak deseni ve boyayı uysal bir araç olmaktan çıkarıp bizzat sarsıntının kendisine dönüştürür. Bu eserde İstanbul (Stamboli), kırsaldan kente göçün yarattığı düzensiz kentleşme politikalarının ve kültürel erozyonun trajik nesnesidir. Klasik mekân algısının yok edildiği yapıtta, şehre doğru akan tekinsiz kütleler ve amorf formlar dikkat çeker. Sanatçı, felaketi dışsal bir manzara gibi aktarmaz; insanın vahşileşen ve yabancılaşan iç dünyası üzerinden dışa vurur. Boyanın tuvale hırçın vuruluş biçimi ve çizgilerin deformasyonu, bizzat plastik dilin katastrofik bir karakter kazandığının en somut kanıtıdır.



Görsel 9. Mehmet Güleryüz, "Stamboli Şehre Doğru", 1980, tuval üzerine yağlıboya, 150x170 cm, Özel Koleksiyon.

Neşet Günal, toplumsal gerçekçi sanat anlayışıyla Anadolu insanının varoluş mücadelesini ve toprağa bağlı dramını aktarırken, "Korkuluk" serisiyle bu sorunsalı felsefi bir boyuta taşır. Sanatçının *Korkuluk V* (Görsel 10) adlı eseri, kırsal yaşamın ve toprağın çoraklaşmasını, yani bir nevi ekolojik ve sosyolojik felaketi simgeler. Günal'ın resminde figürler ve mekân, katmanlı toprak dokusunu andıran boya katmanlarıyla inşa edilir. *Korkuluk V*'teki insan figürleri, neredeyse birer amorf forma dönüşmüş, çaresizlik ve korkunun yarattığı travmayla katılaşmıştır. Sanat tarihsel literatürde Günal'ın korkuluk imgesi, şamanik köklere ve bereketi koruma ritüellerine referans verse de modernitenin getirdiği yoksulluk ve yalnızlık karşısında bir trajedinin anıtına dönüşür (bkz. Arda, 2015). Eserdeki soluk, monokromatik ve tekinsiz renk kontrastları, insanın doğa karşısındaki ve kendi ürettiği sistem içerisindeki çaresizliğini -yani içselleştirilmiş bir felaket durumunu- gözler önüne serer.

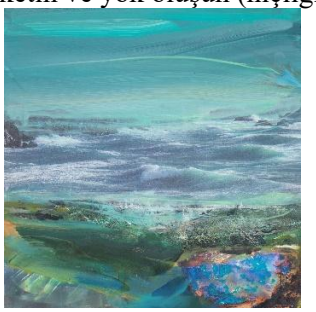
Görsel 10. Neşet Günal, "Korkuluk V", 1987, tuval üzerine yağlıboya, 184x120 cm, Özel Koleksiyon.

Aydın Ayan'ın *Piyonların Piyonları* (Görsel 11) adlı gravürü, egemen güç ilişkilerini, toplumsal hiyerarşileri ve bireyin bu mekanik çarklar arasında ezilerek parçalanmasını konu edinir. Ayan, titiz ve nesnel unsurları kavramsal bir sorgulamayla birleştiren eleştirel-gerçekçi üslubuyla tanınır. Bu yapıtta felaket, doğanın bir gazabı değil; tamamen Adorno ve Horkheimer'ın işaret ettiği (2010) "*aydınlanmanın ve rasyonelleşmenin kendi krizidir*." İnsan, toplumsal ve siyasal bir sistemin (piyonların) oyuncağı haline gelmiş ve özgürlüğünü yitirmiştir (Tansuğ, 1986). Kompozisyondaki nesnelerin ve figürlerin katı, kurallı ama bir o kadar da tekinsiz kurgusu, bireyin mekân içerisinde eritilmesini ve sisteme tabi kılınmasını simgeler. Klasik perspektifin yerini alan klostrofobik ve mekanik alan kurgusu, modern dünyanın birey üzerinde yarattığı sarsıntıyı derin bir biçimsel dil ile hissettirir.

Görsel 11. Aydın Ayan, "Piyonların Piyonları", 1989, kâğıt üzerine çukur baskı, 53x76 cm, İMOGA İstanbul Grafik Sanatlar Müzesi.

1968 kuşağının Paris'te yaşayan önemli temsilcilerinden Utku Varlık'ın *Hiç* (Görsel 12) adlı eseri, felaketi tamamen esrik, düşsel ve metafizik bir düzleme taşır. Varlık'ın sanatı, gerçek ile düş arasında gidip gelen, hüzünlü ve fantastik bir görsellikle karakterizedir. *Hiç* sergisinde ve resminde sanatçı, Doğu ve Batı felsefesindeki "hiçlik" kavramından hareket ederek varoluşsal krizi sorgular. Varlık, renklerin ve kavramların anlamını yitirdiği bir çağda, resmi bir nevi *katarsis* (arınma) aracı olarak görür.

Eserde formlar ve mekân net sınırlarını kaybetmiş; amorf, sisli ve akışkan formlar halinde birbirinin içinde çözünmüştür. Bu çözünme, felaketin ve yok oluşun (hiçliğin) estetik ifadesidir.



Görsel 12. Utku Varlık, "Hiç", 2016, tuval üzerine yağlıboya, 38,5x38,5 cm, Özel Koleksiyon.

Halil Akdeniz, Kavramsal Sanat ve çağdaş plastik dil bağlamında Türkiye'de kültürel coğrafyayı, tarihsel katmanları ve çevre sorunlarını analitik bir dille ele alan öncü sanatçılardandır. Sanatçının *İzmir'den Görsel Notlar* (Görsel 13) adlı çalışması, kentleşme, sanayileşme ve çevre kirliliğinin yarattığı katastrofiyi simgelerle kodlayan bir başyapıttır (bkz. Ergüven, 1998). Akdeniz, geleneksel tuval resminin ötesine geçerek yüzeyi tahrip eder, katmanlı dokular, yazılar ve topografik işaretler kullanır (Bkz. Sağlam, 2015). Bu eserde felaket, doğrudan bir yangın ya da yıkım anı olarak betimlenmez; aksine endüstriyel kirliliğin ve kentsel dönüşümün bıraktığı tekinsiz "*izler*" üzerinden verilir. Yüzeyin amorf lekelere bölünmesi, rasyonel haritacılık çizgileri ile kaotik boya dokularının çatışması, modernitenin doğayı ve tarihi tahrip edişinin plastik bir analizidir.

Görsel 13. Halil Akdeniz, "İzmir'den Görsel Notlar", 1986, tuval üzerine akrilik boya, 117x117 cm, Beymen Sanat Koleksiyonu.

1990'lı yılların Türk resminde figüratif dışavurumculuğun sınırlarını zorlayan Mustafa Horasan, *İsimsiz* (Görsel 14) adlı yapıtında travma ve şoku doğrudan figürün anatomik parçalanışı üzerinden izleyiciye aktarır. Horasan'ın resminde katastrofik imge bizzat insan bedenine kazınmıştır. Figürler adeta eriyerek, çözünerek ya da vahşi fırça darbeleriyle hırpalanarak tuval yüzeyine saçılır. Renk kontrastları son derece tekinsiz ve rahatsız edicidir. Klasik mekân tamamen yok edilmiş; figür kaotik, katmanlı boya katmanlarının içine hapsedilmiştir. Horasan'ın plastik dili 1990'ların toplumsal cinnet, şiddet ve güvensizlik ortamının bireyde yarattığı sarsıntıyı, boyanın tuvale fırlatılış şiddetiyle yeniden üretir.

Görsel 14. Mustafa Horasan, "İsimsiz", 1997, tuval üzerine yağlıboya, 100x160 cm, Özel Koleksiyon.

Genç kuşak çağdaş sanatçılardan Emin Mete Erdoğan'ın *Bir Küre Üzerinde İçe Doğru Şekillenme 2* (Görsel 15) adlı eseri, felaket olgusunu dijital çağın, teknolojinin ve Antroposen çağının getirdiği yeni

bir distopya üzerinden ele alır. Erdoğan, milimetrik, mekanik ve aşırı detaylı bir teknikle çizdiği kompozisyonlarında doğa ile yapay olanı iç içe geçirir.

Bu eserde felaket, doğanın tamamen makineleşmesi ve organik formların geometrik/amorf metalik yapılara dönüşmesidir. Kürenin içe doğru büzülmesi, modern dünyanın kendi içine çöküşünü, ekolojik krizin ve sibernetik geleceğin yaratacağı tekno-katastrofiyi betimler. Çoklu perspektifler ve klasik mekânı sıfırlayan aksonometrik kurgu, insanlığı kendi felaketine (distopyasına) sürükleyişinin çağdaş bir plastik manifestosudur.

Görsel 15. Emin Mete Erdoğan, "bir küre üzerinde içe doğru şekillenme 2", 2015, kağıt üzerine mürekkep ve akrilik boya, 100x70 cm, Özel Koleksiyon.

SONUÇ

Çağdaş Türk resim sanatında katastrofi olgusunun seyri incelendiğinde, erken dönemdeki belgeci, hüzünlü ve dışsal yaklaşımın, çağdaş dönemde yerini nasıl çok katmanlı, felsefi, plastik ve eleştirel bir dile bıraktığını net bir biçimde görülmektedir. Erken dönem Türk ressamları felaketi uzaktan izleyen bir vakanüvis gibiyken; çağdaş Türk sanatçısı felaketin tam ortasında duran, onun acısını tinsel bir yasa dönüştüren ya da yapısal nedenlerini mesafeli bir çevre-kent analiziyle masaya yatıran bir entelektüel aktör konumuna dönüşmüştür. Çevresel felaketler, ekolojik yıkımlar ve depremler gibi katastrofik unsurlar, çağdaş Türk resminde sadece birer "*konu*" olmanın ötesine geçerek, resim dilinin bizzat kendisini dönüştüren, özgünleştiren felsefi birer plastik biçime dönüşmüştür. Sonuç olarak, çağdaş Türk resmindeki katastrofik imgeler, bizlere unutma eğiliminde olan ve sürekli güncellenen tüketim toplumunun hafızasızlığına karşı bir direniş alanı sunar (Nora, 1989). Sanat, bu trajedileri görselleştirerek toplumsal belleği (*kolektif hafıza*) diri tutar, bizi çevreyle, kentle ve kendi ürettiğimiz mekânsal durumlarla yüzleşmeye zorlar.

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THE REAL EROSIVE EFFECT OF INFLATION ON CORPORATE INCOME TAX REVENUES: EVIDENCE FROM TÜRKİYE

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ABSTRACT
The loss in the real value of tax revenues arising from the time lag between the generation of taxable economic activity and the actual collection of taxes has been widely discussed in the public finance literature within the framework of the Olivera–Tanzi effect. This study examines the real erosion of corporate tax revenues caused by inflation in Türkiye over the period 2012Q4–2025Q4 using quarterly data. The main objective is to measure the extent to which inflation reduces the real value of corporate tax revenues by accounting for differences in collection lags across the components of the corporate tax system and to discuss the implications of this process for the class distribution of the tax burden.
The analysis utilizes quarterly Consumer Price Index (CPI) data and general government budget statistics for Türkiye. Different collection lags are assigned to the subcomponents of corporate taxation: declarative corporate income tax is assumed to have an average collection lag of three quarters, while provisional corporate tax is assigned a lag of one quarter. Corporate tax withholding is excluded from the erosion calculations because it is collected at source and therefore involves no collection lag. Real erosion rates are calculated separately for each component and then aggregated into a composite erosion rate for total corporate tax revenues using their respective shares in total collections.
The findings indicate that corporate tax revenues experience substantial real value losses during periods of high inflation. In contrast, wage income taxes collected through withholding are not subject to comparable erosion because they are collected immediately at the source. This asymmetry suggests that inflation, through the timing structure of tax collection, effectively reduces the real tax burden on capital while increasing the relative contribution of labor income to public revenues. The study therefore argues that inflation should be understood not only as a macroeconomic phenomenon but also as a fiscal mechanism that influences the distribution of the tax burden across social classes.
Keywords: Inflation, Corporate Income Tax, Tax Collection Lags, Real Tax Erosion.

1. INTRODUCTION
The effects of inflation on public finance have been extensively examined in the economic literature, particularly with regard to changes in the real value of tax revenues and their distortive impact on fiscal balances. The theoretical framework underlying this study focuses on the erosive effect of collection lags in tax revenues on the purchasing power of the state in an inflationary environment.
One of the pioneering contributions to this literature is that of Olivera (1967), who argued that inflation contains an element of "inertia" arising from the fiscal system itself. According to Olivera, public expenditures respond to increases in the general price level much more rapidly than tax revenues. As a result, tax revenues lag behind expenditures, giving rise to "passive budget deficits." The principal source of these fiscal lags is that taxes are collected on the basis of income earned in a previous period rather than the current one.
The most comprehensive analyses of the theoretical foundations and measurement of tax collection lags were conducted by Vito Tanzi (1977, 1978). Tanzi (1977) defined a "taxable event" as the moment at which a legal tax liability arises and referred to the period between the emergence of this liability and its actual payment into the treasury as the collection lag. In the mathematical model he developed ($R = 1/(1+p)^n$), he demonstrated that the real value of collected taxes (R) declines rapidly as both the monthly inflation rate (p) and the length of the collection lag (n) increase.

Tanzi (1978) further emphasized that this phenomenon could substantially offset the gains governments obtain through the inflation tax (seigniorage) and, in some cases, even lead to a net reduction in total

public revenues. The erosive impact of inflation on the tax system becomes particularly pronounced in fiscal regimes characterized by high tax burdens and lengthy collection lags.

Although tax collection lags are generally viewed as a problem of erosion in the state's real tax revenues, they may also constitute a class-related issue depending on the structure of the tax system. For instance, while income taxes paid by wage earners (labor) through withholding are collected without any collection lag, the existence of a collection lag in the payment of corporate income tax by capital through declaration implies that, during inflationary periods, capital's contribution to the state budget declines in relative terms.

Although Meade (1980), in the specific context of corporate income tax, adopts a position different from that of the present study by arguing that the distortions created by inflation operate to the detriment of capital, he nevertheless acknowledges that highly indebted firms may obtain real profits tax-free as a result of the inflation-induced decline in the real value of their liabilities. In this respect, inflation also generates outcomes that are favorable to capital.

As Tanzi (1977) noted, the total lag of a tax system is calculated as a weighted average of the collection lags associated with individual tax components, where the weights reflect each component's share within the system. In Türkiye, the different statutory payment schedules applicable to the various subcomponents of corporate income tax—namely declarative corporate income tax, provisional corporate income tax, and withholding corporate income tax—make it necessary to take into account the specific collection lag associated with each component when calculating the total real erosion rate of corporate income tax.

Building upon this theoretical framework, the present study aims to reveal the hidden fiscal cost of inflation on public finance (in favor of capital) by analyzing the real tax erosion in corporate income tax collections in Türkiye during the period 2012Q4–2025Q4 on the basis of its subcomponents.

2. METHOD

The primary objective of this study is to formulate the total real erosion rate of corporate income tax and to reveal the erosive effect of inflation on corporate income tax revenues by applying this formulation to the case of Türkiye. Corporate income tax is declared and paid in the year following the fiscal year in which corporate profits are earned. From this perspective, the annual inflation rate could be considered the erosion rate of this tax. However, such a simplified approach does not accurately reflect reality. This is because corporations make provisional corporate income tax payments at specific intervals during the fiscal year in which the profits are generated and subsequently offset these payments against the tax liability declared and paid during the collection period of the following year. The former component is referred to as provisional corporate income tax, while the latter is termed declarative corporate income tax. In addition, certain payments are subject to taxation at source, whereby the tax is withheld and transferred to the government at the time of payment; this component is known as withholding corporate income tax. As can be seen, the collection periods of the components of corporate income tax differ considerably. Therefore, calculating a fixed erosion value for total corporate income tax revenues solely on the basis of the annual inflation rate would be an inappropriate approach. For this reason, the present study adopts a real erosion rate analysis based on quarterly periods, in which the distinctive characteristics of each subcomponent of corporate income tax are taken into account separately.

The real collection model for any tax or tax subcomponent is presented in Equation (1).

$$Real\ Tax\ Revenues^{i}_{t,q} = Nominal\ Tax\ Revenues^{i}_{t,q} \times \frac{CPI_{t-d_i}}{CPI_{t,q}} \tag{1}$$

In this framework, i denotes the tax type; t the year in which the tax is paid; q the qth quarter of year t; d_i the average collection lag of tax i measured in quarters (in other words, t-d_i represents the average quarter in which the income associated with the tax liability was earned); and *CPI* the Consumer Price Index. Accordingly, the real revenue of tax i is obtained by multiplying its nominal revenue by the ratio of the *CPI* in the quarter in which the income was earned to the *CPI* in the quarter in which the tax was collected.

The rate of real tax erosion caused by inflation during the period between the emergence of a tax liability and its collection is initially expressed in Equation (2).

$$\lambda_{t,q}^{i} = 1 - \frac{Real\ Tax\ Revenues_{t,q}^{i}}{Nominal\ Tax\ Revenues_{t,q}^{i}} \tag{2}$$

Here, λ denotes the real erosion rate. Substituting Equation (1) into Equation (2) yields the explicit expression for the real erosion rate of any tax or tax subcomponent, as presented in Equation (3).

$$\lambda_{t,q}^{i} = 1 - \frac{CPI_{t-d_i}}{CPI_{t,q}} \tag{3}$$

Since the collection lag (*d*) differs across tax types and even across subcomponents of the same tax, the real erosion rate (λ) also varies accordingly. This differentiation is particularly relevant for corporate income tax. Because each component of corporate income tax is characterized by a distinct collection lag, the real erosion rates calculated for individual subcomponents can be weighted by their respective revenue shares to obtain a composite measure for the tax as a whole. The total real erosion rate of corporate income tax ($\lambda_{t,q}^{CIT}$) for any country is presented in Equation (4).

$$\lambda_{t,q}^{CIT} = \sum_{i=1}^{n}\left(\frac{CIT_{t,q}^{i}}{CIT_{t,q}} \times \lambda_{t,q}^{i}\right) = \sum_{i=1}^{n}\left[\left(\frac{CIT_{t,q}^{i}}{CIT_{t,q}}\right) \times \left(1 - \frac{CPI_{t-d_i}}{CPI_{t,q}}\right)\right] \tag{4}$$

$i: 1,2,3, \ldots n$

In this equation, *i* denotes the subcomponents of corporate income tax; *n* the number of corporate income tax subcomponents; CIT^{i} the revenue generated by the *i*th corporate income tax subcomponent; and *CIT* total corporate income tax revenue.

Given the specific structure of corporate income tax revenues within the Turkish tax system, three principal components can be identified: declarative corporate income tax, provisional corporate income tax, and withholding corporate income tax. Indeed, these items are classified as subcategories of corporate income tax in the economic classification of government revenues. Adapting Equation (4) to the Turkish corporate income tax structure yields Equation (5).

$$\lambda_{t,q}^{CIT} = \frac{DCIT_{t,q}}{CIT_{t,q}} \times \left(1 - \frac{CPI_{t-d_{DCIT}}}{CPI_{t,q}}\right) + \frac{PCIT_{t,q}}{CIT_{t,q}} \times \left(1 - \frac{CPI_{t-d_{PCIT}}}{CPI_{t,q}}\right) + \frac{WCIT_{t,q}}{CIT_{t,q}} \times \left(1 - \frac{CPI_{t-d_{WCIT}}}{CPI_{t,q}}\right) \tag{5}$$

In this equation, *DCIT* denotes declarative corporate income tax revenue; d_{DCIT} the average collection lag of declarative corporate income tax; *PCIT* provisional corporate income tax revenue; d_{PCIT} the average collection lag of provisional corporate income tax; *WCIT* withholding corporate income tax revenue; d_{WCIT} the average collection lag of withholding corporate income tax; and *CIT* total corporate income tax revenue.

Equation (5) makes it possible to calculate the total real erosion rate of corporate income tax by incorporating the distinct real erosion rate associated with each component.

Naturally, average collection lags vary according to the characteristics of each country's tax system. In the Turkish case, the parameters are assumed to be $d_{DCIT} = 3$, $d_{PCIT} = 1$, and $d_{WCIT} = 0$. This specification reflects the institutional design of corporate taxation in Türkiye. Declarative corporate income tax is paid in April of the fiscal year following the year in which the taxable profits are earned. Assuming that profits are generated, on average, around the midpoint of the fiscal year, the corresponding collection lag can reasonably be approximated as three quarters. Provisional corporate income tax, by contrast, represents an advance payment mechanism through which corporate income tax liabilities are collected throughout the year. Rather than waiting until the end of the fiscal year, corporations calculate their profits and pay provisional taxes on a quarterly basis. These payments are subsequently credited against the final corporate income tax liability declared in the following year. In

other words, the provisional corporate income tax associated with each three-month (quarterly) earnings period is typically paid around the midpoint of the subsequent quarter. Consequently, the average collection lag of provisional corporate income tax can be approximated as one quarter. Finally, withholding corporate income tax is collected at source when certain payments are made during the fiscal year in which the income is generated. Since collection occurs contemporaneously with the taxable transaction, no collection lag arises. Accordingly, the average collection lag of withholding corporate income tax is assumed to be zero.

Once these Türkiye-specific average collection lag parameters have been established, Equation (5) becomes fully operational for empirical application to the Turkish case.

3. RESULTS

This study examines the real erosive effect of inflation on corporate income tax revenues in Türkiye over the period 2012Q4–2025Q4 using quarterly data. In order to calculate the total real erosion rate of corporate income tax in Türkiye, quarterly data on corporate income tax revenues and their subcomponents were obtained from Turkish Ministry of Treasury and Finance (2026). Monthly CPI data obtained from Turkish Statistical Institute (2026) were converted by the authors into quarterly series based on CPI (2011=100). The resulting dataset was then applied to Equation (5) to generate the findings. The results of the calculations are presented in Table 1.

Table 1. Corporate Income Tax Total Erosion Rate Findings (%)

Period	Corporate Income Tax Total Erosion Rate (%)	Period	Corporate Income Tax Total Erosion Rate (%)
2012Q1	-	2019Q1	1,401
2012Q2	-	2019Q2	3,854
2012Q3	-	2019Q3	2,633
2012Q4	3,140	2019Q4	3,270
2013Q1	2,472	2020Q1	2,357
2013Q2	2,466	2020Q2	2,983
2013Q3	1,119	2020Q3	2,523
2013Q4	2,397	2020Q4	4,622
2014Q1	2,956	2021Q1	4,130
2014Q2	2,837	2021Q2	4,323
2014Q3	0,770	2021Q3	4,881
2014Q4	2,005	2021Q4	10,962
2015Q1	1,748	2022Q1	22,252
2015Q2	3,024	2022Q2	15,231
2015Q3	0,415	2022Q3	8,672
2015Q4	2,676	2022Q4	7,934
2016Q1	2,078	2023Q1	16,552
2016Q2	1,561	2023Q2	13,969
2016Q3	1,425	2023Q3	16,375
2016Q4	2,867	2023Q4	12,118
2017Q1	4,542	2024Q1	18,992
2017Q2	2,959	2024Q2	20,336
2017Q3	0,954	2024Q3	8,963
2017Q4	3,825	2024Q4	7,568
2018Q1	2,890	2025Q1	11,239
2018Q2	4,958	2025Q2	13,659

2018Q3	6,758	2025Q3	6,135
2018Q4	6,457	2025Q4	5,985

The findings indicate that corporate income tax collections experience substantial losses in real value under conditions of high inflation. As shown in Table 1, the real erosion rate of corporate income tax in Türkiye was generally at its lowest levels during the period 2013–2017, whereas it reached its highest levels between 2022 and 2025.

Since increases in the CPI constitute the principal determinant of the real erosion rate, the quarterly inflation rate and the real erosion rate of corporate income tax largely follow similar trajectories. However, beginning in 2022, the gap between the quarterly inflation rate and the real erosion rate of corporate income tax widened considerably. Figure 1 illustrates the evolution of the CPI and helps explain this pattern more clearly. During periods in which the CPI remained relatively stable or exhibited only modest growth, the difference between the inflation rate and the real erosion rate of corporate income tax was minimal. By contrast, during periods of rapid CPI acceleration (particularly from 2022 onward), the divergence between the inflation rate and the real erosion rate of corporate income tax became increasingly pronounced.

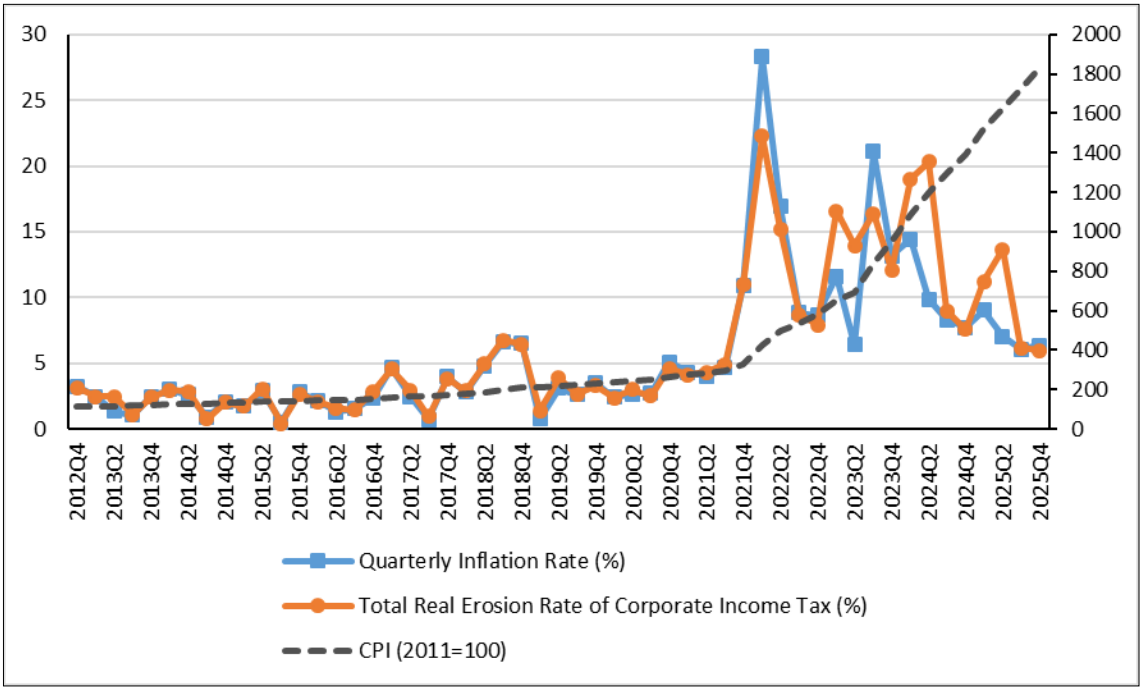

Figure 1. The Trend of CPI, Inflation Rate, and Real Erosion Rate

The relationship between the inflation rate and the real erosion rate of corporate income tax is presented in Figure 2. The two variables exhibit a very strong and positive linear relationship.

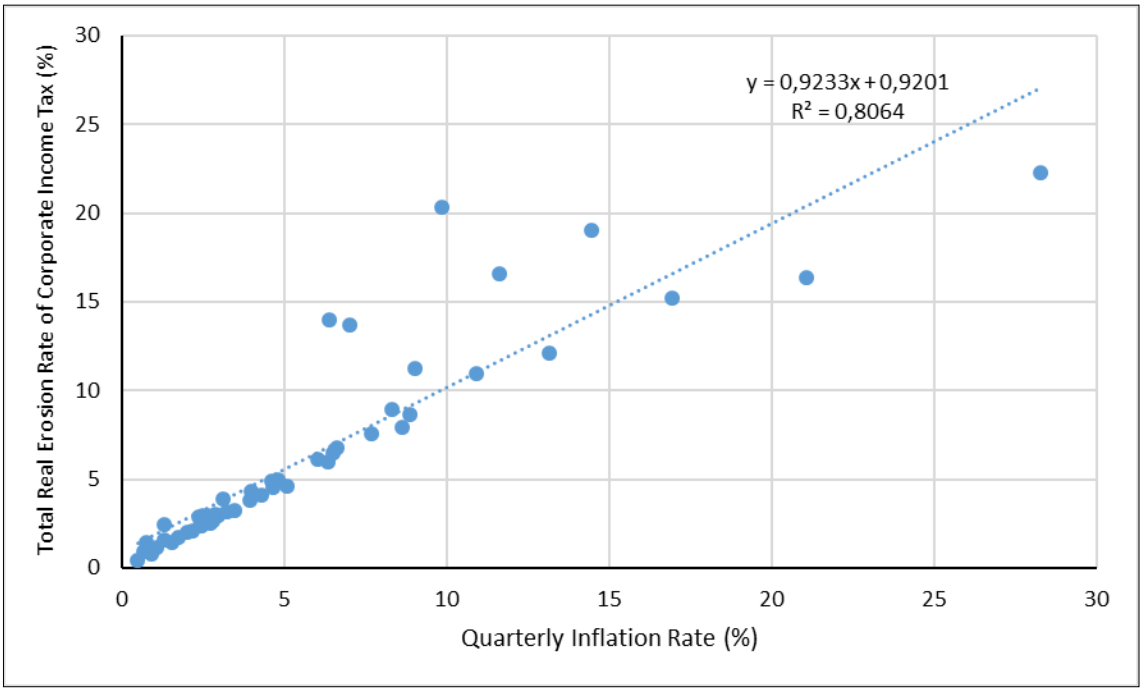

Figure 2. The Relationship Between Inflation Rate and Real Erosion Rate of Corporate Income Tax

Overall, the findings demonstrate that the real erosion rate of corporate income tax remained positive throughout the entire 2012Q4–2025Q4 period. While it closely tracked the inflation rate during periods of relative CPI stability, it increasingly diverged from the inflation rate during periods characterized by accelerating inflation.

4. DISCUSSION

Existing studies on the Olivera–Tanzi effect in Türkiye predominantly examine the aggregate relationship between inflation and tax revenues. However, little attention has been paid to the differential impact of inflation across tax components with distinct collection lags. This study addresses this gap by constructing a quarterly composite erosion measure for corporate income tax revenues based on the collection structure of its subcomponents.

The findings indicate that the real erosion rate of corporate income tax revenues increases substantially during periods of higher inflation. As inflation accelerates, the gap between the time when taxable profits are generated and the time when the corresponding tax liabilities are collected leads to a greater loss in the real value of public revenues. This result is consistent with the theoretical expectations of the Olivera–Tanzi effect, according to which collection lags reduce the purchasing power of tax revenues in inflationary environments. The quarterly erosion measure constructed in this study demonstrates that the inflation-induced loss is not constant over time but varies in accordance with changes in the inflation rate and the composition of corporate income tax collections.

A comparison with wage income taxation reveals an important distributional dimension of this process. Income taxes on wages are collected through withholding at source and therefore involve no effective collection lag. In terms of the framework employed in this study, the collection period coincides with the tax-generating period ($t = d_i$), implying a real erosion rate ($\lambda^i_{t,q}$) of zero. Consequently, inflation does not diminish the real value of tax revenues collected from wage earners. By contrast, a significant portion of corporate income tax revenues is collected with a delay through declaration-based mechanisms. As a result, inflation reduces the real contribution of capital to public revenues while leaving the tax contribution of labor largely unaffected.

This asymmetry suggests that, under inflationary conditions, the timing structure of tax collection may alter the effective distribution of the tax burden between labor and capital, even when statutory tax rates remain unchanged.

From a policy perspective, several measures may mitigate the erosion of corporate income tax revenues. First, shortening collection lags through more frequent advance payments or enhanced withholding mechanisms could reduce the exposure of corporate tax revenues to inflation. Second, inflation-adjusted tax accounting and assessment procedures may help preserve the real value of tax liabilities. Third, and perhaps most importantly, penalties and interest charges on delayed tax payments should be indexed to inflation so that postponing tax payments does not become a source of implicit financial gain for taxpayers. As emphasized by Vito Tanzi (1977), when penalties fail to maintain their real value, delayed tax payments may effectively function as a low-cost or even subsidized source of credit. Ensuring that penalties preserve their real value would therefore reduce incentives for strategic delays in tax payments and contribute to protecting the real revenue capacity of the state during inflationary periods.

Overall, the results suggest that inflation should not be viewed solely as a macroeconomic phenomenon affecting prices and purchasing power. It also operates as a fiscal mechanism that influences the effective incidence of taxation through the timing of tax collection. In this respect, the institutional design of tax administration becomes an important determinant of how inflation affects the distribution of fiscal burdens across different social groups.

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EXAMINING THE EFFECTS OF DISTANCE EDUCATION ON VALUES EDUCATION

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ABSTRACT
Distance education has expanded rapidly in higher education, yet its implications for students' interpersonal relationships remain underexplored. The aim of this study is to examine the effects of distance education on students' friendship relationships. The study focuses on how students establish, maintain, and develop friendships during the distance education process. A qualitative research method was employed, and data were collected through eight open-ended questions and analyzed using content analysis. The findings reveal that distance education weakens the quality of friendships due to the lack of face-to-face interaction, although digital communication tools play a significant role in maintaining social connections.
Keywords: Distance education, friendship relationships, social interaction, university students, values education.

1.INTRODUCTION
Distance education has become a central component of higher education and reshaped higher education by increasing accessibility, flexibility, and technological integration. However, its social consequences remain underexplored. With the advancement of technology, distance education has become increasingly widespread. Especially during the COVID-19 pandemic, distance education transformed into a necessity, affecting not only academic processes but also students' social lives. Friendship relationships play a crucial role in individuals' social and emotional development and are closely associated with values such as friendship, empathy, cooperation, and belonging. Therefore, examining the effects of distance education on friendship relationships is significant for understanding its broader social implications.
University years represent a critical developmental period for social identity formation and interpersonal relationship building. Friendships formed during this period contribute to psychological well-being, academic engagement, and long-term social capital (Tinto, 1993). However, distance education reduces informal interaction spaces such as classrooms, campus life, and spontaneous peer communication. This study explores how distance education affects university students' friendship relationships in terms of emotional connection, communication practices, and social integration.

1.1. Literature Review
Garrison et al. (2000) argue that meaningful online learning requires strong social presence alongside cognitive and teaching presence. Hrastinski (2008) notes that online communication often shifts toward asynchronous interaction, reducing immediacy in relationships.
Rovai (2002) found that online learning environments tend to generate lower levels of sense of community compared to traditional classrooms. Similarly, Junco et al. (2011) highlight that social media supports communication but does not fully replace in-person interaction in forming deep friendships. These studies suggest that while digital tools support continuity of interaction, they may not fully replicate emotional depth and spontaneity in friendship formation.

1.2. Purpose of The Study
The aim of this study is to examine the impact of distance education on university students' friendship relationships. The study seeks to determine how students' processes of forming, maintaining, and developing friendships are affected by distance education. In addition, students' social experiences and communication patterns are evaluated in order to provide a general framework regarding the social dimension of distance education.

1.3. Significance of the Study

This study is important because it examines the effects of distance education on university students' social lives, particularly their friendship relationships.

It aims to reveal whether students' social bonds have weakened and to highlight the social as well as academic dimension of the education process. The findings may contribute to improving distance education practices and creating more effective learning environments.

METHODOLOGY

2.1. Research Design

This study was conducted using a qualitative research method. An interview/survey form consisting of eight open-ended questions was used as the data collection tool. In line with the purpose of the study, university students' experiences and opinions regarding their friendship relationships during distance education were collected. Students' responses were analyzed using content analysis.

2.2 Participants

The study involved 28 volunteer undergraduate students enrolled at different faculties. Participants were recruited through purposive convenience sampling to ensure variation in disciplinary background and online learning exposure.

2.3 Data Collection

The data were collected using a questionnaire consisting of eight open-ended questions. These questions are given below:

1-How do you evaluate distance education in terms of friendship and social relationships?
2-How does distance education affect your friendships with classmates?
3-What is the biggest advantage of distance education in terms of friendship?
4-What is the biggest disadvantage of distance education for friendships?
5- Do you feel emotionally connected to your classmates in distance education?
6- How does online communication affect your friendships?
7- What problems do you face in maintaining friendships during distance education?
8- Would you prefer distance education if it affected friendships?

2.4. Data Analysis

The collected data were analyzed using content analysis. Themes were identified and interpreted based on participants' responses.

3. FINDINGS AND DISCUSSION

The findings of this study indicate that distance education has significant implications for students' friendships and social relationships. Although online learning environments provide opportunities for communication through digital platforms, participants generally perceived these interactions as insufficient to replace face-to-face contact. Overall, the responses suggest that distance education influences not only academic experiences but also the quality of students' interpersonal relationships, emotional connectedness, and opportunities for developing and maintaining friendships. Examples of the responses given by the students to the eight open-ended questions are presented below.

Question 1: *How do you evaluate distance education in terms of friendship and social relationships?*
"It weakens friendships because I cannot meet my classmates face to face." "It is academically useful but makes me feel socially isolated." "I can stay in touch through online communication, but it is not the same as in-person interaction." "It does not affect my friendships much; we communicate through social media."

Participants generally viewed distance education as having a negative impact on friendships and social relationships. Although some appreciated the opportunity to stay connected through online communication, most believed that the lack of face-to-face interaction reduced the quality of their social experiences.

Question 2-How does distance education affect your friendships with classmates?
"My friendships have weakened over time." "We keep in touch online, but our bonds are weaker." "I have fewer opportunities to make new friends." "My relationships continue, but they have become more digital."
Most students reported that their friendships had weakened during distance education. While online communication helped maintain contact, participants indicated that it could not fully replace in-person relationships or support the development of new friendships.

Question 3- What is the biggest advantage of distance education in terms of friendship?
"I can communicate with my friends through online groups." "I can stay connected without time and place limitations." "I can maintain friendships with friends who are far away." "There is no real advantage in terms of friendship."
Students identified the main advantage as the ability to stay in touch with friends regardless of time or location through digital platforms. However, some participants stated that distance education offered no significant benefit for friendships.

Question 4- What is the biggest disadvantage of distance education for friendships?
«The lack of face-to-face interaction weakens relationships." "It is harder to make new friends."
"Communication feels more superficial and less emotional." "Group activities are less effective online."
The most frequently mentioned disadvantage was the absence of face-to-face interaction, which participants believed weakened relationships, limited opportunities to make new friends, and reduced the depth of communication.

Question 5- Do you feel emotionally connected to your classmates in distance education?
"Yes, I feel emotionally connected." "Somewhat, but not strongly." "No, I feel distant from others."
"It depends on how active the class is."
Responses suggested varying levels of emotional connection. While some students felt connected, many reported only partial or weak emotional ties, indicating that engagement depended largely on the level of interaction within the online learning environment.
Question 6- How does online communication affect your friendships?
"It helps maintain communication but remains limited." "It is enough to stay in contact, but not for deep friendships." "It reduces the quality of communication." "It works well for me; I do not have any problems."
Participants generally agreed that online communication helps maintain existing friendships but is less effective in fostering meaningful and deep interpersonal relationships. Some students, however, considered it sufficient for their social needs.

Question 7- What problems do you face in maintaining friendships during distance education?
"Not being able to meet face to face." "Less spontaneous communication." "Weaker bonds with classmates." "Different schedules and time conflicts."
Students commonly reported difficulties such as the inability to meet in person, reduced spontaneous interactions, weaker social bonds, and scheduling conflicts, all of which made it harder to maintain friendships.
Quentin 8- Would you prefer distance education if it affected friendships?
"No, I prefer face-to-face education because of friendships." "Yes, academic convenience is more important." "I prefer a hybrid system." "It depends on the situation."
Most participants preferred face-to-face education when considering the importance of friendships and social interaction. However, some valued the academic flexibility of distance education or expressed a preference for a hybrid model, suggesting that opinions varied depending on individual priorities.

4. CONCLUSION AND RECOMMENDATIONS

Distance education reshapes university students' friendship relationships by reducing spontaneous interaction opportunities while enabling digitally mediated continuity. Although friendships persist,

their emotional depth and expansion potential are constrained. These findings emphasize the importance of integrating structured social interaction mechanisms into online education design.

Based on the findings of this study, educational institutions should implement strategies that strengthen students' social interactions within distance education environments.

Universities are encouraged to design structured online group activities and collaborative learning opportunities that promote communication and relationship building among students. In addition, hybrid education models should be considered to balance academic flexibility with the benefits of face-to-face interaction.

should be provided with guidance and training to develop effective digital communication and social skills.

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DFT, MEP, MOLECULAR DOCKING, AND ADME-BASED IN SILICO EVALUATION OF THE N-(1,3-BENZODIOXOL-5-YL)-2,4-DIOXO-1H-PYRIMIDINE-5-SULFONAMİDE COMPOUND AGAINST BRAF V600E MUTANT KINASE

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ABSTRACT
The BRAF V600E mutation is one of the major oncogenic drivers leading to continuous activation of the RAF/MEK/ERK-MAPK signaling pathway in malignant melanoma. Therefore, BRAF V600E mutant kinase is regarded as a critical molecular target in targeted anticancer drug development studies. In this study, the potential inhibitory candidacy of the N-(1,3-benzodioxol-5-yl)-2,4-dioxo-1H-pyrimidine-5-sulfonamide compound against BRAF V600E mutant kinase was comprehensively investigated using quantum chemical calculations, molecular electrostatic potential (MEP) analysis, molecular docking, and ADME predictions.
The geometry optimization of the title compound was performed at the DFT/B3LYP/6-311++G(d,p) level using Gaussian 09W software; molecular geometry, electrostatic potential distribution, and regions that may contribute to molecular recognition were evaluated from the optimized structure. In the MEP analysis, negative electrostatic potential was found to be concentrated particularly around oxygen and nitrogen atoms, suggesting that these regions may be important as hydrogen-bond acceptor centers and electrophilic interaction sites. Molecular docking studies were carried out in the Schrödinger Maestro 2024-3 environment using 3OG7, the crystal structure of BRAF V600E mutant kinase in complex with PLX4032/vemurafenib, as the target.
As a result of docking, the docking score, Glide Emodel value, and Glide energy value for the title compound were calculated as -5.855 kcal/mol, -70.038 kcal/mol, and -46.807 kcal/mol, respectively. The ligand was observed to form hydrogen bonds with ASP594 and CYS532, a pi-cation interaction with LYS483, and hydrophobic contacts with ALA481, ILE463, VAL471, LEU505, LEU514, ILE527, PHE583, and TRP531 residues. ADME/QikProp analyses further demonstrated that the compound complies with Lipinski's rules, shows no Lipinski violations, and presents a computational profile worthy of preliminary evaluation in terms of drug-like properties.
The obtained findings indicate that the N-(1,3-benzodioxol-5-yl)-2,4-dioxo-1H-pyrimidine-5-sulfonamide compound is a pyrimidine-sulfonamide derivative capable of establishing meaningful interactions with the active site of BRAF V600E mutant kinase and worthy of further investigation in terms of molecular geometry, electrostatic surface properties, and pharmacokinetic profile. However, it should be considered that computational results do not directly prove experimental biological activity; the inhibitory potential of the compound should be supported by enzyme inhibition assays, melanoma cell-line experiments, molecular dynamics simulations, and binding free-energy calculations.
Keywords: BRAF V600E; malignant melanoma; N-(1,3-benzodioxol-5-yl)-2,4-dioxo-1H-pyrimidine-5-sulfonamide; DFT; MEP; molecular docking; ADME; 3OG7.

1.INTRODUCTION
Malignant melanoma constitutes one of the most aggressive clinical entities among skin cancers because of its high metastatic potential, heterogeneity in tumor biology, and treatment resistance. Dysregulated activation of the RAF/MEK/ERK-MAPK signaling pathway is of central importance in melanoma pathogenesis in terms of tumor-cell proliferation, survival, and response to therapy. The V600E mutation in the BRAF gene is considered a fundamental driver event in melanoma development by rendering this signaling pathway constitutively active [1]. Therefore, BRAF V600E mutant kinase is a strategic molecular target for targeted drug design and the development of new inhibitor candidates in malignant melanoma.
Vemurafenib, also known as PLX4032, is one of the clinically successful inhibitors targeting BRAF V600E mutant kinase. Since the 3OG7 PDB structure represents the crystal structure of the BRAF V600E oncogenic mutant kinase in complex with PLX4032/vemurafenib, it is used as a suitable reference model in molecular docking analyses of new inhibitor candidates [2]. Clinical studies have

shown that vemurafenib provides a survival advantage in metastatic melanoma with BRAF V600E mutation and that combined use of BRAF and MEK inhibitors can improve therapeutic efficacy [3,4,5]. Pyrimidine and sulfonamide groups are important chemical motifs that can provide pharmacophoric features such as hydrogen bonding, electrostatic interactions, and hydrophobic complementarity in kinase inhibitor design. The investigation of pyrimidine-sulfonamide hybrids as selective BRAF V600E inhibitors supports the rational evaluation of this chemical scaffold in melanoma-targeted drug design [6]. In this context, the N-(1,3-benzodioxol-5-yl)-2,4-dioxo-1H-pyrimidine-5-sulfonamide compound was considered a suitable candidate structure capable of forming possible hydrogen-bonding, electrostatic, and hydrophobic interactions in the BRAF V600E active site due to its 2,4-dioxopyrimidine core, sulfonamide group, and benzodioxole ring.

In this study, the compound in question was investigated in relation to the target of BRAF V600E-mutant malignant melanoma through Gaussian-based DFT geometry optimization, MEP analysis, Schrödinger Maestro-based molecular docking, and QikProp ADME calculations. Thus, not only the binding potential of the ligand but also its molecular geometry, electrostatic interaction tendency, and drug-like properties were evaluated comprehensively. In light of the current literature, this approach provides an original in silico preliminary evaluation that may contribute to the rational design of new pyrimidine-sulfonamide-based candidate molecules for BRAF V600E-mutant malignant melanoma.

2.MATERIALS AND METHODS

2.1.Quantum chemical calculations and geometry optimization

Geometry optimization is a fundamental computational chemistry procedure performed to determine the most stable and lowest-energy conformation of a molecular structure. In this study, the geometric optimization of the target compound was carried out using the Gaussian 09W software package and the GaussView 5.0 interface program [7,8]. Calculations were performed under gas-phase conditions within density functional theory (DFT) using the B3LYP hybrid functional and the 6-311++G(d,p) basis set. The theoretical foundation of the DFT approach is based on the Hohenberg-Kohn theorems and the Kohn-Sham formalism [9,10]. The B3LYP functional is a widely used hybrid approach combining the Becke exchange functional with Lee-Yang-Parr correlation contributions [11,12].

2.2.Molecular electrostatic potential (MEP) analysis

The molecular electrostatic potential (MEP) surface distribution was analyzed using the checkpoint file obtained from the optimized structure. MEP analysis contributes to the evaluation of possible electrostatic interactions, hydrogen-bond donor-acceptor regions, and binding sites by enabling the identification of electron-rich and electron-poor regions on the molecule [13,14].

2.3.Molecular docking

Molecular docking studies are among the widely used in silico approaches in structure-based drug design and candidate molecule pre-evaluation processes because they enable the prediction of ligand-target protein interactions at the atomic level. The crystal structure of the BRAF V600E oncogenic mutant kinase in complex with PLX4032/vemurafenib, 3OG7, was selected as the target protein [15,2]. The three-dimensional structure of the ligand was prepared in an appropriate chemical format; ligand preparation was performed using the Schrödinger Maestro 2024-3 LigPrep module. At this stage, the OPLS4 force field was selected, the pH 7.2 +/- 0.2 ionization range was evaluated, and the lowest-energy conformation among the optimized structures was subjected to docking [17]. The PubChem database was used as a general chemical-structure verification and data source; it is recommended that the relevant PubChem CID number be clearly specified in the final version of the study [16].

Protein preparation and active-site definition procedures were conducted in the Schrödinger Maestro 2024-3 environment. In the docking analyses, the binding behavior of the title compound was evaluated by considering the experimentally defined protein-ligand complex and the reference residues in the BRAF V600E active site. Although lower docking score, Glide Emodel, and Glide energy values can generally be associated with a more favorable computational binding tendency, these values were not interpreted as direct evidence of experimental biological activity. Therefore, the obtained docking results were evaluated as preliminary computational findings supporting the possible binding mode of the title compound with the 3OG7 target structure.

2.4.ADME and drug-likeness predictions

The evaluation of a compound as a drug candidate depends not only on its binding potential to the target protein but also on its possession of appropriate pharmacokinetic and drug-like properties. In this

context, absorption, distribution, metabolism, and excretion (ADME) parameters and Lipinski's rules are used as important preliminary evaluation criteria in early-stage drug discovery studies [18]. In this study, the drug-likeness and possible oral bioavailability profile of the title compound were evaluated in silico using the QikProp module in Schrödinger Maestro 2024-3 software. LogS predictions and solubility-related interpretations were considered together with computational solubility approaches in the literature [19].

3.RESULTS AND DISCUSSION

3.1.Geometry optimization

The geometric optimization of the N-(1,3-benzodioxol-5-yl)-2,4-dioxo-1H-pyrimidine-5-sulfonamide molecule was performed using Gaussian 09W and GaussView 5.0 [7,8]. The calculations were carried out at the DFT/B3LYP/6-311++G(d,p) level under gas-phase conditions. The optimized structure shows that the molecule exhibits a three-dimensional arrangement favorable for both polar and aromatic interactions through the benzodioxole ring, sulfonamide bridge, and dioxopyrimidine core. Selected bond lengths and bond angles are presented in Table 1, and the optimized molecular structure is shown in Figure 1.

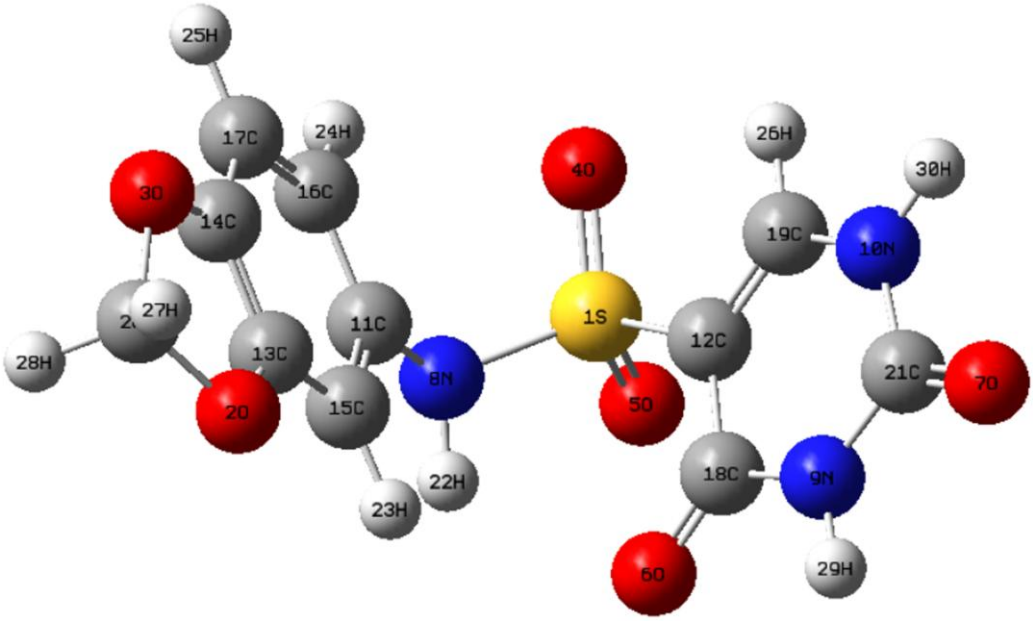

Figure 1. Optimized structure of the N-(1,3-benzodioxol-5-yl)-2,4-dioxo-1H-pyrimidine-5-sulfonamide molecule obtained at the DFT/B3LYP/6-311++G(d,p) level.

Table 1. Selected geometric parameters calculated at the DFT/B3LYP/6-311++G(d,p) level for N-(1,3-benzodioxol-5-yl)-2,4-dioxo-1H-pyrimidine-5-sulfonamide.

Structural parameters	Bond lengths (Å)	Structural parameters	Bond lengths (Å)
S1-O4	1.4569	N10-C21	1.399
S1-O5	1.453	N10-H30	1.010
S1-N8	1.682	C11-C15	1.410
S1-C12	1.793	C11-C16	1.395
O2-C13	1.373	C12-C18	1.460
O2-C20	1.434	C12-C19	1.352
O3-C14	1.375	C13-C14	1.390
O3-C20	1.432	C13-C15	1.377
O6-C18	1.215	C14-C17	1.378
O7-C21	1.208	C15-H23	1.082

Structural parameters	Bond lengths (Å)	Structural parameters	Bond lengths (Å)
N8-C11	1.431	C16-C17	1.378
N8-H22	1.016	C16-H24	1.081
N9-C18	1.405	C17-H25	1.081
N9-C21	1.385	C19-H26	1.083
N9-H29	1.013	C20-H27	1.088
N10-C19	1.363		
Bond angles	**Angle (°)**	**Bond angles**	**Angle (°)**
O4-S1-O5	121.6	C13-C14-C17	121.6
O4-S1-N8	108.5	C11-C15-C13	116.6
O4-S1-C12	105.4	C11-C15-H23	121.4
O5-S1-N8	105.4	C11-C16-C17	120.8
O5-S1-C12	108.6	C11-C16-H24	119.0
N8-S1-C12	106.2	C17-C16-H24	120.1
C13-O2-C20	104.8	C14-C17-C16	117.3
C14-O3-C20	104.9	C14-C17-H25	121.3
S1-N8-C11	121.5	C16-C17-H25	121.2
S1-N8-H22	107.6	O6-C18-N9	120.6
C11-N8-H22	114.0	O6-C18-C12	126.2
C19-N9-C21	128.2	N9-C18-C12	113.0
C21-N9-H29	115.5	N10-C19-C12	121.4
C19-N10-C21	123.8	N10-C19-H26	117.1
C19-N10-H30	120.9	C12-C19-H26	121.4
C21-N10-H30	115.2	O2-C20-O3	107.1
N8-C11-C15	118.7	O2-C20-H27	109.4
N8-C11-C16	119.8	O2-C20-H28	109.2
C15-C11-C16	121.3	O3-C20-H27	109.5
S1-C12-C18	120.0	O3-C20-H28	109.3
S1-C12-C19	119.4	H27-C20-H28	111.9
C18-C12-C19	120.4	O7-C21-N9	124.3
O2-C13-C14	109.5	O7-C21-N10	122.7
O2-C13-C15	128.2	N9-C21-N10	112.8
C14-C13-C15	122.1	O3-C14-C17	128.8

3.2.Molecular electrostatic potential (MEP) analysis

The MEP surface of the title compound was analyzed using the checkpoint file obtained from the optimization calculations. MEP analysis helps identify hydrogen-bonding possibilities, electrostatic interaction centers, and regions that may contribute to ligand-receptor recognition by visualizing electron-rich and electron-poor regions on the molecule [13,14].

The MEP map was evaluated in the approximate range of -8.088.10-2 to +8.088.10-2 a.u. In the map, red/orange regions represent negative electrostatic potential, and these areas are observed to be concentrated especially around electronegative atoms such as oxygen and nitrogen. These regions can be considered electrophilic attack centers and hydrogen-bond acceptor sites. In contrast, blue regions indicate positive electrostatic potential and are located in hydrogen-containing and more electron-poor parts; these areas are important for nucleophilic interactions and hydrogen-bond donor regions. The widespread green/yellow regions on the molecular surface suggest that the compound has a balanced electrostatic distribution and may provide both polar and apolar contributions in ligand-receptor interactions.

Overall, MEP analysis reveals that heteroatom-rich regions may play a critical role in molecular recognition and binding interactions. However, since this analysis reflects the electrostatic potential of the isolated molecule, it does not alone explain protonation, solvation, and induced-fit effects in the protein environment. The MEP surface map of the title compound is given in Figure 2.

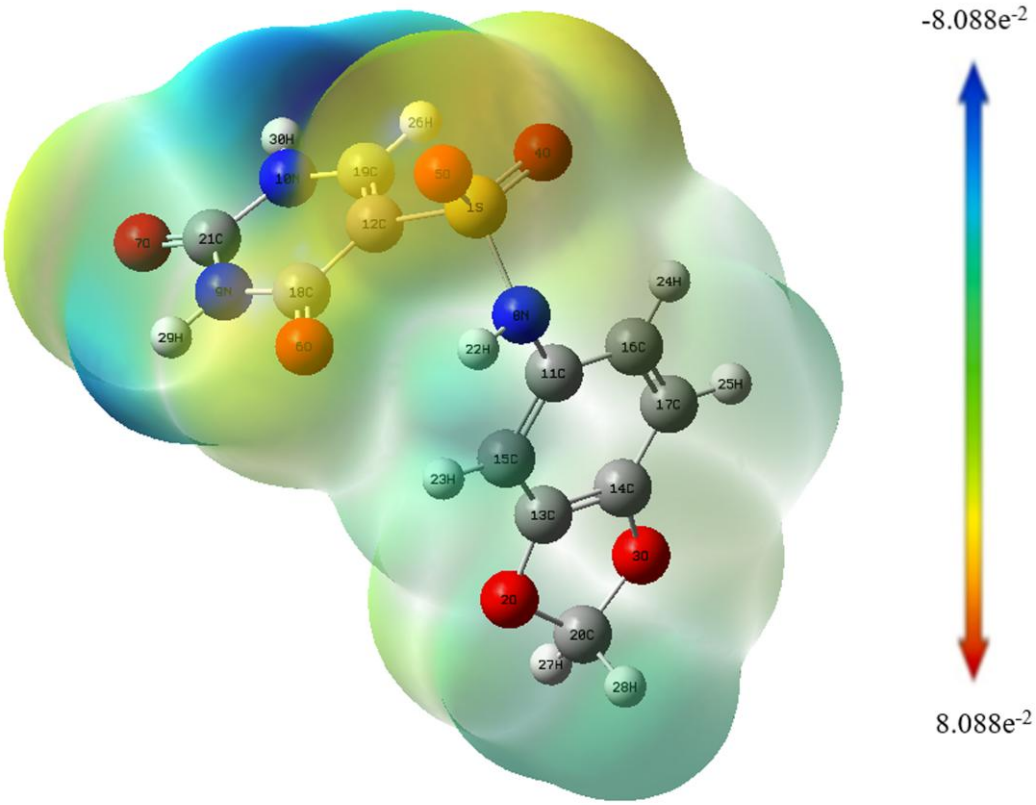

Figure 2. MEP surface map of the N-(1,3-benzodioxol-5-yl)-2,4-dioxo-1H-pyrimidine-5-sulfonamide compound calculated at the DFT/B3LYP/6-311++G(d,p) level.

3.3.Molecular docking studies

In this study, the N-(1,3-benzodioxol-5-yl)-2,4-dioxo-1H-pyrimidine-5-sulfonamide compound was aimed to be evaluated as a potential BRAF inhibitor candidate for BRAF V600E-mutant malignant melanoma. For this purpose, 3OG7, the crystal structure of BRAF V600E mutant kinase in complex with PLX4032/vemurafenib, was used as the target structure [15,2].

In the docking analyses, the binding behavior of the title compound was comparatively evaluated with the experimentally defined protein-ligand complex and the reference interaction regions in the BRAF V600E active site. The docking score, Glide Emodel, and Glide energy values are presented in Table 2. The S-OPLS value reported in the software output was not interpreted as an RMSD metric used in classical co-crystal ligand redocking validation; instead, it was evaluated as a computational output parameter related to pose fit and the scoring process.

Table 2. Molecular docking scores of the N-(1,3-benzodioxol-5-yl)-2,4-dioxo-1H-pyrimidine-5-sulfonamide compound.

PDB ID	Compound	Docking score (kcal/mol)	Glide Emodel (kcal/mol)	Glide energy (kcal/mol)	S-OPLS pose-fit value (Å)
3OG7	N-(1,3-benzodioxol-5-yl)-2,4-dioxo-1H-pyrimidine-5-sulfonamide	-5.855	-70.038	-46.807	0.084

According to the calculated results, the title compound is predicted to exhibit a meaningful computational binding mode against the 3OG7 crystal structure. The docking score, Glide Emodel value, and Glide energy value for the binding of the title compound to the 3OG7 target structure were calculated

as -5.855 kcal/mol, -70.038 kcal/mol, and -46.807 kcal/mol, respectively. Although these values suggest that the compound can adopt a suitable orientation in the BRAF V600E active site, they should not be interpreted as direct evidence of experimental inhibitory activity.

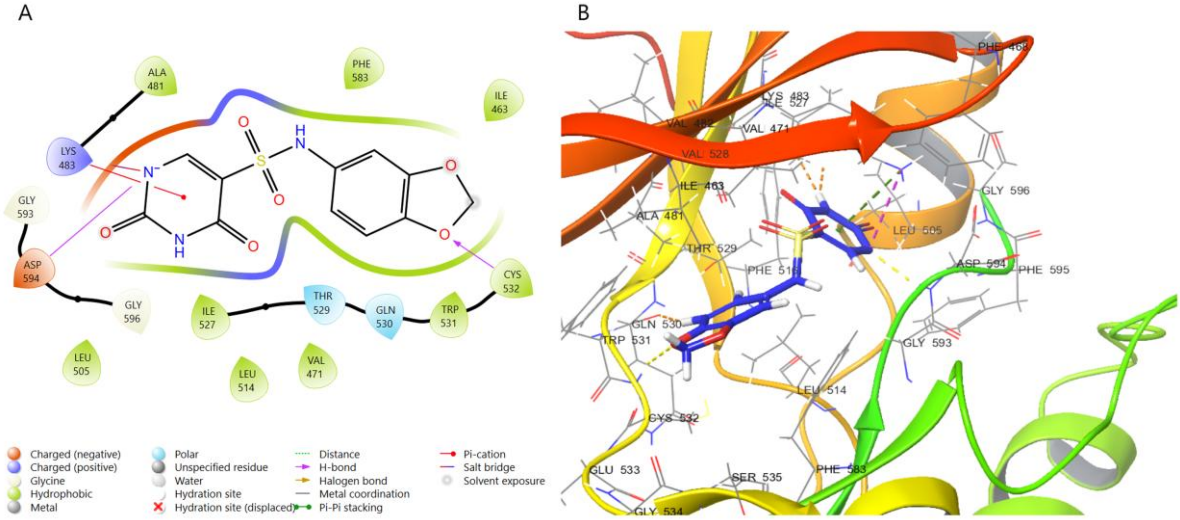

Figure 3. (A) 2D interaction diagram of the N-(1,3-benzodioxol-5-yl)-2,4-dioxo-1H-pyrimidine-5-sulfonamide ligand. (B) 3D visualization of the molecular docking pose showing the interactions of the title compound with the amino acid residues of the 3OG7 crystal structure.

According to the 2D interaction map, the ligand was stabilized in the 3OG7 active site through hydrogen bonding, pi-cation interaction, and hydrophobic contacts. The heteroatom centers in the 2,4-dioxopyrimidine ring of the ligand formed a hydrogen bond with the ASP594 residue. The ether oxygen in the benzodioxole ring established a second hydrogen bond with the CYS532 residue. In addition, the conjugated pi-electron system of the 2,4-dioxopyrimidine ring showed a pi-cation interaction with the LYS483 residue. The benzodioxole aromatic ring, pyrimidine scaffold, and hydrophobic surface of the ligand formed hydrophobic contacts with ALA481, ILE463, VAL471, LEU505, LEU514, ILE527, PHE583, and TRP531 residues. These interactions indicate that the compound may exhibit a multifaceted and directionally supported binding mode in the BRAF V600E active site.

3.4.ADME prediction

The calculated ADME parameters reveal that the title compound is compliant with Lipinski's rules and shows no Lipinski violations. The molecular weight being below 500 Da, the hydrogen-bond acceptor and donor parameters being within acceptable ranges, and the cLogP value remaining below the threshold value indicate that the compound presents a favorable preliminary profile in terms of drug-like properties. The TPSA value of 143.138 Å² can be interpreted as a parameter that should be carefully evaluated in terms of polar surface area; however, the overall ADME profile supports that the molecule is suitable for further in silico and experimental analyses.

Table 3. ADME prediction results of the title compound.

Compound	TPSA (Å²)	LogS	HBA (≤10)	HBD (≤5)	MW (≤500)	cLogP (≤5)	Lipinski violation
N-(1,3-benzodioxol-5-yl)-2,4-dioxo-1H-pyrimidine-5-sulfonamide	143.138	-1.791	7.50	1.00	311.269	-0.036	0

4.CONCLUSION AND RECOMMENDATIONS

In this study, the N-(1,3-benzodioxol-5-yl)-2,4-dioxo-1H-pyrimidine-5-sulfonamide compound was comprehensively evaluated in terms of its potential inhibitory candidacy against BRAF V600E mutant kinase using DFT, MEP, molecular docking, and ADME calculations. Geometry optimization performed at the DFT/B3LYP/6-311++G(d,p) level showed that the title compound has a stable

molecular geometry and that its heteroatom-rich structure contains suitable chemical regions capable of interacting with the target protein.

MEP analysis showed that negative electrostatic potential is concentrated especially around oxygen and nitrogen atoms in the molecule. This suggests that these regions may act as hydrogen-bond acceptor centers and establish electrostatic interactions with polar amino acid residues in the protein active site. The coexistence of positive and negative potential regions on the molecular surface indicates that the ligand may exhibit a balanced binding profile in terms of both hydrogen bonding and polar/apolar interactions. However, it should be considered that MEP analysis is obtained from the isolated molecule and does not alone explain solvation, protonation, and induced-fit effects in the protein environment.

Molecular docking results showed that the title compound may exhibit a meaningful binding mode within the 3OG7 crystal structure of BRAF V600E mutant kinase. The calculated docking score, Glide Emodel value, and Glide energy value were determined as -5.855 kcal/mol, -70.038 kcal/mol, and -46.807 kcal/mol, respectively. The formation of hydrogen bonds by the ligand with ASP594 and CYS532 residues, a pi-cation interaction with LYS483, and contacts with hydrophobic residues such as ALA481, ILE463, VAL471, LEU505, LEU514, ILE527, PHE583, and TRP531 suggest that the compound may be stabilized by multifaceted interactions in the active site. This interaction profile supports the pyrimidine-sulfonamide scaffold as a rational starting structure for the BRAF V600E target.

ADME/QikProp predictions revealed that the title compound complies with Lipinski's rules and does not show any Lipinski violations. The molecular weight being below 500 Da, the number of hydrogen-bond acceptors and donors remaining within appropriate ranges, and the cLogP value being at an acceptable level indicate that the compound offers a favorable preliminary profile in terms of drug-like properties. The relatively high TPSA value can be interpreted as a parameter that should be carefully evaluated in terms of polar surface area.

In conclusion, the N-(1,3-benzodioxol-5-yl)-2,4-dioxo-1H-pyrimidine-5-sulfonamide compound may be considered a computationally promising candidate molecule for the BRAF V600E mutant malignant melanoma target. When the obtained DFT, MEP, docking, and ADME findings are considered together, it can be stated that the compound is a pyrimidine-sulfonamide derivative that may contribute to rational drug design studies in terms of its molecular geometry, electrostatic surface properties, interactions with the target protein, and drug-like properties. However, these results are only preliminary computational findings. To confirm the actual biological efficacy of the compound, it should be supported by BRAF V600E enzyme inhibition assays, cytotoxicity and antiproliferative activity analyses in melanoma cell lines, molecular dynamics simulations, MM-GBSA binding free-energy calculations, and appropriate toxicity studies.

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COMPUTATIONAL PRELIMINARY INSIGHTS INTO TLR7/8-MEDIATED IMMUNOMODULATION: A SCHRÖDİNGER GLIDE-BASED MOLECULAR DOCKING ANALYSIS OF THE IMIDAZO[4,5-C]QUINOLINE DERIVATIVE IT-37 WITH HUMAN TOLL-LIKE RECEPTOR 8

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ABSTRACT
This study presents a preliminary computational analysis evaluating the putative binding orientation of IT-37, an imidazo[4,5-c]quinoline derivative, within the ligand-binding pocket of human Toll-like receptor 8 (TLR8) using a Schrödinger Maestro/Glide-based molecular docking approach. The crystal structure of human TLR8 complexed with resiquimod/R848 (PDB ID: 3W3M) was selected as the target structure. Unlike catalytically active enzymes, 3W3M represents a dimeric, agonist-responsive endosomal innate immune receptor. Therefore, the findings of this study were interpreted not in terms of "active site," "enzyme inhibition," or "inhibitory activity," but rather within the framework of an "agonistic ligand-recognition pocket," "receptor modulation," and a "computational binding hypothesis." In the current docking output, IT-37 exhibited a Glide docking score of -5.106 kcal/mol, a Glide Emodel value of -37.754 kcal/mol, and a Glide energy of -26.421 kcal/mol. These values suggest that IT-37 may adopt a structurally plausible binding pose within the ligand-recognition pocket located at the TLR8 dimer interface. However, these docking results alone should not be considered definitive evidence of TLR8 agonism, biological activity, or therapeutic efficacy. In the literature, IT-37 has been discussed by Sabet et al. in the context of TLR-related immunomodulation using a murine macrophage/Bacillus anthracis infection model; however, this evidence does not directly demonstrate experimental activity against human TLR8. Accordingly, rather than claiming direct experimentally confirmed activity of IT-37 on human TLR8, the present study proposes a structure-based computational hypothesis associated with the broader literature on TLR7/8-mediated immunomodulation. To strengthen the translational and publication value of this work, further validation is recommended through R848 redocking, comparative scoring analysis with R848, MM-GBSA binding free energy estimation, 50–100 ns molecular dynamics simulations, and confirmation using a cell-based TLR8 reporter assay.
Keywords: IT-37; TLR8; 3W3M; R848; resiquimod; imidazoquinoline; molecular docking

1. INTRODUCTİON
Toll-like receptors (TLRs) are central members of the pattern recognition receptor family and play a fundamental role in the detection of conserved molecular structures derived from pathogens or damage-associated molecular patterns. By recognizing such molecular signals, TLRs initiate innate immune responses, enhance antigen presentation, regulate cytokine production, and contribute to the direction of adaptive immunity (Akira et al., 2006; Kawai and Akira, 2010; Fitzgerald and Kagan, 2020). Accordingly, the TLR family represents a highly relevant pharmacological target not only in infection biology but also in adjuvant development, antitumor immune activation, and the rational design of immunomodulatory small molecules.
Among the TLR family members, TLR7 and TLR8 are endosomal receptors that recognize single-stranded RNA as well as certain synthetic small-molecule agonists. The recognition of single-stranded RNA through TLR7/TLR8 has been identified as an important component of antiviral immune responses, although this recognition may vary considerably across species (Heil et al., 2004; Diebold et al., 2004). Human TLR8 is particularly important because of its functional relevance in monocytes, macrophages, and other myeloid immune cells. However, species-dependent differences in TLR7 and TLR8 signaling should be carefully considered, since findings obtained from murine models cannot be directly generalized to human TLR8 activity.
Imidazoquinoline derivatives have played a significant role in the development of TLR7/8 pharmacology.

Compounds such as imiquimod and resiquimod/R848 have been shown in early experimental studies to induce immune activation through TLR7- and/or TLR8-mediated mechanisms (Hemmi et al., 2002; Jurk et al., 2002). Owing to their antiviral, adjuvant, and antitumor immunomodulatory potential, these compounds have provided an important foundation for subsequent structure–activity relationship studies and structure-based ligand design approaches. In particular, the structure-guided development of human TLR8-selective agonists has demonstrated that the ligand-binding pocket of TLR8 can be rationally targeted to improve ligand selectivity and immunomodulatory activity (Beesu et al., 2015).

The compound investigated in the present study, IT-37, is an imidazo[4,5-c]quinoline derivative chemically defined as 2-(4-amino-2-(ethoxymethyl)-1H-imidazo[4,5-c]quinolin-1-yl)ethanol. The main experimental context of IT-37 in the literature is based on the study by Sabet, Cottam, and Guiney (2006), in which the immunomodulatory effects of TLR ligands were evaluated in murine macrophages during Bacillus anthracis infection. In that study, IT-37 was examined together with R848 and the TLR9 ligand ISS-1018 in terms of post-infection cytokine production and cell viability. Nevertheless, these findings should not be interpreted as direct evidence of human TLR8 agonism or clinical immunotherapeutic efficacy.

In the present study, the human TLR8 crystal structure complexed with resiquimod/R848, identified by PDB ID: 3W3M, was selected as the target structure. Tanji et al. (2013) demonstrated that ligand recognition in TLR8 occurs at the dimerization interface between two protomers and that agonist binding reorganizes the TLR8 dimer into a signaling-competent conformation. Therefore, 3W3M should not be regarded as an enzymatic active-site model; rather, it represents the ligand-recognition pocket of an agonist-responsive immune receptor dimer.

Molecular docking is a structure-based computational method used to predict possible ligand binding poses and key non-covalent interactions within the binding site of a target macromolecule. The Glide algorithm has been widely used for ligand pose generation, scoring, and virtual screening applications (Friesner et al., 2004; Halgren et al., 2004). However, docking scores should not be interpreted as direct equivalents of experimental binding free energy, cellular receptor activation, or clinical efficacy. Therefore, the present study aims to evaluate the possible binding profile of IT-37 within the ligand-recognition site of human TLR8 using the 3W3M crystal structure as a computational model.

The novelty of this study is positioned in a scientifically cautious and ethically appropriate manner. Previous literature has already reported the experimental evaluation of IT-37 in a TLR-related immunomodulatory context and the structural characterization of human TLR8 in complex with R848. However, to the best of our knowledge, the present study systematically evaluates the binding profile of IT-37 on the human TLR8 crystal structure 3W3M using Schrödinger Glide-based molecular docking and interprets the resulting docking/ADME findings in relation to TLR7/8-mediated immunomodulation. Thus, the contribution of this work is computational and hypothesis-generating, providing a preliminary structural perspective for further experimental investigation.

2. MATERIALS AND METHODS

2.1. Ligand and Target Protein Selection

IT-37 was selected as the ligand in this study. This compound represents a rational candidate for testing the TLR7/8-oriented immunomodulation hypothesis because it contains an imidazo[4,5-c]quinoline core and was evaluated by Sabet, Cottam, and Guiney (2006) among TLR7-related imidazoquinoline ligands. The three-dimensional structure of the ligand was prepared using the LigPrep workflow, with the aim of evaluating appropriate protonation states, tautomeric forms, and conformational states.

The target structure used in this study was PDB ID: 3W3M. According to the RCSB Protein Data Bank record, 3W3M corresponds to the X-ray crystal structure of human TLR8 complexed with resiquimod/R848 and was reported at a resolution of 2.70 Å. Tanji et al. (2013) demonstrated that ligand recognition in this structure occurs at the TLR8 dimer interface. Therefore, the docking region does not represent a classical enzymatic catalytic pocket but rather a receptor dimer interface that is sensitive to agonist binding.

2.2. Protein and Ligand Preparation

During protein preparation, standard steps were considered, including the assignment of bond orders, optimization of protonation states, addition of hydrogen atoms, evaluation of heteroatoms, appropriate

treatment of crystallographic water molecules in relation to the binding pocket, and restrained energy minimization. Sastry et al. (2013) demonstrated that protein–ligand preparation protocols can substantially influence the outcomes of virtual screening and molecular docking studies.
Ligand preparation was performed using the Schrödinger LigPrep module with an OPLS-based force-field approach. The parametrization basis of the OPLS all-atom force field for organic molecules was originally described by Jorgensen, Maxwell, and Tirado-Rives (1996). In the present study, possible ionization states were evaluated within the pH range of 7.2 ± 0.2, and the most appropriate low-energy conformation was selected for subsequent docking analyses.

2.3. Glide-Based Molecular Docking

Molecular docking analyses were carried out using Schrödinger Maestro/Glide 2024-3. During grid generation, the binding position of R848 in the crystallographic structure of 3W3M was used as a reference, and the ligand-recognition pocket located at the TLR8 dimer interface was targeted. GlideScore, Emodel, and Glide energy values were reported as computational scoring components reflecting the steric, electrostatic, and hydrophobic compatibility of the ligand pose (Friesner et al., 2004; Halgren et al., 2004).
For methodological transparency, the docking mode used in the study, such as SP, XP, or another protocol, as well as the grid center and dimensions, selected chain/protomer information, retained water molecules, protonation settings, and the re-docking RMSD value for validation should be explicitly reported. The present revision is based on the numerical docking scores and the 2D/3D interaction map provided in the existing output file; therefore, parameters that were not reported are not expanded as assumptions.

2.4. ADME and Drug-Likeness Evaluation

The drug-likeness and preliminary pharmacokinetic suitability of IT-37 were interpreted using Schrödinger QikProp outputs and Lipinski's rule of five. Lipinski, Lombardo, Dominy, and Feeney (2001) reported that molecular weight, hydrogen-bond donor and acceptor capacity, and lipophilicity parameters are useful preliminary filters for oral absorption and permeability in early-stage drug discovery. However, ADME predictions should not be regarded as substitutes for experimental solubility, permeability, metabolic stability, and toxicity assays.

3. RESULTS AND DISCUSSION

3.1. Docking Scores and General Binding Assessment

Molecular docking of IT-37 into the 3W3M structure yielded a docking score of −5.106 kcal/mol, a Glide Emodel value of −37.754 kcal/mol, and a Glide energy value of −26.421 kcal/mol (Table 1). These values suggest that IT-37 adopts a computationally favorable binding pose within the TLR8 binding pocket. Nevertheless, GlideScore values should not be interpreted as absolute experimental binding free energies. Instead, they should be considered comparatively within the same docking protocol, the same target structure, and an appropriate set of reference ligands (Friesner et al., 2004; Halgren et al., 2004).

Table 1. Molecular docking scores of IT-37 against the human TLR8 crystal structure 3W3M.

PDB ID	Compound	Docking score (kcal/mol)	Glide emodel (kcal/mol)	Glide energy (kcal/mol)	RMS Derivative-S-OPLS (Å)
3W3M	IT-37	-5.106	-37.754	-26.421	0.100

The expressions "active site of the target enzyme" and "potential inhibitory activity" used in the original text are not appropriate for the TLR8 target. The 3W3M structure does not represent an enzyme; rather, it corresponds to a receptor dimer involved in the regulation of innate immune responses. Therefore, the docking results should not be interpreted in terms of inhibitory activity or suppression of cancer cell lines. Instead, they should be evaluated as a possible ligand-binding interaction within the TLR8 ligand-recognition pocket and as a hypothesis for potential immunomodulatory activity (Tanji et al., 2013).

3.2. Amino Acid Interactions within the Binding Pocket

According to the 2D and 3D interaction maps, the imidazoquinoline core of IT-37 establishes aromatic π–π interactions with the Phe405 and Tyr353 residues. Tyr348, Ile349, Val378, and Gly376 appear to stabilize the aliphatic extensions of the ligand through hydrophobic and van der Waals contacts, whereas Ser352 and Gly351 contribute to the polar and steric microenvironment of the binding pocket. Possible polar contacts in the vicinity of Asn404 may also be relevant for the binding orientation of the ligand's amino group. This interaction pattern is consistent with the structural model proposed by Tanji et al. (2013), which demonstrated that agonist recognition in human TLR8 occurs at the dimer interface. However, the dynamic conformational rearrangement of the receptor should be further investigated to confirm whether such binding is sufficient to induce functional activation.

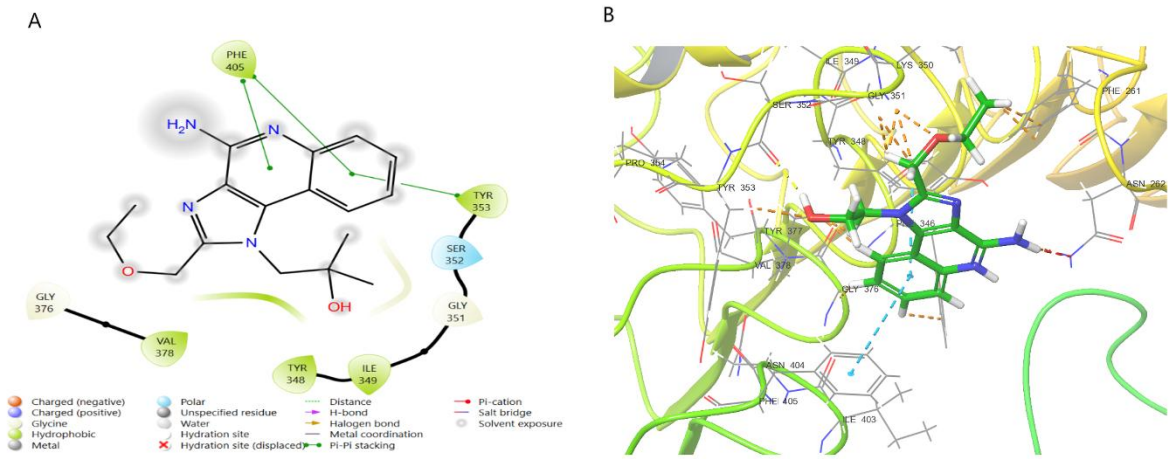

Figure 1. Two-dimensional and three-dimensional molecular interaction maps of IT-37 within the TLR8 binding region.

3.3.Biological Context and Relationship with the Literature

The ability of IT-37 to be accommodated within TLR8 through molecular docking provides a preliminary hypothesis that this compound may be structurally tolerated within the ligand-binding pocket of human TLR8. However, the experimental context reported by Sabet, Cottam, and Guiney (2006) was based on a murine macrophage model and Bacillus anthracis infection. Therefore, these findings should not be directly interpreted as evidence of human TLR8 agonism or clinical immunotherapeutic efficacy. Maintaining this distinction is critical for ensuring the academic accuracy of the biological interpretations presented in the manuscript.

TLR7/8 agonists have attracted considerable research interest due to their potential roles in antiviral immunity, adjuvant development, and reprogramming of the tumor microenvironment. Hemmi et al. (2002) and Jurk et al. (2002) demonstrated the association of imidazoquinoline derivatives with TLR7/8-mediated immune responses, while Fitzgerald and Kagan (2020) emphasized that TLR signaling networks may produce highly context-dependent immunological outcomes. Accordingly, the therapeutic potential of small molecules such as IT-37 should not be evaluated solely on the basis of docking scores. Instead, receptor selectivity, cytokine response profiles, cell-type specificity, and dose-dependent biological effects should also be considered to provide a more comprehensive and biologically meaningful interpretation.

3.4. ADME and Lipinski Evaluation

In the ADME table, the compound name was incorrectly given as "E-6801" in the original text; this should be corrected because the compound investigated in the present study is IT-37. The QikProp outputs indicate that IT-37 generally complies with Lipinski's rule-of-five criteria in terms of molecular weight, cLogP, hydrogen-bond donor/acceptor capacity, and topological polar surface area (TPSA), with no rule violations observed (Table 2). However, the LogS value of −3.039 may suggest a moderate limitation in aqueous solubility.

Therefore, the solubility, membrane permeability, and metabolic stability of IT-37 should be further validated through experimental studies (Lipinski et al., 2001; Daina et al., 2017).

Table 2. Calculated ADME and Lipinski drug-likeness parameters for IT-37.

Compound	**TPSA(Å^2)**	**LogS**	**Based on Lipinski rule**				**Lipinski's violation** (nLV)
			HBA (≤10)	**HBD (≤5)**	**MW (≤500)**	**cLogP (≤5)**	
IT-37	82.894	-3.039	6.40	3.00	286.333	1.386	0

3.5. Methodological Limitations

The most important limitation of this study is that biological interpretations were derived from a single docking pose and a single target crystal structure. In dimeric and conformationally rearranged receptors such as TLR8, ligand binding cannot be fully explained by a static crystal structure alone. Molecular dynamics simulations are required to evaluate the water network within the binding pocket, receptor flexibility, and the behavior of the inter-protomer interface.

A second limitation is the absence of comparative re-docking with the reference ligand R848, experimental binding affinity data, TLR8 cell-based activation assays, and TLR7/TLR8 selectivity analyses. The docking score of −5.106 kcal/mol may suggest a moderate-to-favorable computational fit; however, this value alone does not constitute evidence of agonism, antagonism, cytokine induction, or therapeutic efficacy. Therefore, the present study should be positioned as a computational preliminary finding, and the need for experimental validation should be clearly emphasized.

4. Conclusion and Recommendations

This study demonstrates that IT-37 forms a computationally plausible binding pose within the human TLR8 crystal structure 3W3M. Aromatic π–π interactions, hydrophobic contacts, and possible polar interactions suggest that the ligand may be accommodated within the agonist-recognition pocket located at the TLR8 dimer interface. However, 3W3M is not an enzyme or a cancer cell-line model; therefore, the findings should not be presented in terms of “enzyme inhibition” or “activity against a cancer cell line.” A more accurate academic interpretation is that IT-37 may be considered a potential immunomodulatory ligand candidate within the TLR8 binding pocket.

The biological support for IT-37 in the literature is limited, particularly to the murine macrophage/Bacillus anthracis model reported by Sabet, Cottam, and Guiney (2006). Although this context provides a valuable indication that the molecule may modulate TLR-mediated macrophage responses, it does not provide direct evidence of human TLR8 agonism or clinical immunotherapeutic potential. Accordingly, the present study should be framed as an in silico preliminary analysis that generates a hypothesis for future experimental investigations.

Future studies should validate the docking protocol by performing re-docking analysis of R848 into the 3W3M structure and demonstrating acceptable RMSD values. The binding profile of IT-37 should be compared with reference imidazoquinolines such as R848 and imiquimod, and the docking results should be supported by MM-GBSA analyses. In addition, TLR7/TLR8 reporter cell assays, cytokine response analyses, and experimental ADME/Tox studies should be conducted to verify the receptor selectivity, immunomodulatory activity, and pharmacological reliability of the compound.

In conclusion, the favorable binding pose of IT-37 within the TLR8 binding pocket provides a rational starting hypothesis for research on TLR7/8-related immunomodulation. However, for a reliable academic presentation, computational data should not be overgeneralized into experimental biological conclusions. Instead, docking, ADME, and literature-based findings should be interpreted together with a clear acknowledgment of their translational limitations.

Ethical Statement

This study is entirely in silico in nature and does not involve human participants, patient data, experimental animals, or biological materials. Therefore, ethical committee approval is not required.

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DFT STUDIES OF 1,3-BENZODIOXOLE-5-SULFONAMIDE

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ÖZET
Bu çalışmada, biyolojik açıdan ilgi çekici bir sülfonamit türevi olan 1,3-benzodioksol-5-sülfonamit molekülünün yapısal, titreşimsel ve elektronik özellikleri tamamen kuramsal bir yaklaşımla incelenmiştir. Öncelikle molekülün başlangıç geometrisi oluşturulmuş ve DFT/B3LYP yöntemiyle 6 311++G(d,p) baz seti kullanılarak gaz fazında geometri optimizasyonu gerçekleştirilmiştir. Optimize dilen yapıda bağ uzunlukları, bağ açıları ve dihedral açılar değerlendirilerek molekülün minimum enerji konformasyonu ortaya konmuştur. Ardından teorik IR spektrumuna karşılık gelen harmonik titreşim frekansları hesaplanmış; elde edilen normal titreşim modları VEDA4 programı aracılığıyla + potansiyel enerji dağılımı (PED) katkıları temelinde ayrıntılı biçimde atanmıştır. Özellikle N-H, C-H, C-C, S=O, S-N ve C-O titreşimleri molekülün karakteristik spektroskopik atamaları olarak belirlenmiştir. Bu yaklaşım, yalnızca frekans değerlerinin raporlanmasıyla sınırlı kalmayıp, her bir bandın moleküler hareket içindeki fiziksel karşılığını da açıklamaya olanak sağlamıştır. Çalışmanın elektronik yapı kısmında ise frontier molecular orbital (FMO) analizi uygulanmış; HOMO ve LUMO enerji düzeyleri, enerji aralığı ve temel global reaktivite parametreleri hesaplanmıştır. HOMO-LUMO enerji farkının 5.24 eV olarak bulunması, molekülün belirgin kinetik kararlılığa ve sınırlı kimyasal yumuşaklığa sahip olduğunu göstermektedir. Literatürde bu moleküle ait sistematik bir DFT, teorik IR/PED ve FMO çalışmasına rastlanmaması, mevcut araştırmanın özgün değerini artırmaktadır. Bu nedenle çalışma, deneysel veri üretmeden önce molekülün yapısal ve elektronik davranışını anlamaya yönelik düşük maliyetli ve güvenilir bir ön değerlendirme sunmaktadır. Elde edilen sonuçlar, ileride yapılacak deneysel FT-IR/Raman çalışmaları ve sülfonamit temelli moleküler tasarım araştırmaları için güvenilir bir kuramsal referans sunmaktadır.
Anahtar Kelimeler: 1,3-Benzodioksol-5-sülfonamit; DFT; Teorik IR spektrum; VEDA 4; FMO analizi.

ABSTRACT
This study presents a purely theoretical investigation of the structural, vibrational and electronic properties of 1,3-benzodioxole-5-sulfonamide, a sulfonamide derivative of potential scientific and biological interest. The initial molecular geometry was constructed and fully optimized in the gas phase using the DFT/B3LYP method with the 6-311++G(d,p) basis set. The optimized structure was evaluated in terms of bond lengths, bond angles and dihedral angles, providing a reliable minimum energy conformation for the molecule. Subsequently, the theoretical IR spectrum was obtained from harmonic vibrational frequency calculations, and the corresponding normal modes were assigned in detail using the VEDA4 program on the basis of potential energy distribution (PED) contributions. The N-H, C-H, C-C, S=O, S-N and C-O vibrational modes were identified as the main spectroscopic signatures of the compound. In addition, frontier molecular orbital (FMO) analysis was carried out to clarify the electronic structure and reactivity behavior of the optimized molecule. The calculated HOMO and LUMO energies, energy gap and related global reactivity descriptors revealed that the compound has a relatively stable electronic framework. In particular, the HOMO-LUMO gap of 5.24 eV indicates pronounced kinetic stability and limited chemical softness. Since no systematic DFT based geometry optimization, theoretical IR/PED assignment and FMO analysis appears to have been reported for this molecule, the present work provides an original theoretical contribution. The obtained data may serve as a useful reference for future FT-IR/Raman measurements and for the rational design of sulfonamide-based molecular systems.
Keywords: 1,3-Benzodioxole-5-sulfonamide; DFT; Theoretical IR spectrum; VEDA4; FMO analysis.

1. INTRODUCTION

Molecular modeling has become an essential approach for clarifying the structural, spectroscopic and electronic properties of organic molecules at the atomic level. In particular, Density Functional Theory (DFT) calculations provide reliable information about optimized molecular geometry, vibrational behavior and electronic stability before experimental characterization. Therefore, DFT-based methods are widely used to generate theoretical reference data for molecules with potential chemical and biological relevance [1-6]. Sulfonamide derivatives are an important class of compounds because the sulfonamide group can strongly influence molecular geometry, polarity, hydrogen-bonding ability and vibrational characteristics [7-10]. 1,3-Benzodioxole-5-sulfonamide [11] is a structurally noteworthymolecule since it contains both a benzodioxole ring and a sulfonamide moiety. The coexistence of these fragments may affect the conformational arrangement, electron distribution and characteristic vibrational modes of the molecule. However, detailed theoretical data on its optimized structure, IR assignments and frontier molecular orbital properties are still limited. In this study, 1,3-benzodioxole 5-sulfonamide was investigated using a molecular modeling strategy based on DFT calculations. The molecular geometry was optimized at the B3LYP/6-311++G(d,p) level, and selected bond lengths, bond angles and dihedral angles were evaluated to define the stable molecular conformation.

Subsequently, theoretical IR frequencies were calculated and assigned using VEDA4-based potential energy distribution (PED) analysis, allowing the main N–H, C–H, C–C, C–O, S=O and S–N vibrational contributions to be identified. In addition, frontier molecular orbital (FMO) analysis was performed to evaluate the HOMO–LUMO energy gap and related global reactivity descriptors. The main aim of this work is to establish a systematic theoretical data set for 1,3-benzodioxole-5 sulfonamide by combining geometry optimization, theoretical IR/PED interpretation and HOMO LUMO-based electronic analysis. The obtained results are expected to provide a useful reference for future spectroscopic studies and for the theoretical evaluation of sulfonamide-based molecular systems.

2. MATERIAL AND METHODS

All theoretical calculations were performed using Gaussian 09W [12], and molecular visualization was carried out with the GaussView 5.0 program [13]. The initial structure of 1,3-benzodioxole-5 sulfonamide was constructed in GaussView 5.0 and fully optimized in the gas phase without any symmetry constraints. Geometry optimization was performed using the DFT/B3LYP method with the 6-311++G(d,p) basis set. The optimized structure was evaluated through selected bond lengths, bond angles and dihedral angles. After optimization, harmonic vibrational frequency calculations were carried out at the same theoretical level to obtain the theoretical IR spectrum and to confirm that the optimized structure corresponds to a true minimum on the potential energy surface. The calculated vibrational modes were assigned using the VEDA4 program [14, 15] based on potential energy distribution (PED) analysis. Frontier molecular orbital (FMO) analysis was also performed using the optimized geometry. HOMO and LUMO energy values were used to determine the energy gap and global reactivity parameters, including ionization potential, electron affinity, chemical hardness, chemical softness, electronegativity, chemical potential and electrophilicity index.

3. RESULT AND DISCUSSIONS

The optimized molecular structure of 1,3-benzodioxole-5-sulfonamide is given in Figure 1, and the selected geometrical parameters are summarized in Table 1. The optimized geometry shows that the benzodioxole ring and sulfonamide fragment preserve their structural integrity after DFT optimization. The S1–O4 and S1–O5 bond lengths were both calculated as 1.46 Å, while the S1–N6 and S1–C7 bond lengths were found to be 1.70 and 1.79 Å, respectively. These values indicate that the sulfonamide group adopts a stable arrangement in the optimized structure. In addition, the O4–S1–O5 bond angle of 122.22° and the other bond angles around the sulfur atom confirm the characteristic geometry of the sulfonyl center. The dihedral angle values also show that the sulfonamide group has a defined spatial orientation with respect to the aromatic framework, contributing to the conformational stability of the molecule. The theoretical IR spectrum of the title compound is presented in Figure 2, while the calculated vibrational frequencies and PED assignments are listed in Table 2. The absence of

imaginary frequencies confirms that the optimized structure corresponds to a true minimum on the potential energy surface. The high-frequency region is mainly associated with N–H and C–H stretching vibrations. The N–H stretching modes were calculated at 3472.03 and 3370.38 cm^{-1} with dominant PED contributions, whereas the C–H stretching vibrations appeared in the 3094.85–2900.89 cm^{-1} region. In the mid-frequency region, C–C stretching, H–N–H bending and S=O stretching vibrations were observed. Particularly, the intense S=O stretching contribution at 1263.05 $cm^{-1}$is an important vibrational marker of the sulfonamide group. The lower-frequency region includes S–N stretching, C–O related modes, ring deformations and torsional motions, indicating the coupled vibrational character of the molecule. The HOMO and LUMO distributions of the title compound are shown in Figure 3. The calculated HOMO–LUMO energy gap is 5.24 eV, suggesting that the molecule has a relatively stable electronic structure. The spatial distribution of the frontier orbitals indicates that the electronic density is not localized on a single molecular fragment but is distributed over both the benzodioxole and sulfonamide regions. This orbital distribution suggests that both structural units contribute to the electronic behavior of the compound. Overall, the optimized geometry, theoretical IR/PED assignments and frontier orbital distribution provide a coherent theoretical profile for 1,3 benzodioxole-5-sulfonamide and support its use as a reliable reference structure for future spectroscopic and molecular modeling studies.

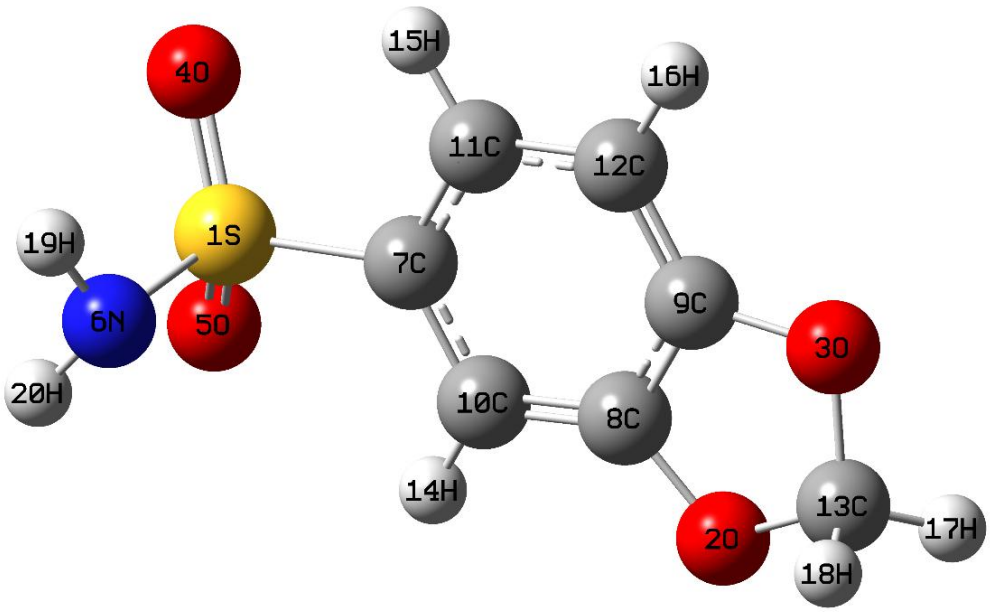

Figure 1. The optimized structure of title compound.

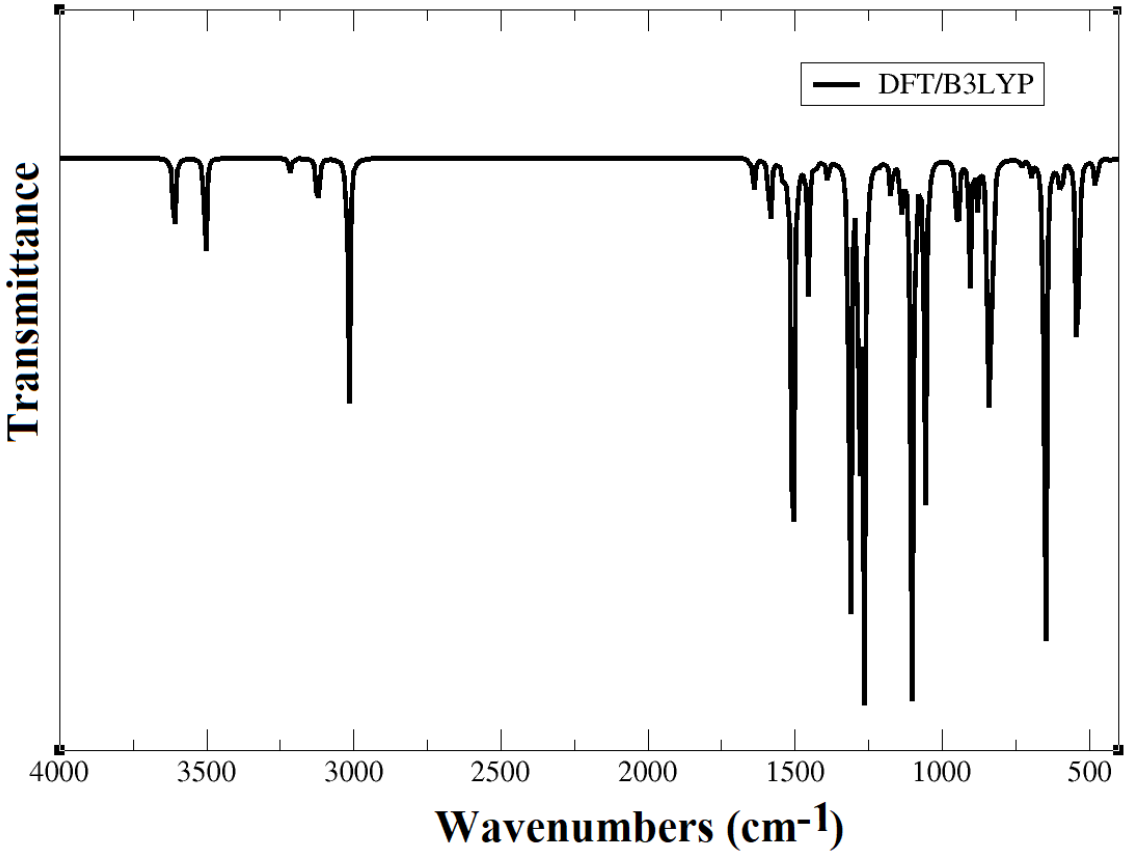

Figure 2. Theoretical IR spectrum of the title compound.

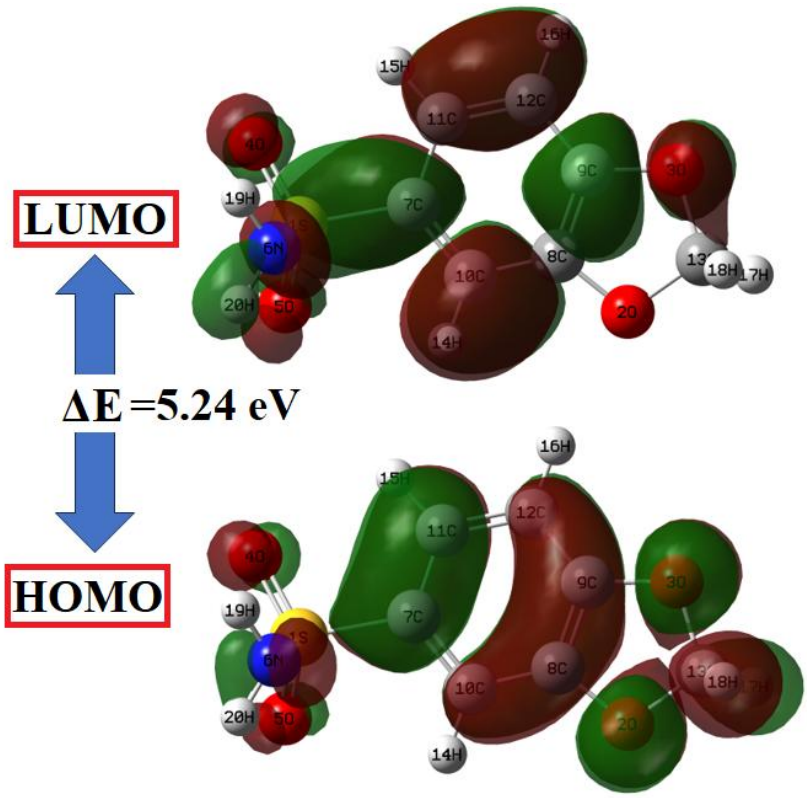

Figure 3. The HOMO and LUMO distributions of the title compound.

Table 1. Selected optimized geometrical parameters

Bond Length (Å)		Bond Angle (°)		Dihedral Angle (°)	
Parameter	**Value**	**Parameter**	**Value**	**Parameter**	**Value**
S1-O4	1.46	O4-S1-O5	122.22	O4-S1-N6-H19	-6.48
S1-O5	1.46	O4-S1-N6	108.17	O4-S1-N6-H20	116.47
S1-N6	1.7	O4-S1-C7	107.54	O5-S1-N6-H19	-138.99
S1-C7	1.79	O5-S1-N6	105.76	O5-S1-N6-H20	-16.04
O2-C8	1.37	O5-S1-C7	108.1	C7-S1-N6-H19	107.43
O2-C13	1.43	N6-S1-C7	103.54	C7-S1-N6-H20	-129.62
O3-C9	1.37	C8-O2-C13	105.5	O4-S1-C7-C10	-163.45
O3-C13	1.44	C9-O3-C13	105.6	O4-S1-C7-C11	16.66
N6-H19	1.02	S1-N6-H19	110.48	O5-S1-C7-C10	-29.69
N6-H20	1.02	S1-N6-H20	109.32	O5-S1-C7-C11	150.42
C7-C10	1.41	H19-N6-H20	111.41	N6-S1-C7-C10	82.18
C7-C11	1.39	S1-C7-C10	118.28	N6-S1-C7-C11	-97.71
C8-C9	1.4	S1-C7-C11	118.9	C13-O2-C8-C9	10.23
C8-C10	1.37	C10-C7-C11	122.82	C13-O2-C8-C10	-172.46
C9-C12	1.38	O2-C8-C9	109.48	C8-O2-C13-O3	-16
C10-H14	1.08	O2-C8-C10	128.34	C8-O2-C13-H17	-134.58
C11-C12	1.4	C9-C8-C10	122.13	C8-O2-C13-H18	102.34
C11-H15	1.08	O3-C9-C8	109.54	C13-O3-C9-C8	-9.64
C12-H16	1.08	O3-C9-C12	128.28	C13-O3-C9-C12	172.71
C13-H17	1.09	C8-C9-C12	122.14	C9-O3-C13-O2	15.81
C13-H18	1.1	C7-C10-C8	115.73	C9-O3-C13-H17	134.47
		C7-C10-H14	121.84	C9-O3-C13-H18	-102.74
		C8-C10-H14	122.41	S1-C7-C10-C8	-179.03
		C7-C11-C12	120.25	S1-C7-C10-H14	2.23
		C7-C11-H15	119.48	C11-C7-C10-C8	0.86
		C12-C11-H15	120.26	C11-C7-C10-H14	-177.88
		C9-C12-C11	116.93	S1-C7-C11-C12	179.4
		C9-C12-H16	121.49	S1-C7-C11-H15	-1.56
		C11-C12-H16	121.58	C10-C7-C11-C12	-0.49
		O2-C13-O3	107.2	C10-C7-C11-H15	178.56
		O2-C13-H17	109.52	O2-C8-C9-O3	-0.36

Table 1. Selected optimized geometrical parameters

Bond Length (Å)		Bond Angle (°)		Dihedral Angle (°)	
Parameter	**Value**	**Parameter**	**Value**	**Parameter**	**Value**
		O2-C13-H18	109.51	O2-C8-C9-C12	177.45
		O3-C13-H17	109.39	C10-C8-C9-O3	-177.88
		O3-C13-H18	109.19	C10-C8-C9-C12	-0.06
		H17-C13-H18	111.92	O2-C8-C10-C7	-177.59
				O2-C8-C10-H14	1.14
				C9-C8-C10-C7	-0.59
				C9-C8-C10-H14	178.14
				O3-C9-C12-C11	177.84
				O3-C9-C12-H16	-1.47
				C8-C9-C12-C11	0.46
				C8-C9-C12-H16	-178.85
				C7-C11-C12-C9	-0.19
				C7-C11-C12-H16	179.11
				H15-C11-C12-C9	-179.22
				H15-C11-C12-H16	0.08

Note: Bond lengths are given in Å. while bond and dihedral angles are given in degrees. Decimal points are used throughout the table.

Table 2. Calculated Vibrational Frequencies with PED Assignments of the Title Compound.

Intensity	Unscaled (cm^{-1})	Scaled (cm^{-1})	PED assignments
44.10	3611.43	3472.03	ϑ NH(99)
42.42	3505.70	3370.38	ϑ NH(99)
5.14	3219.11	3094.85	ϑ CH(98)
2.45	3215.27	3091.16	ϑ CH(98)
0.82	3203.56	3079.90	ϑ CH(99)
27.84	3123.65	3003.08	ϑ CH(92)
106.58	3017.36	2900.89	ϑ CH(92)
1.11	1654.56	1590.69	ϑ CC(58)
11.98	1639.30	1576.02	ϑ CC(59)
31.93	1586.54	1525.30	β HNH(76) + τ HNSC(22)
9.17	1540.93	1481.45	β HCH(86)
269.10	1507.80	1449.60	ϑ OC(10) + β HCC(32)

Table 2. Calculated Vibrational Frequencies with PED Assignments of the Title Compound.

Intensity	Unscaled (cm^{-1})	Scaled (cm^{-1})	PED assignments
53.36	1455.33	1399.15	ϑ CC(14) + β CCC(13) + β HCC(23)
3.39	1428.32	1373.19	τ HCOC(73)
10.16	1389.42	1335.79	ϑ CC(56)
207.70	1313.76	1263.05	ϑ SO(84)
133.15	1281.98	1232.50	ϑ CC(10) + β HCC(41)
218.39	1264.97	1216.14	ϑ CC(12) + ϑ OC(14) + β HCC(39)
1.64	1213.73	1166.88	β HCO(44) + τ HCOC(44)
17.60	1173.50	1128.20	ϑ OC(11) + β CCC(10) + β HCC(15) + β HCO(12)
10.30	1141.54	1097.48	β HCO(31) + τ HCOC(32) + τ COCC(16)
16.24	1134.43	1090.64	ϑ CC(17) + β HCC(36)
213.89	1103.34	1060.75	ϑ SO(56)
26.09	1090.74	1048.64	ϑ SO(19) + β HNS(69)
27.42	1059.01	1018.13	ϑ CC(18) + ϑ SO(10) + β HCC(17)
130.80	1057.44	1016.62	ϑ OC(34) + β OCC(30) + β COC(11)
2.80	954.50	917.66	τ HCCS(48) + τ HCCC(23) + τ CCCC(15)
43.66	947.81	911.22	ϑ OC(38) + β OCC(10) + β COC(19)
54.08	905.28	870.34	ϑ OC(23) + ϑ SC(12) + β CCC(23)
17.95	879.80	845.84	τ HCCS(82)
132.43	842.76	810.23	ϑ SN(36) + τ HNSC(31)
46.67	829.98	797.94	τ HCCS(31) + τ HCCC(45)
10.34	824.10	792.29	ϑ CC(45) + ϑ OC(13)
0.91	738.27	709.77	β OCC(30) + β CCC(11) + β COC(32)
2.87	728.48	700.36	τ CCCC(41) + ω OCCC(37)
7.33	697.94	671.00	ϑ SC(17) + β CCC(25)
212.98	649.45	624.38	ϑ SN(25) + τ HNSC(33)
3.89	610.98	587.40	ϑ SN(14) + τ CCCC(15) + ω SCCC(20) + ω OCCC(22)
18.20	596.31	573.29	ϑ CC(15) + β OCC(11) + β CCC(26)
125.79	540.39	519.53	β CCC(11) + ω ONOS(41)
5.71	481.13	462.56	ϑ SN(11) + β OSO(46) + τ CCCC(14)
8.63	476.30	457.91	β CCC(11) + β OCC(17) + β SCC(13) + ω ONCS(22)
1.04	426.83	410.35	β OSO(12) + τ HCCC(12) + τ CCCC(41) + ω OCCC(12)
2.04	393.33	378.15	β OCC(10) + β OSN(29) + ω ONCS(15)
4.93	360.92	346.99	β OSO(11) + β NSC(15) + ω OCCC(33)
3.52	327.29	314.66	β OSN(23) + ω ONCS(23)
0.59	272.83	262.30	ϑ SC(34) + β CCC(10)

Table 2. Calculated Vibrational Frequencies with PED Assignments of the Title Compound.

Intensity	Unscaled (cm^{-1})	Scaled (cm^{-1})	PED assignments
2.71	256.74	246.83	ϑ SC(12) + β NSC(17) + τ CCCC(16) + ω OCCC(19)
1.13	210.69	202.56	β NSC(20) + τ CCCC(47)
3.01	152.91	147.01	β SCC(54) + ω ONCS(19)
23.50	131.79	126.70	β OSN(13) + τ HNSC(38) + τ COCC(14)
16.09	114.52	110.10	τ HNSC(10) + τ HCOC(10) + τ COCC(36)
2.26	79.11	76.06	τ CCCC(31) + τ COCC(14) + ω SCCC(32)
0.54	30.37	29.20	τ NSCC(90)

Note: ϑ = stretching, β = bending, τ = torsion, ω = out-of-plane bending.

Table 3. Calculated FMO and Global Reactivity Parameters of the Title Compound

Parameters	**Values**
LUMO Energy	-1.34
HOMO Energy	-6.58
Energy Gap (ΔE)	5.24
Ionization Potential (I)	6.58
Electron Affinity (A)	1.34
Chemical Hardness (η)	2.62
Chemical Softness (S)	0.19
Electronegativity (χ)	3.96
Chemical Potential (μ)	-3.96
Electrophilicity Index (ω)	2.99

Note. Values are given in eV, except chemical softness (S), which is expressed in eV^{-1}.

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MEP AND DOCKING ANALYSIS OF 1,3-BENZODIOXOLE-5-SULFONAMIDE

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ÖZET
Bu çalışmada, 1,3-benzodioksol-5-sülfonamit molekülünün elektrostatik yüzey özellikleri ve olası biyomoleküler etkileşim eğilimi tamamen kuramsal bir yaklaşımla araştırılmıştır. Çalışmanın temelini, DFT/B3LYP yöntemi ve 6-311++G(d,p) baz seti kullanılarak elde edilen optimize moleküler geometri oluşturmuştur. Optimize yapı üzerinden moleküler elektrostatik potansiyel (MEP) haritası hesaplanmış ve molekülün elektronca zengin/elektronca fakir bölgeleri üç boyutlu elektrostatik yüzey üzerinde yorumlanmıştır. MEP dağılımı, sülfonil oksijenleri ve benzodioksol halkasındaki oksijen atomlarının güçlü elektron yoğunluğuna sahip başlıca hidrojen bağı kabul edici merkezler olduğunu; sülfonamit grubuna bağlı N-H hidrojenlerinin ise elektrofilik karakter göstererek hidrojen bağı verici bölgeler oluşturduğunu ortaya koymuştur. Bu elektrostatik davranış, molekülün hedef biyomakromoleküllerle yönlenmiş ve seçici etkileşimler kurabileceğini göstermektedir. Çalışmanın ikinci aşamasında, optimize ligand yapısı moleküler docking analizine tabi tutulmuş ve seçilmiş biyolojik hedef proteinin aktif bölgesindeki bağlanma eğilimi değerlendirilmiştir. Docking sonuçları; sülfonamit fonksiyonel grubunun hidrojen bağı, dipol-dipol ve polar temaslar açısından önemli bir rol oynadığını, benzodioksol halkasının ise hidrofobik ve olası pi-temelli etkileşimlerle bağlanma kararlılığına katkı sağlayabileceğini göstermiştir. MEP analizi ile docking etkileşim profili arasındaki uyum, molekülün elektrostatik tanınma bölgelerinin bağlanma modunu yönlendirdiğini desteklemektedir. Literatürde bu molekül için MEP ve docking sonuçlarını birlikte değerlendiren sistematik çalışmaların sınırlı olması, mevcut araştırmanın özgün değerini artırmaktadır. Bu çalışma, deneysel uygulamalardan önce 1,3 benzodioksol-5-sülfonamit molekülünün etkileşim potansiyelini anlamaya yönelik düşük maliyetli, güvenilir ve sürdürülebilir bir teorik ön değerlendirme sunmaktadır.
Anahtar Kelimeler: 1,3-Benzodioksol-5-sülfonamit; MEP analizi; Moleküler docking; DFT; Hesaplamalı kimya.

ABSTRACT
In this study, the electrostatic surface characteristics and possible biomolecular interaction tendency of 1,3-benzodioxole-5-sulfonamide were investigated using a fully theoretical approach. The optimized molecular geometry obtained at the DFT/B3LYP level with the 6-311++G(d,p) basis set was used as the structural basis of the calculations. Molecular electrostatic potential (MEP) analysis was performed on the optimized structure to identify electron-rich and electron-deficient regions on the three dimensional electrostatic surface. The MEP distribution indicated that the sulfonyl oxygen atoms and the oxygen atoms of the benzodioxole ring represent the main electron-rich hydrogen-bond acceptor sites, whereas the N-H hydrogens of the sulfonamide group behave as electrophilic hydrogen-bond donor regions. This electrostatic profile suggests that the molecule may establish directional and selective interactions with biological macromolecular environments. In the second stage, the optimized ligand was subjected to molecular docking analysis, and its binding tendency within the active region of a selected biological target protein was evaluated. The docking results suggest that the sulfonamide moiety may play a key role through hydrogen bonding, dipole-dipole interactions and polar contacts, while the benzodioxole ring may contribute to binding stabilization through hydrophobic and possible pi-related interactions. The consistency between the MEP profile and the docking interaction pattern supports the idea that electrostatic recognition sites govern the binding orientation of the molecule. Since systematic studies combining MEP and docking analyses for this molecule appear to be limited, the present work provides an original theoretical contribution. Overall, this study offers a low-cost, reliable and sustainable preliminary evaluation for understanding the interaction potential of 1,3-benzodioxole-5-sulfonamide before experimental applications.
Keywords: 1,3-Benzodioxole-5-sulfonamide; MEP analysis; Molecular docking; DFT; Computational chemistry.

1. INTRODUCTION

Molecular electrostatic potential (MEP) analysis and molecular docking calculations are widely used complementary tools in computational chemistry for understanding the interaction behavior of organic molecules. While MEP analysis reveals electron-rich and electron-deficient regions on the molecular surface, molecular docking provides a theoretical prediction of how a ligand may orient and interact within the active site of a biological target. Therefore, the combined use of these methods offers valuable insight into molecular recognition, binding tendency and possible structure–interaction relationships [1-8]. Sulfonamide derivatives are of particular interest in this context because the sulfonamide group contains polar oxygen and nitrogen atoms capable of forming hydrogen bonds and electrostatic interactions. These structural features may significantly influence the binding orientation of sulfonamide-based compounds in biological environments. 1,3-Benzodioxole-5-sulfonamide is a noteworthy molecule since it contains both a benzodioxole ring and a sulfonamide moiety. The oxygen atoms in these fragments may act as electron-rich interaction centers, whereas the N–H hydrogens of the sulfonamide group may contribute to hydrogen-bond donor behavior [9-12]. In this study, the optimized geometry of 1,3-benzodioxole-5-sulfonamide was used as the structural basis for MEP and molecular docking analyses. The MEP surface was evaluated to identify the probable electrophilic and nucleophilic interaction regions of the molecule. Subsequently, molecular docking calculations were performed against human carbonic anhydrase II (hCA II, PDB ID: 1CA2) to investigate the possible binding behavior of the compound within the active site. The selection of Hca II is meaningful because sulfonamide-containing molecules can establish polar and hydrogen-bonding interactions in carbonic anhydrase-related binding environments. The main aim of this work is to correlate the electrostatic surface properties of 1,3-benzodioxole-5-sulfonamide with its docking-based interaction profile. By combining MEP analysis with docking results, this study provides a theoretical evaluation of the molecular recognition behavior of the title compound and offers a useful preliminary basis for future structure-based investigations of sulfonamide-derived molecular systems.

2. MATERIAL AND METHODS

The optimized geometry of 1,3-benzodioxole-5-sulfonamide was obtained using Gaussian 09W [13], and molecular visualization was performed with GaussView 5.0 [14]. The molecular electrostatic potential (MEP) surface was generated from the optimized structure to determine the electron-rich and electron-deficient regions of the compound. The color distribution on the MEP surface was used to evaluate possible hydrogen-bond donor and acceptor sites. For molecular docking calculations, the crystal structure of human carbonic anhydrase II (hCA II, PDB ID: 1CA2) was obtained from the RCSB Protein Data Bank [15, 16]. Protein preparation, including removal of unnecessary water molecules and heteroatoms, was carried out using Discovery Studio Visualizer [17]. The optimized ligand structure was then docked into the active region of hCA II using AutoDock Vina [18]. The obtained docking poses were evaluated according to binding affinity values and ligand–protein interaction profiles. The two- and three-dimensional interaction maps of the best binding pose were analyzed using Discovery Studio Visualizer.

3. DISCUSSION and RESULTS

The literature screening presented in Figure 1 indicates that systematic studies focusing specifically on the combined MEP and molecular docking analysis of 1,3-benzodioxole-5-sulfonamide are limited. This supports the originality of the present theoretical investigation. The two- and three-dimensional structures of the molecule are shown in Figure 2. The molecular framework consists of a benzodioxole ring and a sulfonamide group, both of which are important for the electrostatic and binding behavior of the compound. In particular, the oxygen atoms of the sulfonyl and benzodioxole fragments may act as electron-rich centers, whereas the N–H groups of the sulfonamide moiety may contribute to hydrogen-bond donor interactions. The MEP surface of the molecule is given in Figure 3. The electrostatic potential distribution was calculated in the range of approximately $\pm 5.186\times10^{-2}$ a.u. The negative potential regions are mainly localized around the sulfonyl oxygen atoms and the oxygen atoms of the benzodioxole ring, indicating possible hydrogen-bond acceptor sites. In contrast, the positive potential region is concentrated around the sulfonamide N–H hydrogens, suggesting their possible role as hydrogen-bond donor sites. This distribution shows that the molecule possesses well defined

electrostatic recognition regions that may guide its interaction with biological targets. The docking results of 1,3-benzodioxole-5-sulfonamide against human carbonic anhydrase II (hCA II, PDB ID: 1CA2) are summarized in Table 1, and the corresponding 3D and 2D interaction maps are presented in Figure 4. Among the ten docking poses, Mode 1 exhibited the most favorable binding affinity with a value of −6.5 kcal/mol, while the other modes showed weaker affinities between −5.6 and −4.7 kcal/mol. The best binding pose was stabilized by several interactions within the active site, including conventional hydrogen bonds with THR199 and THR200, a π-donor hydrogen bond with HIS94, a π-sulfur interaction with HIS64 and π-alkyl contacts involving LEU198, VAL121 and VAL143. These interactions are consistent with the MEP findings, since the electron-rich oxygen atoms and the polar sulfonamide region appear to play a key role in ligand–protein recognition. Overall, the combined MEP and docking results suggest that the electrostatic character of the molecule contributes directly to its binding orientation and interaction stability within the hCA II active site.

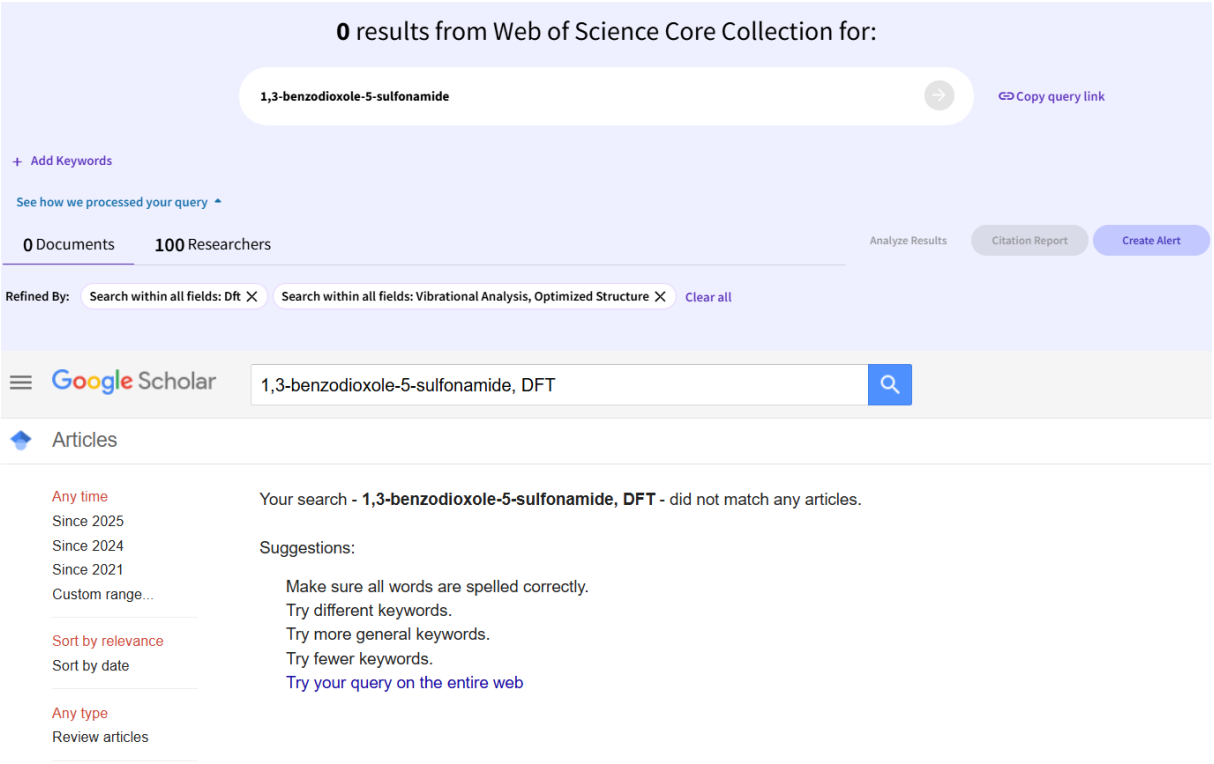

Figure 1. Literature review of the subject of study.

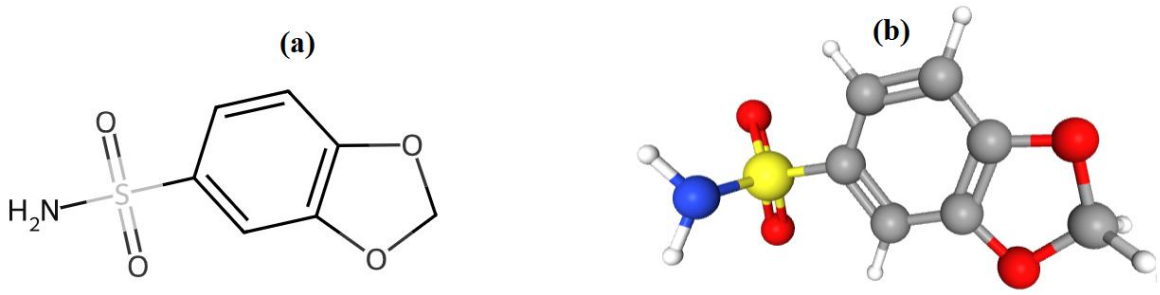

Figure 2. 2- and 3-dimensional forms of the molecule.

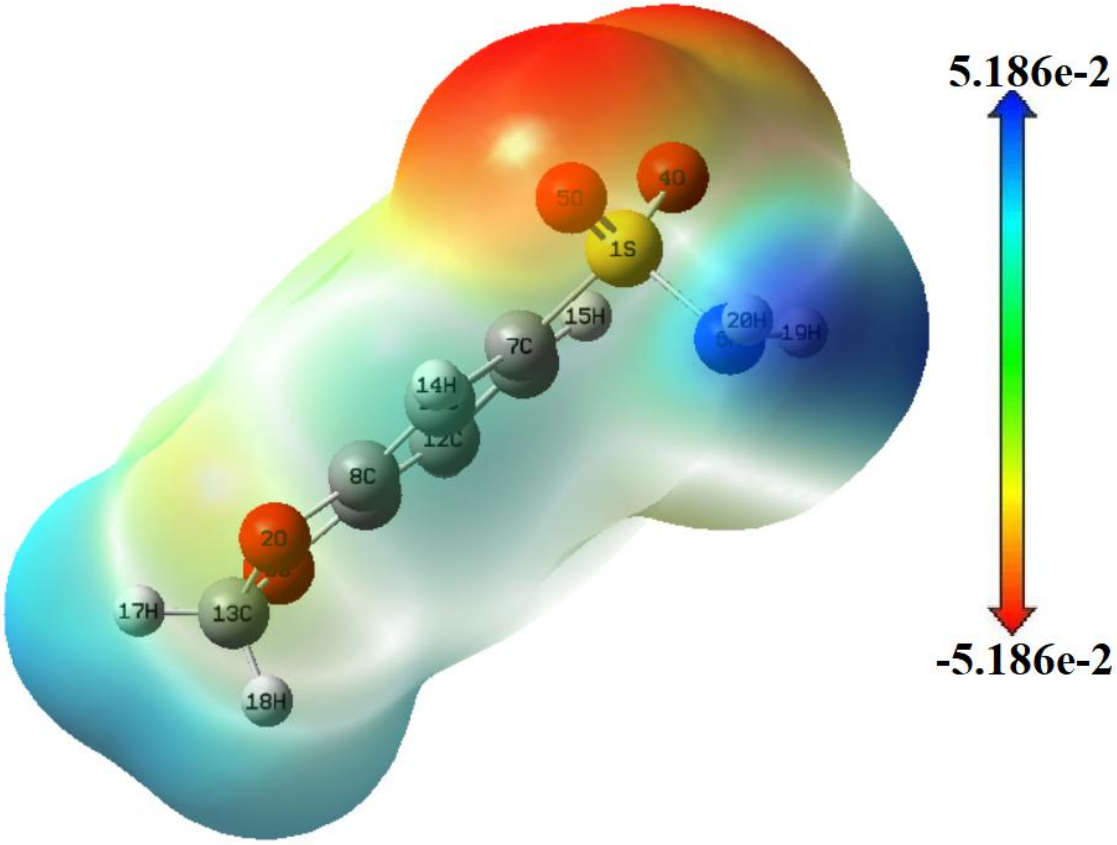

Figure 3. The molecule's MEP surface and MEP scale.

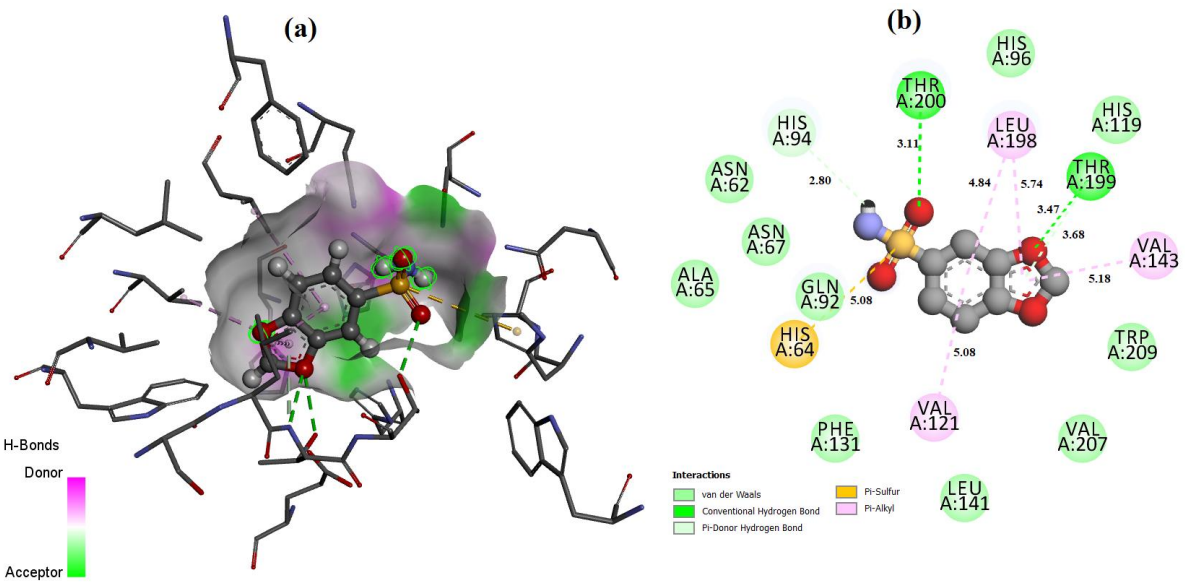

Figure 4. Molecular Docking scores of 3D (a) and 2D (b) ligand+ hCA II (PDB ID: 1CA2) interactions.

Table 1. Molecular docking results of 1,3-benzodioxole-5-sulfonamide against hCA II (PDB ID: 1CA2).

Mode	Binding affinity (kcal/mol)	RMSD l.b. (Å)	RMSD u.b. (Å)
1	-6.5	0.000	0.000
2	-5.6	1.970	2.345

3	-5.2	2.838	4.929
4	-5.0	18.249	19.536
5	-5.0	16.874	18.044
6	-4.9	17.559	18.598
7	-4.8	19.369	20.899
8	-4.7	22.526	23.118
9	-4.7	17.344	18.727
10	-4.7	16.712	18.083

Note. The most favorable docking pose was obtained for Mode 1 with a binding affinity of -6.5 kcal/mol. RMSD l.b. and RMSD u.b. represent the lower and upper bound root-mean-square deviation values relative to the best binding mode, respectively.

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LETONYA MUTFAK KÜLTÜRÜ
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ÖZET
Bu çalışmanın amacı, Letonya mutfak kültürünü tarihsel gelişimi, öne çıkan yiyecek ve içecekleri, günlük öğün düzeni ile gastronomi mekânları ve etkinlikleri çerçevesinde incelemektir. Letonya mutfak kültürünün biçimlenmesinde ülkenin coğrafi konumu, iklim koşulları, tarımsal üretim olanakları ve farklı toplumlarla kurduğu tarihsel ilişkiler belirleyici olmuştur. Uzun ve soğuk kışlar ile kısa üretim dönemleri, yerel ve mevsimsel ürünlerin kullanılmasına; tuzlama, tütsüleme, salamura ve fermantasyon gibi saklama yöntemlerinin yaygınlaşmasına zemin hazırlamıştır. Bu doğrultuda Letonya mutfağı, tahıllar, hayvansal ürünler, dayanıklı sebzeler ve doğadan elde edilen besinler çevresinde şekillenmiştir. Baltık Alman, İsveç, Polonya ve Rus etkileri ile Sovyet döneminde yaygınlaşan toplu beslenme uygulamaları ise yerel mutfak kültürüne farklı ürün, tarif ve hazırlama tekniklerinin dâhil olmasını sağlamıştır. Çalışmada Letonya mutfağında öne çıkan yiyecekler; içerikleri, hazırlanma ve sunulma biçimleri ile tüketim özellikleri bakımından ekmekler, süt ürünleri, atıştırmalıklar ve başlangıçlar, çorbalar, ana yemekler ve tatlılar başlıkları altında sınıflandırılarak incelenmiştir. Huş ağacı suyu, kvass ve Riga Black Balsam ise Letonya içecek kültürünün farklı örnekleri olarak ele alınmıştır. Günlük öğün düzeninin incelenmesi, geleneksel beslenme alışkanlıkları ile çağdaş tüketim biçimlerinin bir arada sürdüğünü göstermektedir. Restoranlar, yerel pazarlar, üretim tesisleri, müzeler ve gastronomi etkinlikleri de yerel ürünlerin ve geleneksel üretim bilgisinin tanıtılmasına katkıda bulunmaktadır. Sonuç olarak Letonya mutfak kültürü, doğal çevreye uyum sağlayan uygulamalar ile farklı tarihsel ve kültürel etkilerin yerel koşullarda dönüştürülmesi sonucunda oluşmuş çok katmanlı ve dinamik bir yapı sergilemektedir.
Anahtar Kelimeler: Letonya, Mutfak, Mutfak Kültürü

ABSTRACT
The aim of this study is to examine Latvian culinary culture within the framework of its historical development, prominent foods and beverages, daily meal patterns, and gastronomic venues and events. The country's geographical location, climatic conditions, agricultural production capabilities, and historical relationships with different societies have been decisive in shaping Latvian culinary culture. Long, cold winters and short growing seasons have fostered the use of local and seasonal products and the widespread adoption of preservation methods such as salting, smoking, pickling, and fermentation. Accordingly, Latvian cuisine has developed around grains, animal-based products, hardy vegetables, and foods gathered from the wild. Baltic German, Swedish, Polish, and Russian influences, as well as the mass catering practices that became widespread during the Soviet era, have led to the inclusion of various ingredients, recipes, and preparation techniques in the local culinary culture. In this study, prominent foods in Latvian cuisine are classified and examined under the headings of breads, dairy products, snacks and appetizers, soups, main courses, and desserts, based on their ingredients, preparation and presentation methods, and consumption characteristics. Birch juice, kvass, and Riga Black Balsam are examined as distinctive examples of Latvian beverage culture. An analysis of daily meal patterns reveals the coexistence of traditional eating habits and contemporary consumption patterns. Restaurants, local markets, production facilities, museums, and gastronomic events also contribute to the promotion of local products and traditional production knowledge. In conclusion, Latvian culinary culture exhibits a multilayered and dynamic structure shaped by practices adapted to the natural environment and by the transformation of diverse historical and cultural influences within the local context.
Keywords: Latvia, Cuisine, Culinary Culture

GİRİŞ

Yeme ve içme, yaşamın sürdürülebilmesi için temel gereklilikler arasında yer almakla birlikte tarih boyunca yalnızca fizyolojik ihtiyaçların karşılanmasına yönelik eylemler olarak değerlendirilmemiş; birçok toplumda refahın, zenginliğin ve toplumsal statünün göstergesi olmuştur (Özgen, 2017: 2). Bunun yanı sıra gelenekler, törenler ve ritüeller içinde çeşitli simgesel anlamlar kazanmıştır. Bu bakımdan yeme ve içme pratikleri, toplumların yaşam biçimleri, değer sistemleri ve tarihsel gelişimleri hakkında bilgi sunan göstergelerden biri olarak değerlendirilebilir. Her toplumun kendine özgü bir mutfak kültürü bulunmaktadır (Sürücüoğlu ve Özçelik, 2008: 1289). Mutfak kültürünün oluşumu ve gelişimi; coğrafi yapı, iklim, ekonomik faaliyetler, üretim biçimleri, tarihsel süreçler ve kültürler arası etkileşimler gibi çeşitli unsurlardan etkilenmektedir. Dolayısıyla bir ülkenin mutfak kültürünün incelenmesi, yalnızca tüketilen yiyecek ve içeceklerin değil, bunların üretimini, hazırlanmasını ve tüketimini biçimlendiren çevresel, tarihsel ve toplumsal koşulların da ele alınmasını gerektirmektedir. Bu çalışmanın odağını oluşturan Letonya, Kuzey Avrupa'da, Riga Körfezi ile Baltık Denizi'nin doğ kıyısında yer alan üç Baltık ülkesinden biridir. Estonya'nın güneyinde ve Litvanya'nın kuzeyinde bulunan ülke, Doğu ve Batı Avrupa arasındaki coğrafi konumu nedeniyle tarih boyunca siyasal, ekonomik ve kültürel etkileşimlere açık olmuştur (Michelin Guide, t.y.). Ülkenin doğal çevre koşulları da Letonya mutfak kültürünün temel özelliklerinin oluşmasında belirleyici bir rol oynamıştır. Uzun ve soğuk kışlar, kısa yazlar ve görece düşük verimli topraklar, geleneksel mutfağın yerel,mevsimselve uzun süre saklanabilen ürünler çevresinde gelişmesine yol açmıştır. Tarımsal üretim tarihsel olarak ülkenin temel geçim kaynaklarından birini oluştururken yaklaşık 500 kilometrelik kıyı şeridi, balığın beslenme kültüründe önemli bir yer edinmesini sağlamıştır. Bu koşullar; tahıllar, süt ürünleri, et, balık, patates, kök sebzeler ve doğadan toplanan ürünlere dayalı bir mutfak yapısının gelişmesine katkıda bulunmuştur (Pīgozne-Brinkmane, 2004: 3). Letonya mutfak kültürünün gelişiminde doğal çevrenin yanı sıra ülkenin tarihsel süreç içerisinde farklı toplumlarla kurduğu ilişkiler de etkili olmuştur. Letonya topraklarında farklı dönemlerde egemenlik kuran Alman, İsveç, Polonya ve Rus yönetimleri ile Letonya'nın Sovyetler Birliği yönetimi altında bulunduğu yaklaşık elli yıllık dönem, ülkenin yiyecek ve mutfak kültürü üzerinde çeşitli etkiler bırakmıştır (Beitāne vd., 2022: 159). Letonya'nın Avrupa'nın doğu ve batısından gelen kültürel etkilerin kesişiminde yer alması, ülkenin zengin bir mutfak geleneği geliştirmesinde etkili olmuştur. Dört mevsimin belirgin biçimde yaşanması ve her mevsimde farklı ürünlerin bulunabilmesi, bu mutfak geleneğine belirgin bir mevsimsel nitelik kazandırmıştır (Make Food and Drinks Like a Local, t.y.). Günümüzde Letonya mutfağı, küreselleşmenin etkisiyle farklı ürünlere ve mutfak teknolojilerine daha açık bir nitelik kazanmıştır. Bununla birlikte yerel ve mevsimsel ürünlerin çağdaş bir anlayışla değerlendirilmesi, Letonya'nın mutfak mirasının yeniden canlandırılmasına katkı sağlamaktadır (Beitāne vd., 2022: 162). Bu çerçevede çalışma, Letonya mutfak kültürünü tarihsel gelişimi, öne çıkan yiyecek ve içecekleri, öğün alışkanlıkları ile gastronomi mekânları ve etkinlikleri üzerinden değerlendirmeyi amaçlamaktadır.

LETONYA MUTFAĞININ TARİHSEL GELİŞİMİ

Letonya mutfağının tarihsel gelişimi; tarımsal üretim koşulları, toplumsal sınıf ilişkileri ve ülkenin geçirdiği siyasal değişimlerle yakından bağlantılıdır. Sanayileşme öncesi dönemde düşük tarımsal verim, kötü hasatlar ve hayvan hastalıkları, özellikle kırsal nüfusun gıdaya erişimini sınırlandırmıştır. Köylülerin günlük beslenmesi büyük ölçüde tahıl, un ve mevsimsel ürünlere dayanırken et ve süt ürünleri daha çok özel günlerde tüketilmiştir. Kışlık yiyecek stoklarının hazırlanmasında et ve balığın tuzlanması, tereyağının saklanması, bitkisel ürünlerin salamura edilmesi ve süt ürünlerinin çeşitli yöntemlerle korunması başlıca uygulamalar arasında yer almıştır (Beitāne vd., 2022: 160). 13. yüzyıldan itibaren bölgede kurulan Alman egemenliği, Letonya'daki toplumsal ve ekonomik eşitsizliklerin beslenme alışkanlıklarına da yansımasına neden olmuştur. Köylülerin beslenmesi büyük ölçüde yerel, mevsimsel ve erişilebilir ürünlerle sınırlı kalırken toplumun üst kesimleri daha çeşitli gıdalara ulaşabilmiştir. Riga'nın Hansa Birliği'ne katılmasıyla tuz, ringa balığı, şarap ve baharat gibi ithal ürünler bölgeye girmiş; ancak bu ürünler özellikle Alman nüfusun ve varlıklı kesimlerin sofralarında yaygınlık kazanmıştır (Beitāne vd., 2022: 160). Baltık Alman etkisi zamanla kırsal yemek uygulamalarına da yansımış; günümüzde Letonya mutfağında yaygın olarak tüketilen pişmiş lahana turşusu, Almanlardan miras kalan yemek geleneklerinden biri olmuştur (Pīgozne-Brinkmane, 2004: 4). Baltık Alman etkisi, Letonca yemek kitaplarının ortaya çıkışında da belirleyici olmuştur. Malikâne mutfaklarında çalışan

Letonyalı aşçıların Almanca bilmemesi, tariflerin Letoncaya çevrilmesini gerekli kılmış ve ilk Letonca yemek kitabı 1795 yılında yayımlanmıştır. Bununla birlikte erken dönem yemek kitaplarında yerel köylü mutfağını belgelemekten çok Batı Avrupa kökenli tariflere yer verilmiştir. Geleneksel Letonya yemeklerinin yazılı kültürde görünürlük kazanması ise ancak 19. yüzyılın sonlarında başlamıştır (Spalvēna, 2021: 219). 18. yüzyılın sonları ile 19. yüzyılda doğal ekonomiden sanayi ekonomisine geçiş, serfliğin kaldırılması, köylülerin toprak mülkiyeti edinmesi ve tarım, sanayi ile ticaretin gelişmesi, Letonya halkının beslenme alışkanlıklarında önemli değişimlere yol açmıştır. Patatesin yaygınlaşarak köylüler için "ikinci ekmek" hâline gelmesi, kırsal beslenmede belirgin bir dönüşüm yaratmıştır. Üretim olanaklarının genişlemesiyle tahıl stokları artmış, gelişen hayvancılık etin yeterli miktarda bulunmasını sağlamış ve sebze çeşitliliği artmıştır. Meyve ağaçları yetiştirilmeye başlanmış; pirinç, baharat, çay ve kahve gibi satın alınan ürünlere erişim kolaylaşmıştır. Aynı dönemde fırınlı ocaklar ve çeşitli mutfak araçları yaygınlaşmış, farklı gıda koruma yöntemleri kullanılmaya başlanmıştır (Beitāne vd., 2022: 160). 1918'de bağımsız Letonya devletinin kurulmasının ardından mutfak kültürü, ulusal kimliğin inşası ve uluslaşma sürecinin önemli unsurlarından biri hâline gelmiştir. Bu dönemde yerel ürünlerin tüketimi teşvik edilmiş; Letonya köylü mutfağına ait yemekler ile Baltık Almanlarından benimsenen yemekler, yerel gelenekler, ihtiyaçlar ve ekonomik koşullar doğrultusunda ulusal mutfak anlayışı içinde bir araya getirilmiştir. Özellikle 1934'te otoriter rejimin kurulmasından sonra milliyetçi devlet politikaları; ev ekonomisi eğitimi, mutfak terminolojisinin ve tariflerin standartlaştırılması, ulusal tarif repertuvarının oluşturulması ve modern gıda koruma yöntemlerinin yaygınlaştırılması yoluyla ulusal mutfağın kurumsallaşmasını desteklemiştir (Beitāne vd., 2022: 161; Spalvēna, 2021: 219). Letonya'da Sovyet döneminde toplu beslenme sistemi aracılığıyla Rus, Orta Asya ve Kafkas mutfaklarına ait yemekler yaygınlaşmıştır. Bunlardan bazıları zamanla Letonya mutfağına dâhil olmuş ve özellikle bayram ve kutlama sofralarında yer edinmiştir. Bağımsızlığın yeniden kazanılmasının ardından toplumda önceki Sovyet yaşam tarzından uzaklaşma ve yeni bir Avrupa kimliği edinme isteği güçlenmiştir. Bu dönüşüm yemek kültürüne; geçmişin yeniden değerlendirilmesi, iki savaş arası döneme ait idealize edilmiş mutfağın canlandırılması, Batı'ya yönelim ve küresel mutfağın yoğun biçimde benimsenmesi şeklinde yansımıştır (Beitāne vd., 2022: 161).

LETONYA'YA ÖZGÜ YİYECEK VE İÇECEKLER

Yiyecekler

Letonya mutfak kültüründe öne çıkan yiyecekler, içerikleri ve tüketim biçimleri dikkate alınarak ekmekler, süt ürünleri, atıştırmalıklar ve başlangıçlar, çorbalar, ana yemekler ve tatlılar başlıkları altında sınıflandırılmış ve aşağıda açıklanmıştır.

Ekmekler

Rupjmaize: Kolay üretilebilmesi ve besleyici niteliği sayesinde yüzyılı aşkın süredir Letonya mutfağının temel ürünlerinden biri olan geleneksel bir çavdar ekmeğidir. Koyu renkli ve yoğun dokulu bu ekmek, iri öğütülmüş çavdar unu, malt ve kimyon tohumlarıyla hazırlanmaktadır. Malt ve kimyon tohumları, ekmeğe kendine özgü tatlı-ekşi bir aroma kazandırmaktadır. Geleneksel olarak odun ateşiyle ısıtılan fırınlarda pişirilen rupjmaize; tereyağı, yoğun aromalı peynirler, soğuk et ürünleri veya tütsülenmiş balıkla birlikte tüketilmektedir. Ayrıca başlangıçlardan ana yemeklere ve tatlılara kadar Letonya mutfağındaki çeşitli yemeklerin hazırlanmasında kullanılmaktadır (Michelin Guide, t.y.).
Görseli Şekil 1'de sunulmuştur.

Şekil 1. Rupjmaize
Kaynak: Bearas, 2011

Saldskābmaize: Letoncada "tatlı-ekşi ekmek" anlamına gelmektedir (TasteAtlas, t.y.-a). Genellikle elenmiş çavdar unundan hazırlanmaktadır. Hamurun sıcak suyla haşlandıktan sonra mayalandırılması, ekmeğe kendine özgü hafif tatlı-ekşi lezzetini kazandırmaktadır. Daha seyrek olarak buğday unundan veya çavdar ve buğday unu karışımından da hazırlanabilmektedir. Ancak bu şekilde hazırlanan ekmek daha hızlı sertleşmekte ve yalnızca çavdar unuyla yapılan saldskābmaize kadar aromatik olmamaktadır (Vikipēdija, 2019). Görseli Şekil 2'de sunulmuştur.

Şekil 2. Saldskābmaize
Kaynak: Brabender GmbH, 2014

Letonya'da ekmeğe büyük değer verilmekte; eski bir inanışa göre yere düşen ekmek temizlenmek amacıyla üflenmekte ve saygı göstergesi olarak öpülmektedir (Ošiņa ve Ošiņš, 2014).

Süt Ürünleri

Süt ürünleri Letonya mutfağında önemli bir yere sahiptir. Biezpiens adı verilen taze peynirin yanı sıra ekşi krema, ekşitilmiş süt, kefir ve çeşitli peynir türleri de yaygın olarak tüketilmektedir. Biezpiens, kahvaltıda ekşi krema ve taze otlarla yenmekte; salata, kek ve tatlılarda da kullanılmaktadır. Öğle yemeklerinde ise haşlanmış patates, hafif tuzlanmış ringa balığı, taze soğan ve ekşi kremayla birlikte sunulabilmektedir. Letonya'ya özgü ürünlerden biri olan Rucavas baltais sviests, normal tereyağına göre daha düşük yağ oranına sahip beyaz bir tereyağıdır. Kaņepju sviests ise kavrulmuş ve öğütülmüş kenevir tohumlarının tereyağı veya kenevir yağıyla karıştırılmasıyla hazırlanmaktadır. Letonya peynirlerine tohum, kuruyemiş, kuru meyve ve çeşitli otlar eklenebilmekte; peynirler tütsülenerek ya da yağ içinde olgunlaştırılarak da sunulabilmektedir. Kimyon tohumlu taze ekşi süt peyniri olan Jāņi peyniri, Jāņi yaz festivalinde servis edilmektedir ve Letonya kültürünün bir sembolü olarak kabul edilmektedir (Wikipedia, 2026). Bu peynirin görseli Şekil 3'te sunulmuştur.

Şekil 3. Jāņi Peyniri
Kaynak Xil, 2007

Atıştırmalıklar ve Başlangıçlar

Pīrāgi veya Pīrādziņi: Letonya mutfağının en tanınmış lezzetlerinden biri olarak kabul edilmektedir. Mayalı hamurdan küçük, hafif ve yarım ay biçiminde hazırlanan bu yiyeceğin içi, yağlı pastırma veya domuz eti küpleri ve soğanla doldurulmaktadır. Doğum günlerinden Noel kutlamalarına kadar pek çok önemli ve özel günde sofralarda yer alan geleneksel yiyeceklerden biri olarak tüketilmektedir (Michelin Guide, t.y.). Görseli Şekil 4'te sunulmuştur.

Şekil 4. Pīrāgi veya Pīrādziņi
Kaynak: Ošiņa ve Ošiņš, 2014

Kartupeļu Pankūkas: Letonya mutfağında yaygın olarak tüketilen patates mücveridir. Rendelenmiş patatesin yumurta, un, tuz ve karabiberle karıştırılmasıyla hazırlanan karışım, küçük porsiyonlar hâlinde tavaya alınarak yassılaştırılmakta ve her iki yüzü altın sarısı bir renk alana kadar kızartılmaktadır. Geleneksel olarak ekşi krema, kekreyemiş sosu, taze soğan veya tereyağından biri ya da birkaçıyla birlikte servis edilmektedir. Geçmişte ekonomik ve pratik bir ev yemeği olarak değerlendirilen kartupeļu pankūkas, 2000'li yılların ortalarından itibaren Riga'daki kafe menülerinde daha sık yer almaya başlamıştır. Bu dönemde ördek eti ve kekreyemiş sosu ya da tütsülenmiş somon ve ekşi krema gibi tamamlayıcılarla sunularak daha çağdaş ve seçkin bir nitelik
kazanmıştır (Latvian Eats, 2017). Görseli Şekil 5'te sunulmuştur.

Şekil 5. Kartupeļu Pankūkas
Kaynak: Latvian Eats, 2017

Ķiploku Grauzdiņi: Letonya mutfağına özgü geleneksel bir sarımsaklı ekmek türü ve atıştırmalıktır. Hazırlanırken rupjmaize adı verilen çavdar ekmeği dilimlenmekte ve tereyağında veya sıvı yağda her iki yüzü birkaç dakika kızartılmaktadır. Tavadan alınan ekmek dilimlerinin fazla yağı kâğıt havlu üzerinde süzdürülmekte, ardından her iki yüzü sarımsak dişleriyle ovulmaktadır. Bu yiyecek fırında da hazırlanabilmekte; bu yöntemde ekmek dilimlerinin üzerine sıvı yağ gezdirilmekte veya tereyağı sürülmektedir. Servis öncesinde dilimlerin üzerine tuz serpilmekte ve genellikle soğuk bira eşliğinde sunulmaktadır (TasteAtlas, t.y.-b). Görseli Şekil 6'da sunulmuştur.

Şekil 6. Ķiploku Grauzdiņi
Kaynak: Bearas, 2015

Çorbalar

Aukstā Zupa: Koyu pembe rengiyle dikkat çeken geleneksel bir Letonya soğuk çorbası olarak bilinmektedir. Genellikle pancar, salatalık, kefir, haşlanmış yumurta ve sütlü sosis kullanılarak hazırlanmaktadır. Dereotu ve taze soğan çorbaya ferah bir aroma katmakta, isteğe bağlı olarak az miktarda sirke de eklenebilmektedir. Hazırlanan malzemeler tuz ve karabiberle tatlandırıldıktan sonra iyice karıştırılmakta ve soğuması için buzdolabında bekletilmektedir. Çorba çoğunlukla koyu renkli ekmek dilimleriyle birlikte servis edilmektedir. Daha çok yaz aylarında tüketilen bir yemek olması nedeniyle kış döneminde restoranlarda bulunması oldukça zor olmaktadır
(TasteAtlas, t.y.-c). Görseli Şekil 7'de sunulmuştur.

Şekil 7. Aukstā Zupa
Kaynak: Make Food and Drinks Like a Local, t.y.

Skābeņu Zupa: Bu çorbanın adı, yapımında kullanılan kuzukulağı yapraklarından gelmektedir. Letoncada skābs sözcüğü "ekşi" anlamına gelmektedir. Genellikle sıcak servis edilmekle birlikte sıcak havalarda ferahlatıcı bir seçenek olarak soğuk da tüketilebilmektedir. Çorba; et suyu, inci arpa, patates, soğan ve limon suyu kullanılarak hazırlanmaktadır. Tarife çoğunlukla tütsülenmiş domuz kaburgası da eklenmektedir. Servis sırasında ekşi krema ve haşlanmış yumurta ile garnitürlenmektedir (Michelin Guide, t.y.). Görseli Şekil 8'de sunulmuştur.

Şekil 8. Skābeņu Zupa
Kaynak: Pīgozne-Brinkmane, 2004

Zivju Zupa: Letonya'nın göl ve nehirlerinde bulunan çeşitli tatlı su balıkları, ülkenin geleneksel mutfak kültüründe önemli bir yere sahiptir. Balık çorbasının hazırlanmasında öncelikle küçük balıklar kaynatılarak yoğun aromalı bir çorba suyu elde edilmekte ve bu sıvı süzülmektedir. Daha sonra balık parçaları, patates, havuç ve çeşitli aromatik otlar eklenerek pişirme işlemi tamamlanmaktadır.

Servis sırasında dereotu ve ekşi krema ile zenginleştirilebilen çorba, Letonya'nın doğal su kaynakları ile yerel beslenme pratikleri arasındaki ilişkiyi yansıtan geleneksel örneklerden biridir (Ošiņa ve Ošiņš, n2014).
Görseli Şekil 9'da sunulmuştur.

Şekil 9. Zivju Zupa
Kaynak: Ošiņa ve Ošiņš, 2014

Sēņu Zupa: Mantar toplama, Letonya'da yaygın bir kültürel etkinlik ve geleneksel uğraş olarak kabul edilmektedir. Ülkede yetişen çeşitli yabani mantarlar, hem berrak et suyuyla hazırlanan çorbalarda hem de kremalı çorba çeşitlerinde kullanılmaktadır. Özellikle bolet mantarıyla hazırlanan çorbalar, belirgin aroması ve yoğun lezzetiyle öne çıkmaktadır. Çorbanın tadı, kullanılan mantar türlerine göre değişiklik göstermektedir. Letonya'da mantarlar, kış aylarında tüketilmek üzere kurutularak veya dondurularak saklanmaktadır (Ošiņa ve Ošiņš, 2014). Görseli Şekil 10'da sunulmuştur.

Şekil 10. Sēņu Zupa
Kaynak: Ošiņa ve Ošiņš, 2014

Ana Yemekler

Pelēkie Zirņi ar Speķi: Letonya'nın ulusal yemeği olarak kabul edilmektedir. Nohuda benzeyen yerel gri bezelye, kavrulmuş soğan ve küp şeklinde doğranmış tütsülenmiş domuz etiyle hazırlanan yemeğin yerel halkın kurutulmuş ve uzun süre saklanabilen gıda stoklarından yararlandığı dönemlerde ortaya çıktığı düşünülmektedir. Geleneksel olarak kefirle ya da çavdar ekmeği dilimleriyle birlikte servis edilmesi önerilmektedir (TasteAtlas, t.y.-d). Görseli Şekil 11'de sunulmuştur.

Şekil 11. Pelēkie Zirņi ar Speķi
Kaynak: Pīgozne-Brinkmane, 2004

Karbonāde: Letonya mutfağının Viyana şnitzeline özgü yorumu olan Karbonāde, ince biçimde dövülmüş domuz etinin una ve çırpılmış yumurtaya, bazı tariflerde ise galeta ununa bulanarak kızartılmasıyla hazırlanmaktadır. Genellikle mantar sosuyla servis edilmekte; yanında patates, salata, turşu veya çavdar ekmeği tercih edilebilmektedir.

Letonya'da evlerde ve kafeteryalarda yaygın olarak tüketilen Karbonāde, düğün ziyafetlerinde de sunulan geleneksel yemeklerden biri olarak kabul edilmektedir (TasteAtlas, t.y.-e). Görseli Şekil 12'de sunulmuştur.

Şekil 12. Karbonāde
Kaynak: JIP, 2019

Karbonāde ar Kaulu: Letonya mutfağında yaygın olarak tüketilen domuz eti yemeklerinden biri olarak bilinmektedir. Kemikli domuz pirzolasıyla yapılan bu yemekte et, önce kısa süre kızartılmakta, ardından tavada yumuşayana kadar pişirilmektedir (Michelin Guide, t.y.). Görseli Şekil 13'te sunulmuştur.

Şekil 13. Karbonāde ar Kaulu
Kaynak: Visit Jūrmala, t.y.

Tatlılar

Rupjmaizes Kārtojums: Çavdar ekmeği kırıntıları, siyah frenk üzümü veya keklik üzümü reçeli ve çırpılmış kremayla hazırlanan geleneksel bir Letonya tatlısıdır. Üzeri rendelenmiş bitter çikolata, tarçın ya da her ikisiyle süslenmektedir. Çoğunlukla taze orman meyveleri ve lor peynirli dondurmayla birlikte servis edilmektedir (Ošiņa ve Ošiņš, 2014). Görseli Şekil 14'te sunulmuştur.

Şekil 14. Rupjmaizes Kārtojums
Kaynak: Ošiņa ve Ošiņš, 2014

Sklandrauši: Letonya'da 16. Yüzyıldan beri hazırlanmakta olan ve 2013 yılında Geleneksel Özellik Garantili (TSG) statüsü kazanan yuvarlak biçimli geleneksel bir turta olarak bilinmektedir. Mayasız çavdar unundan hazırlanan hamur, yuvarlak parçalar hâlinde açılmakta ve kenarları yukarı doğru kıvrılarak şekillendirilmektedir. İç harcı, üst üste yerleştirilen patates ve havuç katmanlarından oluşmaktadır. Hazırlanan hamur işi, pişirilmeden önce krema ile kaplanabilmekte ve üzerine tarçın ya da kimyon tohumu serpilebilmektedir. Geleneksel olarak soğuk tüketilmekte ve çay veya süt eşliğinde servis edilmektedir (TasteAtlas, t.y.-f). Görseli Şekil 15'te sunulmuştur.

Şekil 15. Sklandrauši
Kaynak: Laucis, Alksnāja, & Gabrāns, t.y.

İçecekler

Letonya mutfak kültüründe doğadan mevsimsel olarak elde edilen, fermantasyon yoluyla hazırlanan ve çeşitli bitkisel bileşenlerden üretilen içeceklere rastlanmaktadır. Bu kapsamda huş ağacı suyu, kvass ve Riga Black Balsam aşağıda ele alınmıştır.

Huş Ağacı Suyu: Letonya'da bahar mevsimiyle ilişkilendirilen geleneksel içeceklerden biri olarak bilinmektedir. İlkbaharda huş ağaçlarının gövdelerine küçük delikler açılmakta ve ağacın doğal biçimde süzdüğü su toplanmaktadır. Taze, hafif tatlı ve ferahlatıcı bir tada sahip olan bu içecek, içerdiği mineraller nedeniyle geleneksel olarak arındırıcı özelliklerle de ilişkilendirilmektedir. Huş ağacı suyu yalnızca doğrudan tüketilmemekte; aynı zamanda beyaz şarap, kehribar renkli şarap, köpüklü şarap ve şurup yapımında da kullanılabilmektedir. Huş ağacı suyunun toplanma dönemi oldukça kısa sürmektedir; çünkü toplama işlemine ancak toprağın çözülmesinden sonra başlanabilmekte ve işlem yapraklar açmadan önce sona erdirilmektedir (Michelin Guide, t.y.). Görseli
Şekil 16'da sunulmuştur.

Şekil 16. Huş Ağacı Suyu

Kaynak: Mosāns, 2013

Kvass: Berrak olmayan bir görünüme sahip fermente bir içecek olan kvass; su, malt özü, maya, şeker ve çavdar ekmeği kabukları kullanılarak hazırlanmaktadır. Tatlı ve ekşi özellikler taşıyan içecekte çavdar ekmeğinin belirgin aroması, arpa maltının sağladığı tatlılıkla dengelenmektedir. Alkol oranı yüzde 1'in altında olduğundan çoğu zaman alkollü bir içecek olarak değerlendirilmemektedir. Letonya'da özellikle yaz gündönümünde düzenlenen Jāņi kutlamalarında kvass yaygın olarak tüketilmektedir (Michelin Guide, t.y.). Görseli Şekil 17'de sunulmuştur.

Şekil 17. Kvass
Kaynak: Liftarn, 2006

Riga Black Balsam: Letonya'ya özgü bu alkollü içeceğin, 1752 yılında eczacı Abraham Kunze tarafından iyileştirici özelliklere sahip olduğu düşüncesiyle geliştirildiği belirtilmektedir. Dünyanın en eski bitter markalarından biri olarak kabul edilen bu içecek; tatlımsı ve acı tatların yanı sıra umami tada da sahip olmaktadır. Kediotu, pelin otu, zencefil ve centiyane kökü gibi bitkilerin de aralarında bulunduğu 17 bitkisel bileşen dâhil olmak üzere toplam 24 doğal bileşen içermektedir. Üretim sürecinin ayrıntılarının yalnızca usta damıtıcı ve çırağı tarafından bilinmesi, içeceğe özgün ve gizemli bir nitelik kazandırmaktadır (Michelin Guide, t.y.). Görseli Şekil 18'de sunulmuştur.

Şekil 18. Riga Black Balsam
Kaynak: Dağdeviren, 2026

LETONYA MUTFAĞINDA ÖĞÜNLER

Letonya'da günlük beslenme düzeni, görece hafif bir kahvaltı, günün temel öğünü niteliğindeki öğle yemeği ve günün ilerleyen saatlerinde tüketilen daha küçük öğünlerden oluşmaktadır. Kahvaltıda çoğunlukla kahve, çay veya süt gibi bir içecekle birlikte peynir, sosis, domates ya da salatalık içeren sandviçler; ayrıca haşlanmış yumurta veya omlet tüketilmektedir (Pīgozne-Brinkmane, 2004; Wikipedia, 2026). Bunun yanı sıra, Letonya mutfağında "Zemnieku Brokastis" olarak adlandırılan "Çiftçi Kahvaltısı" da bulunmaktadır. Çiftliklerde kolaylıkla temin edilebilen ürünlere dayanan bu doyurucu yemek; tütsülenmiş sosis, patates, yumurta, süt, tereyağı ve dereotuyla hazırlanmaktadır. İçerdiği zengin ve besleyici malzemeler nedeniyle İngiliz kahvaltısının Letonya mutfağındaki karşılığı olarak değerlendirilebilir (Michelin Guide, t.y.). Saat 12.00 ile 15.00 arasında yenilen öğle yemeği, genellikle günün en kapsamlı öğünüdür ve et veya balık, patates, pirinç ya da karabuğday ile taze salata gibi farklı besinleri içerebilmektedir. Bu öğüne başlangıç olarak çorba ve sonrasında tatlı da eşlik edebilir. Öğle yemeği ile supper arasında, genellikle bir atıştırmalık, taze meyve, tatlı veya küçük bir porsiyon tuzlu yiyecekten oluşan launags adlı daha küçük bir öğün bazen tüketilebilmektedir. İşten eve dönüldüğünde ise ikinci bir öğle yemeği ya da supper hazırlanmakta ve bu öğün çoğunlukla saat 18.00-19.00 arasında yenmektedir.

Söz konusu öğün çorba, çeşitli salatalar, öğle yemeğine benzer sıcak yemekler veya süt temelli geleneksel bir çorbadan oluşabilir. Bununla birlikte hazır ve dondurulmuş yiyeceklerin yanı sıra sandviç, çeşitli hamur işleri ve pizza tüketimi de günümüzde yaygınlaşmıştır. Ayrıca yatmadan önce naksniņas olarak adlandırılan küçük bir atıştırmalığın tüketilmesi de Letonya'daki beslenme alışkanlıkları arasında yer almaktadır (Pīgozne-Brinkmane, 2004; Wikipedia, 2026).

LETONYA'DA GASTRONOMİ MEKÂNLARI VE ETKİNLİKLERİ

2017 tarihli Food Lover's Guide to the Riga – Gauja Region adlı rehberde, Riga-Gauja bölgesindeki gastronomi turizminin restoranlar, yerel pazarlar, bira fabrikaları, şaraphaneler, üretici çiftlikleri, gastronomi müzeleri ve tematik etkinliklerden oluşan geniş bir yapı sergilediği görülmektedir. Rehberde tanıtılan gastronomik faaliyetlerde yerel ve mevsimsel ürünlerin kullanılması, geleneksel üretim yöntemlerinin sürdürülmesi ve ziyaretçilere tadım yapma, üretim süreçlerini gözlemleme ve uygulamalı etkinliklere katılma olanağı sunulması öne çıkmaktadır. Rehberde restoranlar, çiftliklerden, ormanlardan, göllerden ve Baltık Denizi'nden elde edilen yerel ürünleri öne çıkaran işletmeler olarak tanıtılmış; pazarlarda çiftçi ve küçük üreticilerin ürünlerini doğrudan tüketicilere sunduğu, üretim

tesislerinde ise ziyaretçilere üretim süreçlerini tanıma ve ürünleri tatma olanağı sağlandığı belirtilmiştir. Aşağıda söz konusu rehberde yer verilen gastronomi mekânları ve etkinliklerinden bazıları açıklanmıştır (Food Lover's Guide to the Riga – Gauja Region, 2017).

Restoranlar: Riga'daki *Le Dome* deniz ürünleri ve yerel çiftlik ürünleriyle; *Restorāns 3* ormanlardan ve tarlalardan elde edilen ürünlere dayalı menüsüyle; *3 Pavāru Restorāns* Riga-Gauja bölgesindeki çiftçi ve üreticilerden temin edilen ürünleri kullanmasıyla; *Bibliotēka No. 1* geleneksel Letonya yemeklerini çağdaş biçimde yorumlamasıyla; *Valtera Restorāns* ise yerel çiftliklerden sağlanan kırsal ürünlere dayalı mevsimsel menüsüyle öne çıkmaktadır. Sigulda'daki *Aparjods, Kungu Rija ve Fazenda; Cēsis'teki Priede, Cēsis Wine Bar ve Café 2Locals; Valmiera'daki Rātes Vārti, Agnese, Parks* ve *Vecpuisis* de yerel ürünleri, geleneksel mutfağı veya mevsimsel malzemeleri öne çıkaran işletmeler arasında tanıtılmıştır.

Pazarlar ve Satış Alanları: *Riga Central Market, Kalnciems kvartāls Fair, Cēsis Market, Valmiera Market* ve *Straupe Rural Goods Market*, çiftçilerin ve küçük ölçekli üreticilerin ürünlerini doğrudan tüketicilere sunduğu başlıca gastronomi alanlarıdır. Bu alanlarda, pazara göre değişmekle birlikte, peynir, bal, tütsülenmiş et ve balık, ekmek, reçel, bitki çayı, sebze, meyve ve çeşitli mevsimsel ürünler satışa sunulmaktadır. *Straupe Rural Goods Market*, yerel ve mevsimsel ürünlere, gıda güvenliğine ve ekolojik sürdürülebilirliğe dayalı üretim anlayışıyla ayrıca dikkat çekmektedir.

İçecek Odaklı Gastronomi Mekânları: Letonya'da bira ve meyve şarabı üretimi, gastronomi turizminin önemli bileşenlerindendir. *Valmiermuiža Craft Brewery* ve *Raiskumietis Brewery*, geleneksel ve zanaatkâr yöntemlerle bira üretmekte; ziyaretçilere üretim süreçlerini tanıma ve ürünleri tatma olanağı sunmaktadır. *Matilde Winery*, şaraplarının yanı sıra çeşitli bitkilerle aromalandırılan ev yapımı vermutuyla; *Zilver Winery*, kendi yetiştirdiği meyve ve orman meyvelerinden üretilen şaraplarıyla; *Krimulda Manor Winery* ise malikâne şarapları ve tadım programlarıyla öne çıkmaktadır. *Aldaris Beer Museum*'da tarihî bira üretim ekipmanları ve bira atölyeleri aracılığıyla Letonya'nın bira kültürü ve üretim yöntemleri tanıtılmaktadır.

Gastronomik Deneyim Alanları: Letonya'daki bazı işletmeler ziyaretçilere ürünleri tatma, üretim aşamalarını gözlemleme veya uygulamalı etkinliklere katılma fırsatı sunmaktadır. *R Chocolat Factory*, çikolata yapımı atölyeleriyle; *Medus Kāre*, farklı çiçek ve orman ballarının tadımıyla; *Silkalni*, şifalı bitkilerin yetiştirilmesi, toplanması, kurutulması ve bitki çayı üretimiyle; *Āraiši Windmill* ise geleneksel un öğütme süreci ve arpa unundan hazırlanan değirmenci yemeğiyle öne çıkmaktadır. *Valmiera Museum* bünyesinde de ekmeğin üretim süreci, süt ürünlerinin Letonya kültüründeki yeri ve şifalı bitkiler ile baharatların mutfakta kullanımı üzerine eğitici programlar düzenlenmektedir.

Riga Restaurant Weeks: Riga'da ilkbahar ve sonbaharda düzenlenen ve restoranların özel fiyatlı üç aşamalı menüler sunduğu gastronomi etkinlikleridir.

Riga Festival Restaurant: Riga Şehir Festivali sırasında Spīķeri Meydanı'nda oluşturulan açık restoran alanıdır. Riga'daki seçkin restoranlar, yerel ürünlerden hazırlanan mevsimsel yemekleri canlı müzik, yarışmalar ve çeşitli eğlence etkinlikleri eşliğinde ziyaretçilere sunmaktadır.

Riga Food: Baltık bölgesinin önde gelen gıda sektörü fuarlarından biridir. Etkinlik; gıda endüstrisindeki yeniliklerin tanıtılması, üreticiler ile sektör temsilcilerinin bir araya getirilmesi ve aşçı, pastacı ve barmenlerin uygulamalı gösterilerine yer verilmesi bakımından önem taşımaktadır.

Cēsis Castle Medieval Days: Cēsis Orta Çağ Kalesi'nde düzenlenen etkinlikte tarihî beceriler, geleneksel zanaatlar ve Orta Çağ dönemine özgü yiyecek ve içecekler tanıtılmaktadır.

Jacob's Festival: Hasadın ardından yeni mahsulden çavdar ekmeğinin ilk kez pişirilmesini kutlayan geleneksel bir etkinliktir. Festival kapsamında özel ekmekler ve krepler sunulmakta; peynir, bal, ekmek, bitki çayı ve el sanatları ürünleri satan yerel üreticiler de etkinliğe katılmaktadır.

Saulgriezis: Valmiermuiža'da düzenlenen bir etkinliktir. Yerel çiftlik ürünleri, el sanatları, canlı müzik, dans ve Valmiermuiža birası etkinliğin temel unsurlarını oluşturmaktadır.

Valmiera Restaurant Week: Valmiera'daki restoranların özel fiyatlı üç aşamalı menüler sunduğu bir gastronomi haftasıdır.

Sigulda ve Çevresi Restaurant Weeks: Sigulda ve çevresindeki restoranların nisan ve kasım aylarında olmak üzere yılda iki kez özel fiyatlı menüler sunduğu gastronomi etkinlikleridir.

Savour the Flavour at Valmiermuiža: Rehbere göre Valmiermuiža bira fabrikasının çevresinde, Letonya'nın mevsimsel kutlamalarıyla bağlantılı olarak yılda sekiz kez düzenlenen bir yiyecek, içecek

ve el sanatları fuarıdır. Etkinlik kapsamında geleneksel Letonya yemekleri, yaratıcı atölyeler ve eski Letonya geleneklerini tanıtan çeşitli faaliyetler gerçekleştirilmektedir.

SONUÇ VE DEĞERLENDİRME

Bu çalışma, Letonya mutfak kültürünün doğal çevre koşulları, tarihsel deneyimler ve kültürler arası etkileşimlerin birleşimi sonucunda şekillendiğini ortaya koymaktadır. İklim ve tarımsal koşullar, yerel ürünlerin kullanımını ve uzun süreli saklama yöntemlerinin gelişimini belirlerken farklı siyasal ve kültürel dönemler mutfağın ürün, tarif ve hazırlama teknikleri bakımından çeşitlenmesine katkı sağlamıştır. Bu etkilerin yerel malzemeler ve tüketim alışkanlıkları doğrultusunda yeniden yorumlanması, Letonya mutfağına özgün ve çok katmanlı bir nitelik kazandırmıştır (Pīgozne Brinkmane, 2004). Letonya mutfağının farklı siyasal dönemlerde ulusal kimlik, toplu beslenme uygulamaları ve küresel eğilimler doğrultusunda yeniden biçimlenmesi ise bu mutfak kültürünün değişen toplumsal koşullara uyum sağlayan dinamik bir yapıya sahip olduğunu göstermektedir (Beitāne vd., 2022).

Çalışmada ele alınan yiyecek ve içecekler, Letonya mutfak kültürünü biçimlendiren çevresel ve tarihsel unsurların yeme ve içme pratiklerine nasıl yansıdığını ortaya koymaktadır. Fermantasyon, tütsüleme, tuzlama ve salamura gibi yöntemler, mevsimsel olarak elde edilen ürünlerin saklanma ve tüketim sürelerinin uzatılmasına olanak sağlamıştır. Bazı yiyecek ve içeceklerin bayramlar, özel günler ve mevsimsel dönemlerle ilişkilendirilmesi ise mutfak kültürünün yalnızca beslenme gereksinimini karşılamadığını; toplumsal aidiyetin, ortak belleğin ve kültürel sürekliliğin korunmasına da katkı sağladığına işaret etmektedir.

Letonya'daki öğün düzeni ve güncel tüketim alışkanlıkları, geleneksel uygulamalarla çağdaş yaşam biçimlerinin bir arada bulunduğunu göstermektedir. Geleneksel öğünlerin ve yerel ürünlerin varlığını sürdürmesine karşılık hazır ve dondurulmuş yiyeceklerin, sandviçlerin, hamur işlerinin ve pizzanın yaygınlaşması, günlük beslenme pratiklerinin değişen yaşam koşullarına uyum sağladığını düşündürmektedir. Bu durum, Letonya mutfak kültürünün geçmişten aktarılan unsurları korurken yeni tüketim biçimlerine de açık olduğunu ortaya koymaktadır.

Restoranlar, yerel pazarlar, üretim tesisleri, gastronomi müzeleri ve çeşitli etkinlikler, Letonya mutfak kültürünün görünürlük kazanmasında ve ziyaretçilere aktarılmasında işlevsel bir rol üstlenmektedir. Yerel ve mevsimsel ürünlerin çağdaş pişirme ve sunum biçimleriyle değerlendirilmesi, geleneksel mutfak mirası ile günümüz gastronomi anlayışı arasında bir bağ kurulmasını sağlamaktadır. Üretim süreçlerini tanıtan tadım programları ve uygulamalı etkinlikler ise gastronomik deneyimin yalnızca yiyecek ve içecek tüketimiyle sınırlı kalmadığını; yerel üretim bilgisinin ve mutfak uygulamalarının tanıtılmasını da kapsadığını göstermektedir.

Gelecekte yapılacak araştırmalarda Letonya'nın farklı bölgelerindeki yiyecek ve içeceklerin, hazırlama yöntemlerinin ve tüketim alışkanlıklarının saha çalışmalarıyla incelenmesi, ülke içindeki bölgesel farklılıkların daha ayrıntılı biçimde belirlenmesine katkı sağlayabilir. Kırsal ve kentsel alanlardaki beslenme pratiklerinin karşılaştırılması, geleneksel tariflerin günümüzde geçirdiği değişimin anlaşılmasını kolaylaştırabilir. Ayrıca Letonya, Estonya ve Litvanya mutfak kültürlerini karşılaştıran çalışmalar, Baltık coğrafyasında ortak olan ürün ve tekniklerin farklı tarihsel ve ulusal bağlamlarda nasıl anlamlandırıldığını ortaya koyabilir.

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THE PROBLEM OF COMPARABILITY OF FINANCIAL STATEMENTS IN A HIGH-INFLATION ENVIRONMENT: A LITERATURE REVIEW FROM THE PERSPECTIVE OF ACCOUNTING STANDARDS AND FINANCIAL REPORTING

YÜKSEK ENFLASYON ORTAMINDA FİNANSAL TABLOLARIN KARŞILAŞTIRILABİLİRLİĞİ SORUNU: MUHASEBE STANDARTLARI VE FİNANSAL RAPORLAMA PERSPEKTİFİNDEN BİR LİTERATÜR İNCELEMESİ

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ÖZET

Finansal tabloların temel niteliklerinden biri olan karşılaştırılabilirlik, finansal tablo kullanıcılarının işletmelerin finansal durumlarını farklı dönemler itibariyle veya farklı işletmelerle kıyaslayarak değerlendirmesine olanak sağlanmasıdır. Ancak küresel ekonomide yaşanan son değişimler enflasyon oranlarının yükselmesine yol açmıştır. Venezuela, Arjantin ve Türkiye başta olmak üzere birçok ülkede yaşanan yüksek enflasyon ortamı, firmaların finansal raporlarının karşılaştırılabilirliğini azaltmaktadır. Parasal değerlerin satın alma gücündeki azalmalar özellikle tarihi maliyet esasına göre raporlanan kalemlerin enflasyonist ortamda gerçek değerleriyle raporlanmasını güçleştirmektedir. Bu durum yüksek enflasyon ortamında farklı işletmelere veya farklı dönemlere ait finansal tabloların karşılaştırılabilirliğini azaltarak finansal tablo kullanıcılarının karar alma süreçlerini olumsuz etkilemektedir. Bu kapsamda yüksek enflasyonist ortamlarda finansal tabloların doğru şekilde raporlanması, finansal tablo kullanıcıları doğru bilgiye erişimi ve finansal bilginin faydalığı açısından önem taşımaktadır. Bu çalışmanın amacı, yüksek enflasyon ortamında hazırlanan finansal tablolarının karşılaştırılabilirliği sorununu ele alan literatürü değerlendirmek ve enflasyon muhasebesinin bu sorunun çözümündeki katkılarını ortaya koymaktır. Literatür, yüksek enflasyonun işletmelerin varlık, yükümlülük, gelir ve giderlerinin finansal tablolarında gerçeğe uygun sunumunu zorlaştırdığı ve bu durumun finansal tablolarının karşılaştırılabilirliğini güçleştirdiğini göstermektedir. Ayrıca enflasyon muhasebesi uygulamasıyla farklı satın alma güçleriyle finansal tablolarda yer alan kalemlerin cari satın alma gücüne göre düzeltilerek sunulmasının finansal tabloların karşılaştırılabilirliğini artırdığı belirtilmiştir. Sonuç olarak yüksek enflasyonist ortamlarda finansal raporların karşılaştırılabilirliğinin korunması amacıyla enflasyon muhasebesinin etkin biçimde uygulanmasının önemli olduğu değerlendirilmektedir.

Anahtar kelimeler: Enflasyon muhasebesi, finansal raporlama, finansal tablolar, karşılaştırılabilirlik, IAS 29, yüksek enflasyon.

ABSTRACT

One of the fundamental characteristics of financial statements is comparability, which allows users of financial statements to compare the financial positions of businesses over time or across businesses. But recent changes in the global economy have driven up inflation rates. High inflation in many countries, such as Venezuela, Argentina and Turkey, reduces the comparability of firms' financial reports. Loss of purchasing power makes it difficult to report the real values of monetary values in an inflationary environment. This is particularly true for items reported on a historical cost basis. This situation reduces the comparability of financial statements of different businesses or different periods in a high inflation environment, negatively affecting the decision-making processes of financial statement users. In this context, the accurate reporting of financial statements in high inflationary environments is important for financial statement users to access correct information and for the usefulness of financial information. The aim of this study is to evaluate the literature addressing the issue of comparability of financial statements prepared in a high inflation environment and to highlight the contributions of inflation accounting in solving this problem. The literature shows that high inflation makes it difficult to present the assets, liabilities, income, and expenses of businesses in a true and fair manner in financial statements, and this situation complicates the comparability of financial statements .It has also been stated that the application of inflation accounting, by adjusting and presenting items in financial statements with different purchasing powers according to their current purchasing power, increases the

comparability of financial statements. In conclusion, it is considered important to effectively implement inflation accounting in order to maintain the comparability of financial report in high-inflationary environments.

Keywords: Inflation accounting, financial reporting, financial statements, comparability, IAS 29, high inflation

INTRODUCTION

According to the International Accounting Standards Board (IASB), the main objective of financial reporting is to offer valuable information to the consumers of financial statements, mainly to the investors and creditors (IFRS Foundation, 2018). The Board's published conceptual framework states that meaningful financial information should not only have characteristics such as being relevance, understandability, verifiable and timeliness but should also be "comparable" (IFRS Foundation, 2018). Comparability is a quality that makes the information in the financial statements more usable. It is the most important property that allows readers of financial statements to compare the information of other entities or different periods for the same entity while making decisions. Hence comparability is the soul of the financial reporting system (IFRS Foundation, 2018; Wang, 2014). In this regard, the comparability of financial statements of different firms or of different periods of the same business requires the purchasing power of the monetary values in these tables to be equal. However, the global economic balances are changing due to rising commodity prices, rising global risk levels and vulnerabilities of political systems, leading to hyperinflation in developing economies such as Argentina, Venezuela and Turkey (IMF, 2026). The financial statements generated on historical cost basis have lost the features of faithful representation and comparability in the economies that have economic instability and excessive inflation (Slimane & Aouadi, 2026). The quality of financial reports created according to the historical cost principle, especially its comparability, is considerably jeopardized by excessive inflation and the constant and fast decline of purchasing power. This study mainly aims to investigate the systematic problems that high inflation creates concerning the comparability of financial reports within the framework of accounting standards. In this study, the existing approaches in the literature are evaluated in order to examine the comparability of financial reports within the framework of accounting standards and to emphasize the role of inflation accounting in solving these problems.

RESEARCH AND FINDINGS

The Notion of Comparability in Financial Statements

Comparability is one of the properties that increase the utility of financial information, together with verifiability, timeliness, and understandability, according to the Conceptual Framework of the International Accounting Standards Board (IASB) (IFRS Foundation, 2018). Comparability is a qualitative property that allows consumers of financial statements to compare between various organizations or between different periods of the same business (Barth, 2013; De Franco et al., 2011). There is other empirical research that tries to measure this principle while structurally dissimilar economic events are reported in a way that improves the quality of financial information. The focus was on the measurement of comparability, and an empirical analysis was performed based on the assumption that identical economic occurrences should result in similar financial reports(De Franco et al., 2011). The study revealed that high comparability minimizes the discrepancy among investors' forecasts and improves the quality of financial information.In the literature, it is generally agreed that we should differentiate the concept of comparability from that of uniformity. In this context, comparability refers to the reporting of smilar economic events in a smilar manner, while structurally dissimilar economic events are reported in a manner that provides the most accurate portrayal(Schipper & Vincent, 2003). Therefore, proper comparability necessitates accounting for identical economic events in similar ways only. However, macroeconomic instabilities with changes in the purchasing power of money immediately affect the comparability, which is an important attribute that increases the value of financial information. The ability to compare financial statements prepared on a historical cost basis is predicated on the assumption that the purchasing power of money is stable. In fact, inflation causes variations in the purchasing power of money and, thus, decreases the comparability of financial IAS 29 is based on the principle of reindexing financial statements using a specific method to eliminate the distorting effects of inflation. The initial step in the implementation process is selecting an index that represents the

general price level. Then the elements in the balance sheet with respect to the assets and liabilities are classified into monetary and non-monetary categories according to their responses to inflation(Choi & Meek, 2011). Monetary items are not adjusted. Nonmonetary items are adjusted with reference to the current purchasing power by comparing the index value at the date of procurement and the index value at the reporting date. Therefore, the non-monetary items are given at their updated prices, not their historical cost values, since the values of non-monetary items are not constant against inflation (Kirk, 2005; Umut, 2024). All revenue and expense items included in the income statement are adjusted to reflect their purchasing power as of the reporting date using the index in effect on the date they were incurred (IFRS Foundation, 2024).

These correction processes allow for re-expressing the financial reports with the purchasing power of the present period and assure the comparability of these reports (Barth, 2013; De Franco et al., 2011). However, one should remember that the amendments made under IAS 29 provide a relative improvement rather than absolute correctness. The fact that the adjustment operations are performed under certain assumptions limits the capacity of the enterprises to fully and openly reflect their current economic situations in the financial statement (Konchitchki, 2011). In addition to the limits pointed out by Konchitchki (2011), it is noticed that the price indices utilized in the adjustment process do not adequately reflect the sectoral and structural inflation affecting each business (Choi & Meek, 2011). Adjusting historical cost-based data to account for different cost components and sectoral inflations using a general price index provides a basis for modifying businesses' financial reports; however, this approach leads to discrepancies because it does not consider sector-specific effects. Finally, the time expenses of inflation adjustment, qualified staff, and technology infrastructure are also a burden for enterprises (Akçin, 2023).

RESULT

High inflation severely diminishes one of the essential attributes of financial statements—comparability. Financial reports, which are created on a historical cost basis without regard to the changes in the purchasing power of money, do not reflect the genuine financial condition and performance of enterprises. Such a condition makes it difficult to compare different businesses or different times for the same business. Therefore, in high-inflationary economies, the knowledge included in financial reports created on a historical cost basis lowers decision-making processes.Literature studies show that inflation accounting is a key way to mitigate these detrimental consequences. The IAS 29 Financial Reporting in Hyperinflationary Economies standard enhances the reliability, comparability, and fair presentation of the reports created by restating financial accounts in terms of the current purchasing power. In this sense, inflation accounting, in addition to making a technical adjustment to financial statements, also contributes to the quality of financial information and to its more effective application in the decision-making process. However, in addition to these positive contributions of inflation accounting, it is also useful to recognize the limitations encountered in practice. The literature shows that the general price index employed in corrective operations is inadequate to represent the actual inflation encountered by firms and the additional costs brought about by the inflation accounting process. Therefore, the adjustments under IAS 29 address the unfavorable elements caused by the historical cost principle instead of giving an absolute repair and complete comparability in financial reports.

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ASİMETRİK TABAKALAR ARASI HİBRİT ÇİFT KAVİSLİ KOMPOZİT YAPILARIN YARI-STATİK MEKANİK DAVRANIŞININ İNCELENMESİ

INVESTIGATION OF THE QUASI-STATIC MECHANICAL BEHAVIOR OF ASYMMETRIC INTER-PLY HYBRID DOUBLE-CURVED COMPOSITE STRUCTURES

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ÖZET

Fiber takviyeli kompozit yapılar; yüksek özgül dayanım, rijitlik, düşük yoğunluk ve enerji absorbsiyon kabiliyetleri sayesinde havacılık, savunma, otomotiv ve denizcilik gibi birçok mühendislik uygulamasında yaygın olarak kullanılmaktadır. Özellikle karbon fiber ve Kevlar fiber takviyeli kompozit yapılar, hafiflik ile yüksek mekanik performansı bir arada sunmaları nedeniyle son yıllarda dikkat çekmektedir. Bu çalışmada düz dokuma karbon/epoksi, dimi dokuma karbon/epoksi ve Kevlar/epoksi esaslı monolitik ve hibrit çift kavisli kompozit yapıların farklı katman dizilimleri, yükleme hızları ve uç geometrileri altındaki yarı-statik batma davranışları deneysel olarak incelenmiştir. Numuneler epoksi reçine matrisi kullanılarak çift kavisli formda üretilmiş ve ASTM D6264/D6264M standardına uygun olarak test edilmiştir. Deneylerde yarı küresel ve konik uç geometrileri kullanılmış olup 1.25 mm/dk ve 100 mm/dk yükleme hızlarında yarı-statik batma testleri gerçekleştirilmiştir. Elde edilen sonuçlar değerlendirildiğinde Kevlar takviyeli yapıların daha yüksek enerji absorbsiyon kapasitesi ve daha sünek deformasyon davranışı sergilediği belirlenmiştir. Dimi dokuma karbon takviyeli yapıların ise düz dokuma karbon yapılara göre daha stabil kuvvet davranışı ve daha yüksek taşıma kapasitesi gösterdiği gözlemlenmiştir. Hibrit kompozit yapılarda katman diziliminin mekanik performansı doğrudan etkilediği, özellikle karbon fiberin dış yüzeyde bulunduğu dizilimlerde maksimum kuvvet değerlerinin arttığı tespit edilmiştir. Ayrıca konik uç kullanılan testlerde temas alanının azalmasına bağlı olarak gerilme yoğunlaşmalarının arttığı ve hasarın daha lokal bölgelerde oluştuğu değerlendirilmiştir. Yükleme hızının artmasıyla birlikte kompozit yapıların daha rijit davranış sergilediği ve maksimum kuvvet değerlerinde artış meydana geldiği görülmüştür. Sonuç olarak elyaf cinsi, dokuma tipi, katman dizilimi, uç geometrisi ve yükleme hızının çift kavisli kompozit yapıların yarı-statik batma davranışı üzerinde önemli etkiye sahip olduğu ortaya konulmuştur.

Anahtar Kelimeler: yarı-statik batma, mekanik davranış, uç geometrisi, katman dizilimi, hibrit kompozit

ABSTRACT

Fiber-reinforced composite structures are widely used in many engineering applications such as aerospace, defense, automotive, and marine due to their high specific strength, rigidity, low density, and energy absorption capabilities. Carbon fiber and Kevlar fiber-reinforced composite structures, in particular, have attracted attention in recent years because they offer a combination of lightness and high mechanical performance. In this study, the quasi-static indentation behavior of monolithic and hybrid double-curved composite structures based on düz carbon/epoxy, dimi carbon/epoxy, and Kevlar/epoxy with different layups, loading rates, and indenter geometries was experimentally investigated. Samples were produced in a double-curved form using an epoxy resin matrix and tested according to the ASTM D6264/D6264M standard. Hemispherical and conical indenter geometries were used in the experiments, and quasi-static indentation tests were performed at loading rates of 1.25 mm/min and 100 mm/min. The results indicated that Kevlar-reinforced samples exhibited higher energy absorption capacity and more

ductile deformation behavior. Dimi carbon-reinforced samples on the other hand, were observed to show more stable force behavior and higher load-carrying capacity compared to düz woven carbon counterparts. It was determined that the layup configuration directly affects the mechanical performance in asymmetric hybrid composite structures, and that the maximum force values increase, especially in layup where the carbon fiber is on the outer surface. In addition, it was evaluated that stress concentrations increased and damage occurred in more localized regions due to the decrease in the contact area in tests using a conical indenter. It was observed that composite structures exhibited more rigid behavior and that the maximum force values increased with increasing loading rate. In conclusion, it was shown that fiber type, weave type, layup arrangement, indenter geometry, and loading rate have a significant effect on the quasi-static indentation behavior of double-curved composite structures.
Keywords: quasi-static indentation, mechanical behavior, indenter geometry, stacking sequence, hybrid composites.

1. GİRİŞ

Fiber takviyeli polimer kompozitler; yüksek özgül dayanım, yüksek rijitlik, düşük yoğunluk, korozyon direnci ve üstün enerji absorpsiyon özellikleri sayesinde günümüzde havacılık, savunma, otomotiv, denizcilik ve spor ekipmanları gibi birçok mühendislik uygulamasında yaygın olarak kullanılmaktadır [1,2]. Geleneksel metalik malzemelerle karşılaştırıldığında daha yüksek dayanım/ağırlık oranı sunmaları, kompozit malzemelerin özellikle hafiflik ve yüksek performans gerektiren yapısal uygulamalarda tercih edilmesini sağlamaktadır. Karbon fiber takviyeli kompozitler yüksek elastisite modülü, üstün rijitlik ve yüksek taşıma kapasitesi sunmaları nedeniyle mühendislik uygulamalarında önemli bir yer edinmiştir. Buna karşılık aramid esaslı Kevlar fiberler; yüksek darbe dayanımı, enerji absorpsiyon kapasitesi ve hasar toleransı özellikleriyle öne çıkmaktadır. Karbon fiberlerin yüksek rijitliği ile Kevlar fiberlerin sünek davranışının bir araya getirilmesi amacıyla geliştirilen hibrit kompozit yapılar, son yıllarda araştırmacılar tarafından yoğun şekilde incelenmektedir [3–8]. Hibritleşme yaklaşımı sayesinde farklı fiber türlerinin avantajları tek bir yapı içerisinde birleştirilerek daha dengeli mekanik özellikler elde edilebilmektedir **[5,6,8].**. Kompozit yapıların servis koşullarında maruz kaldığı en önemli yükleme türlerinden biri lokal darbe ve batma yüklemeleridir. Uçak gövde panelleri, denizcilik yapıları, otomotiv parçaları ve koruyucu ekipmanlar kullanım sırasında çeşitli yabancı cisim çarpmalarına veya düşük hızlı darbe etkilerine maruz kalabilmektedir. Bu nedenle kompozit yapıların batma davranışının incelenmesi, güvenli tasarım açısından kritik önem taşımaktadır [9,10]. Özellikle yarı-statik batma testleri, düşük hızlı darbe davranışının kontrollü laboratuvar koşullarında değerlendirilmesine olanak sağlayan yaygın deney yöntemlerinden biridir **[10,11].** ASTM D6264/D6264M standardı bu amaçla geliştirilen ve kompozit laminatların penetrasyon direncinin değerlendirilmesinde sıklıkla tercih edilen standart test yöntemlerinden biridir [11]. Yarı-statik batma davranışı; fiber türü, fiber mimarisi, tabaka dizilimi, yükleme hızı, numune geometrisi ve batıcı uç geometrisi gibi birçok parametreden etkilenmektedir. Gebhardt ve arkadaşları [9], eğrisel kompozit yapıların düşük hızlı darbe davranışını incelemiş ve geometrik formun hasar mekanizmaları üzerinde belirleyici rol oynadığını göstermiştir. Benzer şekilde Sutherland ve Soares [10], yarı-statik test yönteminin düşük hızlı darbe davranışını temsil etmede etkili bir yöntem olduğunu ortaya koymuştur. Fotouhi ve arkadaşları [3], karbon ve cam fiber takviyeli kompozit laminatların yarı-statik batma davranışını karşılaştırmış ve fiber türünün maksimum yük taşıma kapasitesi ile hasar gelişimi üzerinde belirleyici olduğunu bildirmiştir.

Hibrit kompozit laminatlar üzerine gerçekleştirilen çalışmalarda, katman diziliminin ve hibritleşme stratejisinin mekanik performansı önemli ölçüde değiştirdiği belirtilmektedir. Kumar ve arkadaşları [4], hibrit kompozit laminatlarda hasar oluşumunun fiber yerleşimi ile doğrudan ilişkili olduğunu göstermiştir. Bulut ve Erklig [5] tarafından gerçekleştirilen çalışmada hibrit kompozit plakalarda yarı-statik girinti davranışı araştırılmış ve hibrit yapının enerji absorpsiyon kapasitesini artırdığı belirlenmiştir. Benzer şekilde Bulut ve arkadaşları [6], hibritleşmenin yarı-statik penetrasyon direncini artırdığını ve hasar ilerlemesini geciktirdiğini bildirmiştir. Andrew ve arkadaşları [7] hibrit takviye yamalarının quasi-statik batma davranışı üzerindeki etkisini incelemiş ve katman konfigürasyonunun hasar gelişiminde önemli rol oynadığını bildirmiştir Wang ve arkadaşları [8]ise karbon/Kevlar hibrit kompozitlerde katman diziliminin maksimum kuvvet, enerji absorpsiyonu ve hasar mekanizmaları üzerinde önemli etkileri olduğunu ortaya koymuştur. Son yıllarda gerçekleştirilen çalışmalar, yalnızca

hibritleşmenin değil aynı zamanda fiber mimarisinin de mekanik davranış üzerinde belirleyici olduğunu göstermektedir. Düz (düz) ve dimi (dimi) dokuma karbon kumaşların farklı dokuma mimarilerine bağlı olarak yük transfer mekanizmaları ve gerilme dağılımları değişebilmektedir. Düz (düz) ve dimi (dimi) dokuma karbon kumaşların farklı yük transfer mekanizmalarına sahip olduğu, bunun da gerilme dağılımı ve lokal rijitlik üzerinde etkili olabildiği çeşitli çalışmalarda belirtilmiştir [12,13]. Pach ve arkadaşları [14] ile Pach ve Pawłowska [15], aramid ve karbon fiber içeren hibrit kompozitlerde fiber yerleşiminin penetrasyon davranışını önemli ölçüde değiştirdiğini bildirmiştir. Wang ve arkadaşları [16] ise karbon/Kevlar hibrit örgü kompozitlerde yarı-statik girinti ve düşük hızlı darbe davranışlarını inceleyerek karbon fiberlerin dış yüzeyde yer aldığı dizilimlerin daha yüksek maksimum kuvvet değerleri sağladığını göstermiştir.Literatürde yarı-statik batma davranışı üzerine çok sayıda çalışma bulunmasına rağmen, çift kavisli geometrik forma sahip monolitik ve hibrit kompozit yapıların aynı çalışma kapsamında karşılaştırmalı olarak incelendiği araştırmalar oldukça sınırlıdır. Ayrıca düz karbon, dimi karbon ve Kevlar fiberlerin hem monolitik hem de farklı hibrit dizilimler altında değerlendirilmesi, farklı uç geometrileri ve yükleme hızlarının birlikte ele alınması literatürde yeterince araştırılmamıştır. Bu çalışmada, çift kavisli geometriye sahip düz karbon/epoksi, dimi karbon/epoksi ve Kevlar/epoksi esaslı monolitik yapılar ile karbon-Kevlar hibrit kompozit yapılar yarı-statik batma testleri altında deneysel olarak incelenmiştir. Çalışma kapsamında fiber mimarisinin, katman diziliminin, yükleme hızının ve batıcı uç geometrisinin mekanik davranış üzerindeki etkileri değerlendirilmiştir. Ayrıca monolitik ve hibrit yapıların maksimum kuvvet, deformasyon davranışı, enerji absorpsiyon kapasitesi ve hasar mekanizmaları karşılaştırılarak kompozit yapı tasarımında optimum fiber yerleşimine ilişkin önemli bulgular ortaya konulmuştur.

2. MATERYAL VE METOT

2.1 Kullanılan Malzemeler

Bu çalışmada takviye malzemesi olarak düz dokuma (düz) karbon fiber, dimi dokuma (dimi) karbon fiber ve Kevlar® 29 aramid fiber kumaşlar kullanılmıştır. Matris malzemesi olarak Hexion LR285 epoksi reçinesi ve LH287 sertleştiricisi tercih edilmiştir. Reçine ve sertleştirici üretici tavsiyelerine uygun olarak 100:40 oranında karıştırılmıştır. Karbon fiber takviyeli kompozit yapılarda iki farklı dokuma mimarisi kullanılmıştır. Düz dokuma (düz) karbon kumaşlar daha yüksek yerel rijitlik sağlarken [8,16], dimi dokuma (dimi) karbon kumaşlar daha dengeli yük transferi ve deformasyon davranışı sergilemektedir [16,18]. Buna karşılık Kevlar® 29 aramid fiberler ise yüksek enerji absorpsiyonu kapasitesi ve hasar toleransı özellikleri nedeniyle hibrit yapıların üretiminde tercih edilmiştir [14,16,18].

2.2 Numune Üretimi

Deney numuneleri el yatırma yöntemi kullanılarak çift kavisli geometrik formda üretilmiştir. Üretim sürecinde karbon ve Kevlar kumaş katmanları belirlenen dizilimlere göre yerleştirilmiş ve epoksi reçine ile emprenye edilmiştir. Monolitik numuneler sekiz katmandan oluşacak şekilde hazırlanırken, hibrit numunelerde farklı karbon-Kevlar dizilimleri uygulanmıştır. Üretim sonrasında numuneler oda sıcaklığında kürlenmeye bırakılmış ve deney boyutlarına uygun şekilde kesilerek testlere hazırlanmıştır. Tüm numunelerde aynı üretim parametreleri kullanılarak malzeme kaynaklı değişkenliklerin minimum seviyeye indirilmesi amaçlanmıştır.

2.3 Deneysel Tasarım

Çalışma kapsamında hem monolitik hem de hibrit kompozit yapılar değerlendirilmiştir.
Monolitik grupta;

- PC8R (Düz Karbon/Epoksi)
- TC8R (Dimi Karbon/Epoksi)
- K8R (Kevlar/Epoksi) numuneleri incelenmiştir.

Hibrit grupta ise karbon ve Kevlar fiberlerin farklı katman dizilimlerine sahip kombinasyonları oluşturulmuştur. Bu kapsamda;

- K2PC6
- K2TC6
- PC2K6
- TC2K6

- KPC8R
- KTC8R
- PCK8R
- TCK8R numuneleri değerlendirilmiştir.

Deney programı kapsamında;

- Fiber mimarisi
- Katman dizilimi
- Yükleme hızı
- Batıcı uç geometrisi parametrelerinin yarı-statik batma davranışı üzerindeki etkileri araştırılmıştır.

Tablo 1. Numune Kodları ve Katman Dizilimler

Numune Kodu	**Katman Dizilimi**
PC8R	8 Kat Düz Karbon
TC8R	8 Kat Dimi Karbon
K8R	8 Kat Kevlar
K2PC6	2 Kat Kevlar + 6 Kat Düz Karbon
K2TC6	2 Kat Kevlar + 6 Kat Dimi Karbon
PC2K6	2 Kat Düz Karbon + 6 Kat Kevlar
TC2K6	2 Kat Dimi Karbon + 6 Kat Kevlar
KPC8R	4 Kat Kevlar + 4 Kat Düz Karbon
KTC8R	4 Kat Kevlar + 4 Kat Dimi Karbon
PCK8R	4 Kat Düz Karbon + 4 Kat Kevlar
TCK8R	4 Kat Dimi Karbon + 4 Kat Kevlar

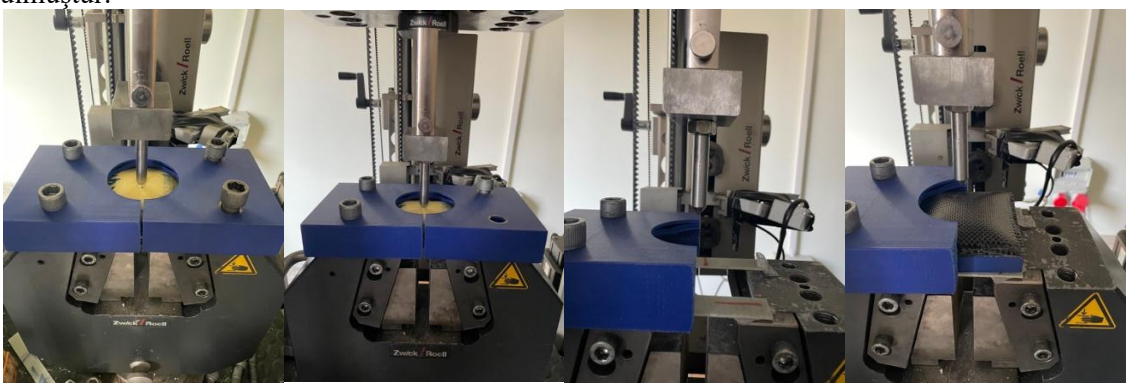
2.4 Yarı-Statik Batma Testleri

Yarı-statik batma deneyleri ASTM D6264/D6264M-12 standardına uygun olarak Zwick Roell Z250 üniversal test cihazında gerçekleştirilmiştir [11].

Deneylerde Ø12.7 mm çapında iki farklı batıcı uç kullanılmıştır:

- Yarı küresel uç
- Konik uç

Numuneler 1.25 mm/dk ve 100 mm/dk yükleme hızlarında test edilmiştir. Deneyler boyunca kuvvet-yer değiştirme verileri sürekli olarak kayıt altına alınmış ve her numune için maksimum kuvvet, deformasyon davranışı ve hasar gelişimi değerlendirilmiştir. Elde edilen kuvvet-yer değiştirme eğrileri kullanılarak monolitik ve hibrit kompozit yapıların mekanik performansları karşılaştırılmıştır.Yarı-statik batma testleri sonucunda elde edilen veriler doğrultusunda fiber mimarisi, katman dizilimi, yükleme hızı ve uç geometrisinin kompozit yapıların batma davranışı üzerindeki etkileri ayrıntılı olarak incelenmiştir. Deneylerde ASTM D6264/D6264M-12 standardına uygun olarak kullanılan Zwick Roell Z250 test sistemi, deney fikstürü ile yarı küresel ve konik batıcı uçlara ait görseller Şekil 1'de sunulmuştur.



Şekil 1. ASTM D6264/D6264M-12 standardına uygun yarı-statik batma deneylerinde kullanılan Zwick Roell Z250 test sistemi, deney fikstürü ile yarı küresel ve konik batıcı uçlara ait görüntüler.

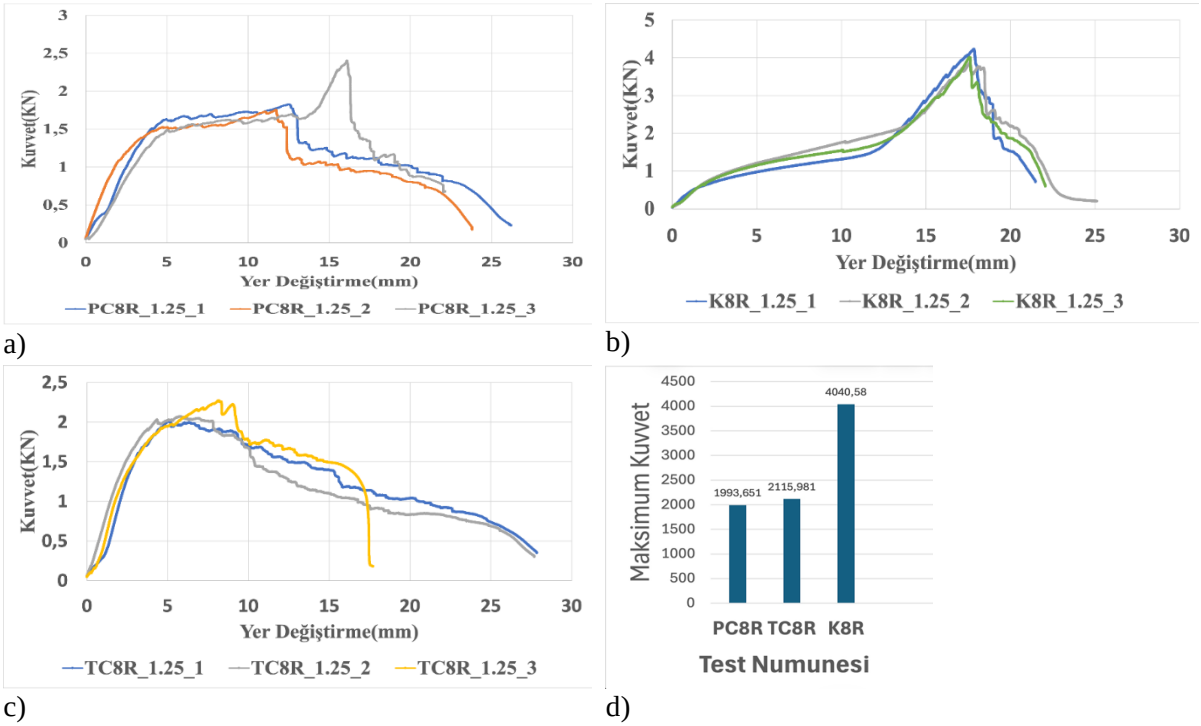
3. BULGULAR VE TARTIŞMA

3.1 Monolitik Kompozit Yapıların Yarı-Statik Batma Davranışı

Monolitik kompozit yapılara ait kuvvet-yer değiştirme eğrileri incelendiğinde fiber mimarisinin mekanik davranış üzerinde belirgin bir etkiye sahip olduğu görülmüştür (Şekil 2). Yarı küresel uç ve 1.25 mm/dk yükleme hızında gerçekleştirilen deneylerde Kevlar takviyeli K8R numunesi 4040.58 N maksimum kuvvet değeri ile en yüksek taşıma kapasitesini göstermiştir. Aynı koşullarda test edilen TC8R ve PC8R numuneleri sırasıyla 2115.98 N ve 1993.65 N maksimum kuvvet değerlerine ulaşmıştır (Şekil 2d).

Kevlar fiber takviyeli yapıların daha yüksek maksimum kuvvet göstermesi, aramid liflerin yüksek enerji absorpsiyon kapasitesi ve sünek deformasyon karakteristiği ile ilişkili olabilir (Şekil 2b). Pach ve ark. [14] aramid takviyeli hibrit kompozitlerde daha geniş deformasyon bölgeleri ve daha yüksek enerji absorpsiyonu gözlemlemiştir. Benzer şekilde Pach ve Pawłowska [15], Kevlar içeren kompozit yapılarda hasarın daha kontrollü ilerlediğini ve ani kırılmaların azaldığını bildirmiştir. Wang ve ark. [16] ise Kevlar katmanlarının yapının hasar toleransını artırdığını rapor etmiştir. Bu bulgular, mevcut çalışmada gözlenen sünek deformasyon davranışının literatürde bildirilen eğilimlerle uyumlu olduğunu göstermektedir.

Dimi karbon takviyeli TC8R numuneleri (Şekil 2c) düz karbon takviyeli PC8R numunelerine (Şekil 2a) göre daha yüksek maksimum kuvvet ve daha dengeli yük taşıma davranışı sergilemiştir. Fotouhi ve ark. [3], farklı fiber türlerinin (cam ve karbon fiber) kompozit laminatların maksimum yük taşıma kapasitesi ve hasar gelişimi üzerinde belirleyici olduğunu bildirmiştir. Hassan ve ark. [12] ise dokuma mimarisinin gerilme dağılımını değiştirerek hasar ilerlemesini etkilediğini göstermiştir. Bu durum, dimi dokuma mimarisinin sağladığı daha homojen yük transferi ile ilişkili olabilir.Monolitik yapıların kuvvet-yer değiştirme eğrileri genel olarak değerlendirildiğinde, Kevlar takviyeli yapıların daha yüksek deformasyon kapasitesine sahip olduğu, karbon fiber takviyeli yapıların ise daha rijit bir davranış sergilediği görülmüştür. Karbon fiberlerin yüksek elastik modülü nedeniyle başlangıç rijitliği artarken, Kevlar fiberlerin sünek yapısı hasarın ilerlemesini geciktirmiş ve daha yüksek enerji absorpsiyonu sağlamıştır [14,16,18]. Bu durum farklı mühendislik uygulamalarında kullanılacak kompozit yapıların tasarımında fiber seçiminin önemini ortaya koymaktadır.



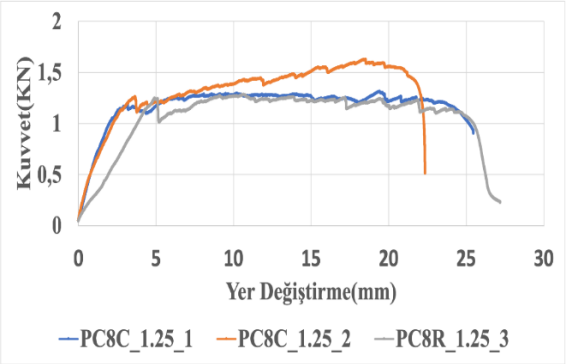
Şekil 2. Monolitik kompozit numunelere ait yarı-statik batma deneylerinden elde edilen kuvvet–yer değiştirme eğrileri (a, b, c) ve maksimum kuvvet değerlerinin karşılaştırılması (PC8R, TC8R ve K8R) (d).

3.2 Uç Geometrisinin Etkisi

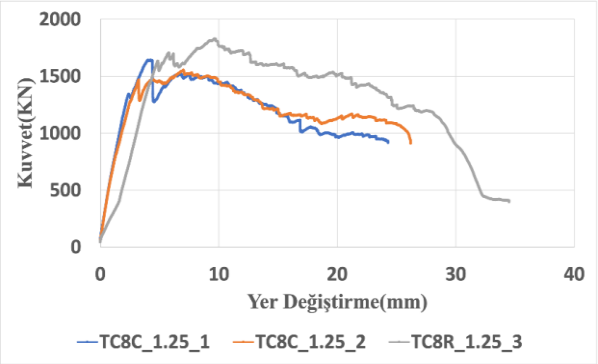
Batıcı uç geometrisinin kompozit yapıların yarı-statik batma davranışı üzerinde önemli bir etkiye sahip olduğu belirlenmiştir. Yarı küresel uç kullanılan numuneler ile konik uç kullanılan numuneler karşılaştırıldığında, konik uç geometrisinin daha küçük temas alanı oluşturduğu ve bu nedenle daha yüksek gerilme yoğunlaşmalarına neden olduğu görülmüştür.

Düz karbon takviyeli numunelerde PC8R (Şekil 2a) ve PC8C (Şekil 3a) sonuçları karşılaştırıldığında, konik uç kullanılan PC8C numunesinin daha düşük maksimum kuvvet değerleri sergilediği belirlenmiştir. Benzer durum dimi karbon takviyeli TC8R (Şekil 2c) ve TC8C (Şekil 3b) numunelerinde de gözlemlenmiştir. Konik uç altında hasar daha lokal bölgelerde oluşmuş ve ani kuvvet düşüşleri daha erken meydana gelmiştir.Çift kavisli monolitik numunelerde konik uç kullanımının maksimum kuvvet değerlerinde belirgin düşüşlere neden olduğu görülmüştür. Özellikle dimi karbon takviyeli numunelerde yarı küresel uca kıyasla yaklaşık %8.87, düz karbon takviyeli numunelerde ise yaklaşık %29.8 oranında azalma meydana gelmiştir. Bu durum konik ucun oluşturduğu yüksek gerilme yoğunlaşmaları ile açıklanabilir.Yarı küresel uç kullanılan numunelerde ise yük daha geniş bir alana yayıldığından hasar ilerlemesi daha kontrollü gerçekleşmiş ve numuneler daha yüksek deformasyon değerlerine ulaşabilmiştir. Bu durum kompozit yapıların daha kararlı bir kuvvet-yer değiştirme davranışı sergilemesine katkı sağlamıştır.

Elde edilen sonuçlar, uç geometrisinin kompozit laminatların penetrasyon direnci ve hasar mekanizmaları üzerinde belirleyici bir parametre olduğunu göstermektedir. Benzer eğilimler Sutherland ve Soares [10] tarafından yarı-statik testlerin düşük hızlı darbe davranışını temsil etmedeki etkinliği kapsamında, Djele ve Karakuzu [17] tarafından ise yarı-statik batma davranışına ilişkin deneysel çalışmalarda rapor edilmiştir.



a)



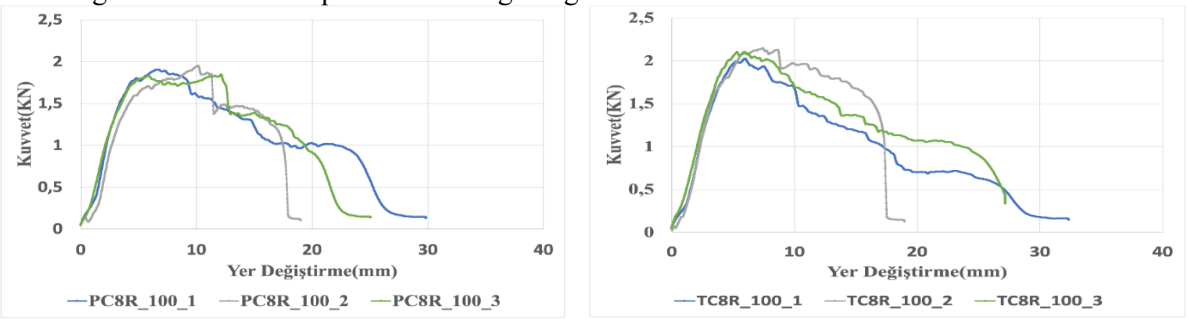
b)

Şekil 3. Konik (C) batıcı uç geometrisi ve 1.25 mm/dk test edilen PC8 (a) ve TC8 (b) monolitik kompozit numunelerine ait kuvvet–yer değiştirme eğrilerinin karşılaştırılması.

3.3 Yükleme Hızının Etkisi

Yükleme hızının kompozit yapıların mekanik davranışı üzerindeki etkisini incelemek amacıyla yarı küresel uç altında 1.25 mm/dk ve 100 mm/dk yükleme hızlarında deneyler gerçekleştirilmiştir. Elde edilen sonuçlar yükleme hızının artmasıyla birlikte maksimum kuvvet değerlerinde belirgin artış meydana geldiğini göstermiştir (Şekil 4). Düz karbon takviyeli PC8R ve dimi karbon takviyeli TC8R numunelerinde 100 mm/dk yükleme hızında elde edilen maksimum kuvvet değerleri, 1.25 mm/dk yükleme hızında elde edilen sonuçlardan daha yüksek bulunmuştur (Şekil 4a, b). Ayrıca yüksek hız altında gerçekleştirilen deneylerde kuvvet-yer değiştirme eğrilerinin daha dik bir karakter sergilediği ve yapıların deformasyona karşı daha rijit davrandığı gözlemlenmiştir. Dimi karbon takviyeli çift kavisli numunelerde yükleme hızının 1.25 mm/dk'dan 100 mm/dk'ya çıkarılması maksimum kuvvet değerinde yaklaşık %9.91 oranında artış sağlamıştır. Düz karbon takviyeli numunelerde ise bu artış yaklaşık %6.39 olarak belirlenmiştir. Sonuçlar, yükleme hızının artmasıyla birlikte kompozit yapıların daha yüksek direnç gösterdiğini ortaya koymaktadır. Bu durum polimer matris malzemesinin viskoelastik davranışı ile açıklanabilir [10,17]. Yükleme hızının artmasıyla birlikte matris deformasyon için daha kısa süreye sahip olmakta ve yapı genel olarak daha yüksek direnç göstermektedir. Sonuç olarak kompozit laminatlar daha yüksek maksimum kuvvet değerlerine ulaşabilmektedir. Literatürde Djele ve Karakuzu

[17] ile Wang ve ark. [16], yükleme hızındaki artışın kompozit yapıların mekanik davranışı üzerinde belirleyici olduğunu ve daha rijit bir tepki oluşmasına katkı sağladığını bildirmiştir. Mevcut çalışmada elde edilen bulgular da bu çalışmalarla genel olarak uyumluluk göstermektedir. Yükleme hızının etkisi genel olarak değerlendirildiğinde, yüksek hızlarda gerçekleştirilen testlerde yapıların daha yüksek yük taşıdığı ancak deformasyon kabiliyetlerinin kısmen azaldığı görülmüştür. Bu durum özellikle darbe dayanımı ve enerji absorpsiyonu açısından tasarlanacak kompozit yapılarda yükleme hızının dikkate alınması gereken önemli bir parametre olduğunu göstermektedir.



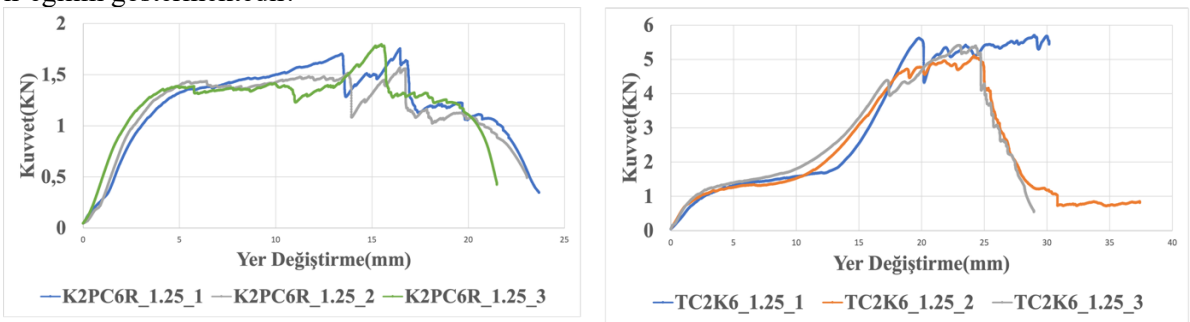
a) b)

Şekil 4. Yarı küresel (R) uc geometrisi ve 100 mm/dk hız ile test edilen PC8 (a) ve TC8 (b) monolitik kompozit numunelerine ait kuvvet–yer değiştirme eğrilerinin karşılaştırılması.

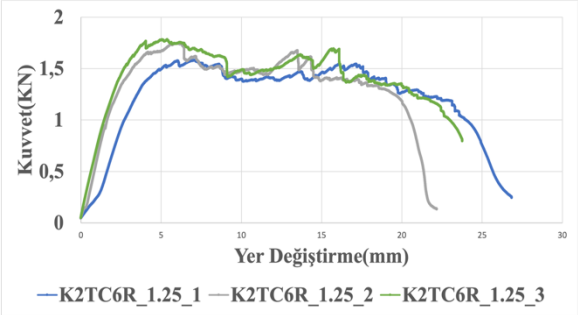
3.4 Hibrit Kompozit Yapıların Yarı-Statik Batma Davranışı

Hibrit kompozit yapılarda katman diziliminin mekanik performansı belirleyen en önemli parametrelerden biri olduğu görülmüştür. 2+6 katmanlı hibrit yapıların karşılaştırılmasında TC2K6 (Şekil 5b) numunesi 5407.04 N maksimum kuvvet değeri ile tüm hibrit numuneler arasında en yüksek performansı göstermiştir. Karbon fiberlerin dış yüzeyde bulunması yapının eğilme rijitliğini artırırken (Şekil 5b, d), Kevlar katmanları iç bölgede enerji absorpsiyonu sağlayarak hasarın ilerlemesini geciktirmiştir. Wang ve ark. [8] karbon/Kevlar hibrit laminatlarda karbon katmanlarının dış yüzeyde yer aldığı dizilimlerin daha yüksek maksimum yük taşıma kapasitesi sağladığını bildirmiştir. Andrew ve ark. [7] hibrit kompozitlerde katman konfigürasyonunun hasar gelişimi ve maksimum kuvvet üzerinde belirleyici olduğunu bildirmiştir. Bu nedenle TC2K6 numunesinin en yüksek performansı göstermesi yalnızca kullanılan fiber türleriyle değil, aynı zamanda katman yerleşimiyle de ilişkilidir.

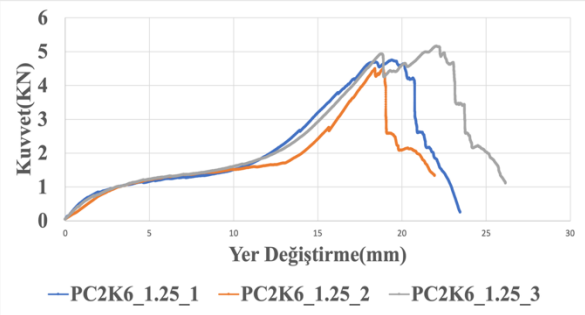
Kevlar katmanlarının dış yüzeyde bulunduğu K2PC6 ve K2TC6 numunelerinde (Şekil 5a, c) maksimum kuvvet değerlerinin daha düşük olduğu görülmüştür. Bulut ve ark. [6], Kevlar içeriğinin artmasının enerji absorpsiyon kapasitesini artırmasına rağmen yapısal rijitliği azaltabildiğini belirtmiştir. Sangilimuthukumar ve ark. [18] da Kevlar dış yüzeyli hibrit yapılarda daha yüksek deformasyon kapasitesi elde edildiğini rapor etmiştir. Mevcut çalışmada elde edilen sonuçlar da benzer bir eğilim göstermektedir.



a) b)

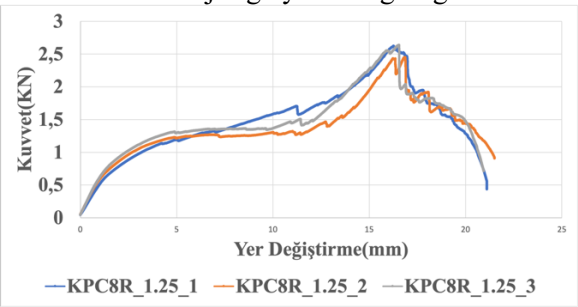


c)

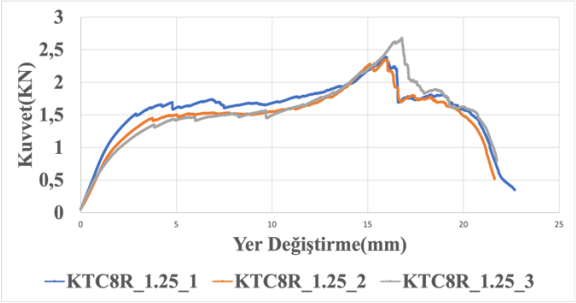


d)

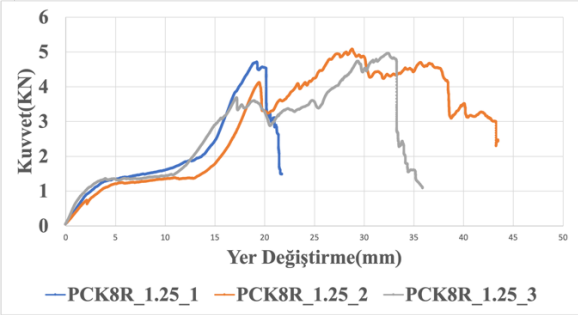
Şekil 5. 1.25 mm/dk yükleme hızında test edilen 2+6 katman dizilimine sahip hibrit kompozit numunelerin (K2PC6R (a), TC2K6 (b), K2TC6R (c) ve PC2K6 (d)) kuvvet–yer değiştirme eğrileri. 4+4 katmanlı hibrit yapılar incelendiğinde karbon fiberlerin dış yüzeyde yer aldığı dizilimlerin daha yüksek maksimum kuvvet değerleri sergilediği belirlenmiştir (Şekil 6). Özellikle PCK8R (Şekil 6c) ve TCK8R (Şekil 6d) numuneleri, Kevlar'ın dış yüzeyde bulunduğu hibrit konfigürasyonlara göre daha yüksek taşıma kapasitesi göstermiştir (Şekil 6a, b). Karbon fiberlerin yüksek elastik modülü ve rijitlik özellikleri, yüzey tabakalarında oluşan gerilmelerin daha etkin şekilde taşınmasına katkı sağlamıştır. Buna karşılık Kevlar fiberlerin dış yüzeyde bulunduğu hibrit yapıların daha yüksek deformasyon kapasitesi ve hasar toleransı sergilediği belirlenmiştir. Kevlar liflerin sünek yapısı sayesinde çatlak ilerlemesinin yavaşladığı ve hasarın daha geniş bölgelere yayıldığı gözlemlenmiştir. Bu durum özellikle darbe dayanımı ve enerji absorpsiyonunun ön planda olduğu uygulamalarda Kevlar dış yüzeyli dizilimlerin avantaj sağlayabileceğini göstermektedir.



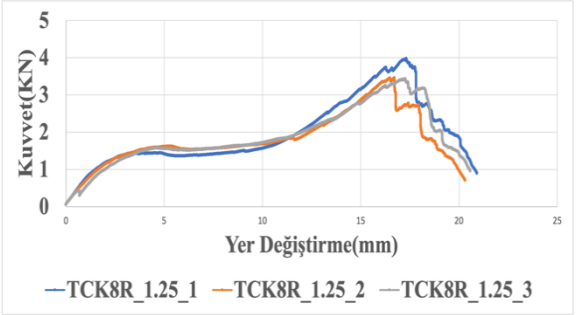
a)



b)



c)



d)

Şekil 6. 1.25 mm/dk yükleme hızında yarı küresel batıcı uç kullanılarak test edilen 4+4 katman dizilimine sahip hibrit kompozit numunelerin (KPC8R (a), KTC8R (b), PCK8R (c) ve TCK8R (d)) kuvvet–yer değiştirme eğrilerinin karşılaştırılması. Monolitik ve hibrit yapıların genel karşılaştırılması yapıldığında hibrit kompozit yapıların daha yüksek mekanik performans sergilediği belirlenmiştir. Özellikle karbon ve Kevlar fiberlerin uygun katman dizilimiyle birlikte kullanılması hem yüksek taşıma kapasitesinin hem de yüksek enerji absorpsiyonunun aynı yapı içerisinde elde edilmesine katkı sağlamıştır. Bu sonuçlar hibritleşme yaklaşımının kompozit yapı tasarımında etkili bir yöntem olduğunu ortaya koymaktadır. Genel olarak değerlendirildiğinde karbon fiberlerin dış yüzeyde kullanıldığı hibrit tasarımlar daha yüksek taşıma kapasitesi ve rijitlik sağlarken, Kevlar fiberlerin dış yüzeyde bulunduğu tasarımlar daha yüksek deformasyon kapasitesi ve hasar toleransı sunmuştur. Bu durum hibrit kompozit tasarımında katman diziliminin kritik bir parametre olduğunu göstermektedir.

4. SONUÇLAR

Bu çalışmada düz karbon/epoksi, dimi karbon/epoksi ve Kevlar/epoksi esaslı monolitik kompozit yapılar ile farklı katman dizilimlerine sahip hibrit çift kavisli kompozit yapıların yarı-statik batma davranışları deneysel olarak incelenmiştir. Fiber mimarisi, katman dizilimi, yükleme hızı ve batıcı uç geometrisinin mekanik davranış üzerindeki etkileri değerlendirilmiş ve aşağıdaki sonuçlara ulaşılmıştır:

• Kevlar liflerin yüksek enerji absorpsiyon kapasitesi ve sünek deformasyon davranışı bu performansın elde edilmesinde etkili olmuştur.

• Aramid kumaşlı monolitik ve hibrit örneklerin diğerlerinden daha kalın olduğu ölçülmüştür. Bu sonuçlar, eşdeğer sayıda katmana sahip ancak daha yüksek kalınlığa sahip aramid yapıların, monolitik karbon yapılara kıyasla üstün temas kuvveti ve enerji emilimi sergilemiştir.

• Dimi karbon takviyeli TC8R numunesi, düz karbon takviyeli PC8R numunesine göre daha yüksek maksimum kuvvet ve daha dengeli kuvvet-yer değiştirme davranışı sergilemiştir. Bu durum dimi dokuma yapısının daha homojen yük transferi sağlamasıyla ilişkilendirilmiştir.

• Konik uç kullanılan testlerde temas alanının azalmasına bağlı olarak gerilme yoğunlaşmaları artmış ve hasar daha lokal bölgelerde meydana gelmiştir.

• Yarı küresel uç kullanılan deneylerde yükün daha geniş bir alana yayılması nedeniyle deformasyon davranışının daha kararlı ilerlediği ve daha yüksek taşıma kapasitesi elde edildiği belirlenmiştir.

• Hibrit kompozit yapılar içerisinde karbon fiberlerin dış yüzeyde yer alması yapısal rijitliği artırırken, Kevlar katmanlarının iç bölgede bulunması enerji absorpsiyon kapasitesine olumlu katkı sağlamıştır.

• Karbon fiberlerin dış yüzeyde konumlandırıldığı hibrit yapılarda maksimum kuvvet değerlerinin arttığı, Kevlar fiberlerin dış yüzeyde bulunduğu yapılarda ise daha yüksek deformasyon kapasitesi ve hasar toleransı elde edildiği belirlenmiştir.

• Monolitik ve hibrit yapıların karşılaştırılması sonucunda hibrit yapıların daha yüksek mekanik performans sunduğu görülmüştür. Karbon ve Kevlar fiberlerin uygun dizilimlerle bir arada kullanılması, yüksek taşıma kapasitesi ile enerji absorpsiyonunun aynı yapı içerisinde elde edilmesine olanak sağlamıştır.

• Elde edilen sonuçlar, yalnızca kullanılan fiber türünün değil, fiberlerin yapı içerisindeki yerleşim sırasının da yarı-statik batma davranışı üzerinde belirleyici bir parametre olduğunu göstermiştir.

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EĞİTİM 4.0 MODELİNİN LİSANS DÜZEYİNDE UYGULAMA OLANAKLARI

OPPORTUNITIES FOR IMPLEMENTING EDUCATION 4.0 MODEL AT THE UNDERGRADUATE LEVEL

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ÖZET

Modern bilgi toplumunda dijital teknolojilerin hızlı gelişimi, işgücü piyasasının değişen talepleri ve yenilikçi düşünme ihtiyacı, yükseköğretim kurumlarında yeni öğretim yaklaşımlarının oluşturulmasını zorunlu kılmıştır. Bu bağlamda, Eğitim 4.0 modeli, geleneksel eğitim sisteminden farklı olarak, öğrenci odaklı, esnek, yenilikçi ve teknoloji tabanlı bir eğitim ortamının oluşturulmasını öngörmektedir. Makale, dijitalleşme, kişiselleştirilmiş eğitim, yapay zeka teknolojilerinin uygulanması, sanal ve etkileşimli öğrenme ortamları, proje tabanlı ve problem tabanlı öğrenme yaklaşımları ve işgücü piyasasıyla entegrasyon da dahil olmak üzere Eğitim 4.0 modelinin temel özelliklerini incelemektedir. Aynı zamanda, bu modelin lisans eğitiminde öğrencilerin yaratıcı düşünme, eleştirel analiz, işbirliği ve dijital yetkinliklerinin geliştirilmesindeki önemi de vurgulanmaktadır. Çalışma, yükseköğretim kurumlarında dijital platformların kullanımının genişletilmesi, esnek müfredatların geliştirilmesi, bireysel öğrenme yörüngelerinin düzenlenmesi ve öğretmenin işlevsel rolünün dönüştürülmesi konularını analiz etmektedir. Makale ayrıca, Eğitim 4.0 modelinin uygulanması sürecinde karşılaşılan başlıca sorunları da incelemektedir: teknolojik altyapının yetersizliği, dijital becerilerin eşit olmayan düzeyi, öğretmenlerin yeni öğretim yöntemlerine uyum sağlama zorlukları ve eğitim kaynaklarına erişimle ilgili sorunlar. Araştırma sonuçları, Eğitim 4.0 modelinin lisans düzeyinde amaçlı ve sistematik bir şekilde uygulanmasının, yükseköğretimin kalitesinin iyileştirilmesine, öğrencilerin pratik becerilerinin geliştirilmesine ve modern iş piyasasının gereksinimlerine uygun yetkinlikler kazanmalarına önemli ölçüde katkıda bulunabileceğini göstermektedir. Makalede ortaya konan teorik yaklaşımlar ve pratik öneriler, yükseköğretim kurumlarında yenilikçi bir eğitim ortamının oluşturulması açısından önem taşımaktadır

Anahtar kelimeler: Eğitim 4.0, yükseköğretim, lisans düzeyi, dijital teknolojiler, yenilikçi öğrenme, yapay zeka

ABSTRACT

The rapid development of digital technologies in the modern information society, the changing demands of the labor market and the need for innovative thinking have necessitated the formation of new teaching approaches in higher education institutions. In this regard, the Education 4.0 model, unlike the traditional training system, envisages the creation of a student-oriented, flexible, innovative and technology-based educational environment. The article examines the main features of the Education 4.0 model, including digitalization, personalized education, the application of artificial intelligence technologies, virtual and interactive learning environments, project-based and problem-based learning approaches, as well as integration with the labor market. At the same time, the importance of this model in developing students' creative thinking, critical analysis, collaboration and digital competencies in undergraduate education is substantiated.

The study analyzes the issues of expanding the use of digital platforms in higher education institutions, developing flexible curricula, organizing individual learning trajectories and transforming the functional role of the teacher. The article also examines the main problems encountered in the process of implementing the Education 4.0 model - the inadequacy of technological infrastructure, the uneven level of digital skills, the difficulties of teachers in adapting to new teaching methods, and issues related to access to educational resources. The research results show that the purposeful and systematic implementation of the Education 4.0 model at the undergraduate level can significantly contribute to improving the quality of higher education, developing students' practical skills, and helping them acquire competencies in line with the requirements of the modern labor market.

The theoretical approaches and practical proposals put forward in the article are considered important in terms of forming an innovative educational environment in higher education institutions.
Keywords: Education 4.0, higher education, undergraduate education, digital technologies, innovative learning, artificial intelligence

GİRİŞ

Bilgi ve iletişim teknolojilerinde yaşanan hızlı gelişmeler, toplumsal yaşamın bütün alanlarında olduğu gibi eğitim sistemlerinde de köklü değişimlerin meydana gelmesine neden olmuştur. Özellikle dijitalleşme sürecinin hız kazanması, yapay zekâ teknolojilerinin yaygınlaşması ve bilgiye erişim olanaklarının artması, geleneksel eğitim anlayışının yeniden değerlendirilmesini zorunlu hale getirmiştir. Endüstri 4.0 olarak adlandırılan yeni sanayi dönüşümü yalnızca üretim süreçlerini değil, aynı zamanda bireylerden beklenen bilgi, beceri ve yeterlilikleri de önemli ölçüde değiştirmiştir. Bu değişim doğrultusunda yükseköğretim kurumlarının çağın gerekliliklerine uygun bireyler yetiştirebilmesi için eğitim süreçlerinde yenilikçi yaklaşımların uygulanması önem kazanmıştır. Schwab'a (2017) göre Endüstri 4.0 süreci yalnızca sanayi alanında değil, eğitim sistemlerinde de köklü dönüşümlerin meydana gelmesine neden olmuştur. Araştırmacı, dijitalleşme sürecinin bireylerden beklenen bilgi ve becerileri değiştirdiğini ve eğitim kurumlarının bu değişime uyum sağlamasının kaçınılmaz olduğunu vurgulamaktadır. Hussin (2018), Eğitim 4.0 yaklaşımının temel amacının öğrencileri geleceğin mesleklerine hazırlamak olduğunu belirtmiş ve bu süreçte yaratıcılık, problem çözme ve dijital okuryazarlık becerilerinin ön plana çıktığını ifade etmiştir.

Bu bağlamda ortaya çıkan Eğitim 4.0 modeli, teknolojik gelişmelerin eğitim süreçlerine entegrasyonunu temel alan çağdaş bir eğitim anlayışı olarak değerlendirilmektedir. Eğitim 4.0 yaklaşımı; öğrenci merkezli öğrenme ortamlarının oluşturulması, bireyselleştirilmiş eğitim süreçlerinin desteklenmesi, dijital öğrenme araçlarının etkin kullanımı ve yaşam boyu öğrenme kültürünün geliştirilmesi gibi temel ilkelere dayanmaktadır. Geleneksel eğitim sistemlerinde bilgi aktarımı ağırlıklı bir yaklaşım benimsenirken, Eğitim 4.0 modelinde öğrencilerin aktif katılımı, araştırma yapma becerileri ve uygulamaya dönük öğrenme deneyimleri vurgulanmaktadır (Zawacki-Richter, Marín, Bond, Gouverneur, 2019).

Günümüzde yükseköğretim kurumları yalnızca teorik bilgi sunan yapılar olmaktan çıkmış, aynı zamanda öğrencilerin problem çözme, eleştirel düşünme, iletişim kurma, takım çalışması yapma ve dijital teknolojileri etkin kullanma becerilerini geliştiren merkezler haline gelmiştir. Bu nedenle lisans düzeyindeki eğitim programlarının çağdaş iş gücü piyasasının ihtiyaçları doğrultusunda yeniden yapılandırılması önemli bir gereklilik olarak ortaya çıkmaktadır. Eğitim 4.0 modeli, öğrencilerin yalnızca akademik başarı elde etmelerini değil, aynı zamanda yenilikçi düşünme yeteneğine sahip, üretken ve değişime uyum sağlayabilen bireyler olarak yetişmelerini hedeflemektedir.

Eğitim 4.0 yaklaşımında öğretmenin rolü de önemli ölçüde değişmiştir. Geleneksel eğitim anlayışında öğretmen bilginin temel kaynağı olarak kabul edilirken, modern eğitim ortamlarında öğretmen daha çok rehberlik eden, öğrenme sürecini organize eden ve öğrencilerin bireysel öğrenme ihtiyaçlarını destekleyen bir konuma sahiptir. Bu durum, öğretim elemanlarının dijital pedagojik yeterliliklerinin geliştirilmesini ve yeni teknolojilere uyum sağlayabilmelerini zorunlu hale getirmektedir. Aynı zamanda öğrencilerin bireysel farklılıklarının dikkate alınması, esnek öğrenme modellerinin uygulanması ve teknolojik araçların etkin biçimde kullanılması Eğitim 4.0 modelinin temel bileşenleri arasında yer almaktadır.

Lisans düzeyinde Eğitim 4.0 modelinin uygulanması, öğrencilerin akademik gelişimlerinin yanı sıra mesleki yeterliliklerinin artırılması açısından da önemli fırsatlar sunmaktadır. Dijital öğrenme platformları, sanal sınıf uygulamaları, yapay zekâ destekli eğitim sistemleri ve çevrim içi öğrenme ortamları sayesinde öğrenciler bilgiye daha hızlı erişebilmekte ve öğrenme süreçlerini bireysel ihtiyaçlarına göre şekillendirebilmektedirler. Ayrıca proje tabanlı öğrenme, problem tabanlı öğrenme ve iş birliğine dayalı öğrenme gibi çağdaş öğretim yöntemleri öğrencilerin uygulamalı beceriler kazanmalarına katkı sağlamaktadır (Zawacki-Richter, Marín, Bond, Gouverneur, 2019).

Bununla birlikte Eğitim 4.0 modelinin uygulanması sürecinde bazı önemli sorunlar da ortaya çıkmaktadır. Özellikle teknolojik altyapının yetersiz olması, dijital araçlara erişimde fırsat eşitsizliği yaşanması, öğretim elemanlarının teknoloji kullanımına ilişkin yeterlilik düzeylerinin farklılık göstermesi ve öğrencilerin dijital bağımlılık gibi sorunlarla karşı karşıya kalması bu sürecin temel

problemleri arasında yer almaktadır. Ayrıca dijital eğitim ortamlarında yüz yüze iletişimin azalması ve sosyal etkileşimin sınırlanması da tartışılan konular arasında bulunmaktadır.
Bu çalışmanın temel amacı, Eğitim 4.0 modelinin kavramsal çerçevesini incelemek ve söz konusu modelin lisans düzeyinde uygulanma perspektiflerini değerlendirmektir. Araştırmada Eğitim 4.0 yaklaşımının yükseköğretim kurumlarına sağlayabileceği katkılar, öğrencilerin akademik ve mesleki gelişimlerine etkileri ile uygulama sürecinde karşılaşılan sorunlar ele alınmıştır. Aynı zamanda yükseköğretimde dijital dönüşüm sürecinin daha etkili biçimde gerçekleştirilebilmesi için gerekli olan pedagojik, teknolojik ve yönetsel düzenlemeler üzerinde durulmuştur.

YÖNTEM

Evren ve Örneklem

Bu araştırma, Eğitim 4.0 modelinin lisans düzeyinde uygulanmasına ilişkin görüşlerin ve mevcut uygulama süreçlerinin değerlendirilmesi amacıyla gerçekleştirilmiştir. Araştırmanın evrenini, yükseköğretim kurumlarında öğrenim gören lisans öğrencileri ile farklı fakültelerde görev yapan öğretim elemanları oluşturmaktadır. Çalışmada özellikle dijital teknolojilerin eğitim süreçlerine entegrasyonu, öğrenci merkezli öğretim uygulamaları ve yapay zekâ destekli eğitim sistemlerine ilişkin görüşlerin belirlenmesine odaklanılmıştır.
Bates'e (2019) göre dijital eğitim araştırmalarında karma yöntem yaklaşımının kullanılması, eğitim süreçlerinin hem nicel hem de nitel boyutlarının daha kapsamlı biçimde değerlendirilmesine olanak sağlamaktadır. Bu nedenle araştırmada nicel ve nitel veri toplama tekniklerinden birlikte yararlanılmıştır. Araştırmanın örneklemini ise amaçlı örnekleme yöntemiyle seçilmiş farklı bölümlerde öğrenim gören lisans öğrencileri ile öğretim elemanları oluşturmaktadır. Örneklem grubunun belirlenmesinde katılımcıların dijital eğitim uygulamalarına ilişkin deneyime sahip olmaları dikkate alınmıştır. Bu doğrultuda araştırmaya farklı akademik alanlardan öğrenciler ve öğretim elemanları dâhil edilerek konuya ilişkin daha kapsamlı verilerin elde edilmesi amaçlanmıştır.
Araştırmada örneklem grubunun çeşitlendirilmesi sayesinde Eğitim 4.0 modeline ilişkin farklı bakış açılarının ortaya konulması hedeflenmiştir. Katılımcıların gönüllülük esasına göre araştırmaya dâhil edilmeleri sağlanmış ve araştırma sürecinde etik ilkelere uygun hareket edilmiştir. Elde edilen verilerin yalnızca bilimsel amaçlarla kullanılacağı katılımcılara bildirilmiş, kişisel bilgilerin gizliliği korunmuştur.
Araştırmanın örneklem grubunu, farklı fakültelerde öğrenim gören toplam 120 lisans öğrencisi ile 25 öğretim elemanı oluşturmaktadır. Katılımcılar amaçlı örnekleme yöntemi doğrultusunda seçilmiş ve araştırmaya gönüllülük esasına göre dâhil edilmiştir. Araştırmaya katılan öğrencilerin yaş aralığı 18-22 arasında değişmekte olup katılımcılar farklı sınıf düzeylerinden seçilmiştir. Öğretim elemanları ise çeşitli akademik alanlarda görev yapan ve dijital eğitim uygulamalarına ilişkin deneyime sahip bireylerden oluşmaktadır. Araştırma, Azerbaycan'daki üç farklı yükseköğretim kurumunda gerçekleştirilmiş ve böylece Eğitim 4.0 modeline ilişkin farklı kurumsal bakış açılarının değerlendirilmesi amaçlanmıştır.
Araştırmada elde edilen nicel verilerin analizinde SPSS 26.0 programından yararlanılmıştır. Katılımcıların görüşlerinin değerlendirilmesinde frekans, yüzde, aritmetik ortalama ve standart sapma gibi betimsel istatistik yöntemleri kullanılmıştır. Ayrıca değişkenler arasındaki ilişkilerin belirlenmesi amacıyla korelasyon analizi uygulanmıştır. Araştırmanın nitel boyutunda elde edilen görüşme verileri ise içerik analizi yöntemiyle değerlendirilmiştir. Görüşme kayıtları tematik biçimde sınıflandırılmış, benzer ifadeler ortak kategoriler altında birleştirilmiş ve katılımcı görüşlerinden doğrudan alıntılar yapılarak bulgular desteklenmiştir.
Araştırmanın geçerlilik ve güvenilirliğini sağlamak amacıyla veri toplama araçları uzman görüşü doğrultusunda yeniden gözden geçirilmiş ve ön uygulama gerçekleştirilmiştir. Anket formunun güvenirlik düzeyi Cronbach Alpha katsayısı ile değerlendirilmiş ve ölçeğin yüksek düzeyde güvenilir olduğu belirlenmiştir (α=0.89). Nitel verilerin güvenilirliğini artırmak amacıyla ise uzman incelemesi ve katılımcı doğrulaması yöntemlerinden yararlanılmıştır.

Veri Toplama Araçları

Araştırmada verilerin elde edilmesi amacıyla nitel ve nicel veri toplama tekniklerinden yararlanılmıştır. Çalışmanın amacı doğrultusunda katılımcıların Eğitim 4.0 modeline ilişkin görüşlerini, dijital eğitim

uygulamalarına yönelik deneyimlerini ve teknoloji temelli öğretim süreçlerine ilişkin değerlendirmelerini belirlemek için anket ve yarı yapılandırılmış görüşme formları kullanılmıştır.
Araştırmanın nicel veri toplama aracı olarak hazırlanan anket formu, ilgili alan yazını incelenerek oluşturulmuştur. Anket maddeleri; dijital teknolojilerin eğitim süreçlerinde kullanımı, çevrim içi öğrenme ortamlarının etkililiği, yapay zekâ destekli uygulamalara yönelik görüşler, öğrenci merkezli öğrenme süreçleri ve Eğitim 4.0 modelinin uygulanmasına ilişkin değerlendirmeleri kapsayacak şekilde düzenlenmiştir. Katılımcıların görüşlerini daha nesnel biçimde ifade edebilmeleri amacıyla beşli Likert tipi derecelendirme ölçeğinden yararlanılmıştır.
Araştırmanın nitel boyutunda ise yarı yapılandırılmış görüşme formu kullanılmıştır. Görüşme soruları hazırlanırken katılımcıların Eğitim 4.0 modeline ilişkin düşüncelerini ayrıntılı biçimde ifade edebilmelerine olanak sağlayacak açık uçlu sorulara yer verilmiştir. Bu kapsamda öğretim elemanları ve öğrencilerle gerçekleştirilen görüşmeler aracılığıyla dijital eğitim süreçlerinin avantajları, karşılaşılan sorunlar, teknolojik altyapının yeterliliği ve öğretim yöntemlerine ilişkin değerlendirmeler elde edilmiştir.
Veri toplama araçlarının hazırlanması sürecinde alan uzmanlarının görüşlerine başvurulmuş ve kapsam geçerliliğinin sağlanmasına dikkat edilmiştir. Ayrıca veri toplama araçlarının anlaşılabilirliğini belirlemek amacıyla ön uygulama gerçekleştirilmiş, gerekli görülen düzenlemeler yapıldıktan sonra araştırmada kullanılmasına karar verilmiştir.
Araştırma sürecinde elde edilen veriler bilimsel etik ilkeleri doğrultusunda toplanmış, katılımcıların kimlik bilgileri gizli tutulmuş ve verilerin yalnızca akademik amaçlarla kullanılacağı belirtilmiştir.

Bağımlı Değişken
Bu araştırmada bağımlı değişken, lisans düzeyinde Eğitim 4.0 modelinin uygulanmasına ilişkin eğitimsel çıktıların ve öğrenci yeterliliklerinin düzeyidir. Araştırma kapsamında özellikle öğrencilerin dijital yetkinlikleri, öğrenme motivasyonları, teknoloji destekli öğrenme süreçlerine uyum düzeyleri, eleştirel düşünme becerileri, problem çözme yeterlilikleri ve akademik performansları bağımlı değişkenler çerçevesinde değerlendirilmiştir.
Araştırmada Eğitim 4.0 modeline dayalı öğretim uygulamalarının öğrenciler üzerindeki etkisinin belirlenmesi amaçlanmıştır. Bu doğrultuda dijital öğrenme ortamlarının kullanımı, yapay zekâ destekli öğretim uygulamaları, proje tabanlı öğrenme yöntemleri ve çevrim içi eğitim süreçlerinin öğrencilerin akademik ve bireysel gelişimlerine olan katkısı incelenmiştir. Öğrencilerin öğrenme süreçlerine aktif katılım düzeyleri, teknoloji kullanım becerileri ve yenilikçi öğrenme ortamlarına uyumları araştırmanın temel bağımlı değişkenleri arasında yer almıştır.
Bunun yanı sıra araştırmada öğretim elemanlarının Eğitim 4.0 modeline ilişkin görüşleri ve dijital pedagojik yeterlilikleri doğrultusunda öğrencilerin öğrenme süreçlerinde meydana gelen değişimler de değerlendirilmiştir. Böylece teknoloji temelli öğretim uygulamalarının lisans düzeyindeki eğitim süreçleri üzerindeki etkilerinin çok yönlü biçimde analiz edilmesi amaçlanmıştır.

Bağımsız Değişkenler
Bu araştırmada bağımsız değişkenler, Eğitim 4.0 modelinin lisans düzeyinde uygulanmasını etkileyen pedagojik, teknolojik ve bireysel faktörlerden oluşmaktadır. Araştırma kapsamında öğrencilerin dijital öğrenme süreçlerine uyumunu, akademik performansını ve teknoloji temelli eğitim uygulamalarına yönelik tutumlarını etkileyen çeşitli değişkenler incelenmiştir.
Araştırmanın temel bağımsız değişkenleri arasında dijital teknolojilerin kullanım düzeyi, çevrim içi öğrenme ortamlarının etkinliği, yapay zekâ destekli öğretim uygulamalarının kullanımı, proje tabanlı öğrenme yöntemleri ve öğrenci merkezli öğretim yaklaşımları yer almaktadır. Bunun yanı sıra öğretim elemanlarının dijital pedagojik yeterlilikleri, teknolojik altyapının yeterlilik düzeyi ve eğitim kurumlarının dijital dönüşüm süreçlerine uyum kapasitesi de araştırmada bağımsız değişkenler olarak değerlendirilmiştir. Araştırmada ayrıca öğrencilerin teknoloji kullanım becerileri, dijital okuryazarlık düzeyleri, çevrim içi eğitim deneyimleri ve bireysel öğrenme özellikleri de bağımsız değişkenler kapsamında ele alınmıştır. Bu değişkenlerin öğrencilerin öğrenme motivasyonu, akademik başarı düzeyi ve Eğitim 4.0 uygulamalarına yönelik tutumları üzerindeki etkisi incelenmiştir.
Bununla birlikte yaş, bölüm, sınıf düzeyi ve teknolojiye erişim imkânları gibi demografik değişkenler de araştırma kapsamında değerlendirilmiş ve Eğitim 4.0 modelinin uygulanma sürecine olan etkileri

analiz edilmiştir. Böylece araştırmada, teknoloji temelli eğitim uygulamalarının yükseköğretimdeki etkilerini çok yönlü biçimde incelemek amaçlanmıştır.

Veri Toplama Araçlarının Uygulanması

Araştırma kapsamında kullanılan veri toplama araçlarının uygulanması belirli bir plan doğrultusunda gerçekleştirilmiştir. Çalışmada nicel verilerin elde edilmesi amacıyla hazırlanan anket formu ile nitel verilerin toplanmasına yönelik yarı yapılandırılmış görüşme formu katılımcılara uygulanmıştır. Veri toplama sürecinde araştırmanın amacı, kapsamı ve uygulanma biçimi katılımcılara ayrıntılı şekilde açıklanmış, araştırmaya katılımın gönüllülük esasına dayandığı belirtilmiştir.

Anket uygulamaları, lisans düzeyinde öğrenim gören öğrenciler ve yükseköğretim kurumlarında görev yapan öğretim elemanları üzerinde gerçekleştirilmiştir. Katılımcılara anket formları hem basılı hem de dijital ortam aracılığıyla ulaştırılmıştır. Özellikle çevrim içi veri toplama sürecinde dijital platformlardan yararlanılmış ve katılımcıların anket sorularını daha kolay yanıtlayabilmeleri sağlanmıştır. Katılımcılardan elde edilen verilerin güvenilirliği açısından anket sorularının eksiksiz ve doğru biçimde cevaplandırılmasına dikkat edilmiştir.

Araştırmanın nitel boyutunda kullanılan yarı yapılandırılmış görüşmeler ise önceden belirlenen görüşme soruları doğrultusunda gerçekleştirilmiştir. Görüşmeler sırasında katılımcıların Eğitim 4.0 modeline ilişkin düşüncelerini ayrıntılı biçimde ifade etmelerine imkân tanınmış ve gerektiğinde ek sorular yöneltilerek daha kapsamlı verilerin elde edilmesi amaçlanmıştır. Görüşmeler yüz yüze ve çevrim içi iletişim araçları üzerinden gerçekleştirilmiş, katılımcıların görüşleri araştırma amacı doğrultusunda kayıt altına alınmıştır.

Veri toplama sürecinde bilimsel araştırma ve etik kurallara uygun hareket edilmiştir. Katılımcıların kimlik bilgilerinin gizli tutulacağı belirtilmiş, elde edilen verilerin yalnızca akademik amaçlarla kullanılacağı konusunda gerekli bilgilendirme yapılmıştır. Ayrıca veri toplama araçlarının uygulanması sürecinde tarafsızlık ilkesine dikkat edilmiş ve katılımcıların görüşlerini özgür biçimde ifade etmelerine uygun ortam oluşturulmuştur.

Uygulama sürecinin sonunda elde edilen nicel ve nitel veriler sistemli biçimde düzenlenmiş, analiz edilmeye hazır hale getirilmiş ve araştırmanın amaçları doğrultusunda değerlendirilmiştir.

BULGULAR

Eğitim 4.0 modeli, dijital dönüşüm sürecinin eğitim alanındaki yansıması olarak ortaya çıkan ve teknolojik yeniliklerin öğretim süreçlerine sistemli biçimde entegrasyonunu esas alan çağdaş bir eğitim yaklaşımıdır. Bu model, yalnızca dijital araçların eğitim ortamlarında kullanılmasını değil, aynı zamanda öğretim anlayışının, öğrenme süreçlerinin ve eğitim kurumlarının işleyiş yapısının yeniden şekillendirilmesini de kapsamaktadır. Endüstri 4.0 süreciyle birlikte bilgi toplumunun gereksinimlerinin değişmesi, yükseköğretim kurumlarının da çağın ihtiyaçlarına uygun yeni öğretim stratejileri geliştirmesini zorunlu hale getirmiştir. Bu bağlamda Eğitim 4.0 yaklaşımı; bireyselleştirilmiş öğrenme, dijital okuryazarlık, yaşam boyu öğrenme, eleştirel düşünme, problem çözme, yaratıcılık, iletişim ve iş birliği becerilerinin geliştirilmesini temel hedefler arasında kabul etmektedir (Miranda, Navarrete, Noguez, Molina-Espinosa, Ramírez-Montoya, Navarro-Tuch, Molina, 2021).

Bonfield ve arkadaşları (2020), dijital öğrenme ortamlarının öğrencilerin öğrenme süreçlerine aktif katılımını artırdığını ve bireysel öğrenme deneyimlerini güçlendirdiğini belirtmektedir. Araştırma kapsamında elde edilen bulgular da bu görüşü desteklemektedir. Kivunja'ya (2019) göre Eğitim 4.0 yaklaşımında öğrencilerin yalnızca akademik bilgi edinmeleri yeterli görülmemekte, aynı zamanda onların eleştirel düşünme, iletişim kurma ve iş birliği becerilerinin geliştirilmesi hedeflenmektedir. Selwyn (2022), dijital eğitim ortamlarının sunduğu avantajların yanında sosyal etkileşimin azalması ve dijital bağımlılık gibi riskleri de beraberinde getirdiğini vurgulamaktadır. Araştırma bulguları da bu görüşle paralellik göstermektedir.

Araştırma kapsamında Eğitim 4.0 modelinin lisans düzeyinde uygulanmasına ilişkin temel boyutlar incelenmiş ve bu yaklaşımın yükseköğretim süreçlerine etkileri değerlendirilmiştir. Elde edilen bulgular, dijital teknolojilerin eğitim ortamlarında kullanılmasının öğrenme süreçlerini daha esnek, erişilebilir ve öğrenci merkezli hale getirdiğini göstermektedir. Özellikle çevrim içi öğrenme platformları, dijital kütüphaneler, sanal sınıf uygulamaları ve mobil öğrenme araçları sayesinde öğrencilerin bilgiye erişim imkânlarının önemli ölçüde arttığı belirlenmiştir. Öğrenciler, zaman ve

mekân sınırlaması olmaksızın ders materyallerine ulaşabilmekte, öğrenme süreçlerini kendi ihtiyaç ve öğrenme hızlarına göre planlayabilmekte ve bireysel öğrenme deneyimleri geliştirebilmektedirler. Bu durum, geleneksel öğretim anlayışından farklı olarak öğrenci merkezli eğitim yaklaşımının güçlenmesine katkı sağlamaktadır.

Araştırma sonuçları, dijital eğitim ortamlarının öğrencilerin öğrenme motivasyonu üzerinde olumlu etkiler oluşturduğunu da ortaya koymaktadır. Özellikle etkileşimli içerikler, simülasyon uygulamaları, dijital değerlendirme araçları ve çoklu ortam materyalleri öğrencilerin ders süreçlerine daha aktif katılım göstermelerine katkı sağlamaktadır. Görsel ve işitsel materyallerle desteklenen öğretim uygulamaları öğrencilerin dikkat düzeylerini artırmakta ve öğrenmenin kalıcılığını güçlendirmektedir. Bunun yanı sıra çevrim içi eğitim ortamları öğrencilerin bağımsız öğrenme becerilerinin gelişmesine ve araştırma odaklı düşünme alışkanlığı kazanmalarına katkı sağlamaktadır.Araştırmada incelenen temel konulardan biri de yapay zekâ teknolojilerinin eğitim süreçlerine entegrasyonudur. Günümüzde yapay zekâ destekli öğretim sistemleri öğrencilerin bireysel öğrenme performanslarını analiz ederek onların ihtiyaçlarına uygun içerikler sunabilmektedir. Bu sistemler, öğrencilerin eksik oldukları alanları belirleyebilmekte, kişiselleştirilmiş geri bildirimler sağlayabilmekte ve öğrenme süreçlerini daha verimli hale getirebilmektedir. Özellikle otomatik ölçme ve değerlendirme sistemleri, veri analitiği uygulamaları ve akıllı öğrenme platformları öğretim süreçlerinin daha sistemli biçimde yönetilmesine imkân tanımaktadır. Yapay zekâ teknolojilerinin eğitim ortamlarında kullanılması aynı zamanda öğretim elemanlarının öğrencilerin akademik gelişimlerini daha yakından takip etmelerine ve öğrenme sürecine ilişkin daha etkili kararlar almalarına katkı sağlamaktadır.Araştırma bulguları, proje tabanlı öğrenme ve problem tabanlı öğrenme yöntemlerinin Eğitim 4.0 modelinin önemli bileşenleri arasında yer aldığını göstermektedir. Bu öğretim yöntemleri öğrencilerin yalnızca teorik bilgi edinmelerini değil, aynı zamanda edindikleri bilgileri uygulamaya dönüştürmelerini de teşvik etmektedir. Özellikle gerçek yaşam problemleri üzerinden gerçekleştirilen uygulamalar öğrencilerin analitik düşünme ve problem çözme becerilerinin gelişmesine katkı sağlamaktadır. Takım çalışmasına dayalı öğrenme süreçleri ise öğrencilerin iletişim kurma, iş birliği yapma, liderlik ve sosyal etkileşim becerilerini geliştirmektedir. Bunun yanı sıra proje tabanlı çalışmalar öğrencilerin araştırma yapma, bilgi üretme ve yenilikçi düşünme yetkinliklerini artırmaktadır.

Araştırmada esnek müfredat anlayışının Eğitim 4.0 modelindeki önemi de değerlendirilmiştir. Geleneksel eğitim sistemlerinde standart ve değişmez müfredat yapıları ön planda tutulurken, Eğitim 4.0 yaklaşımında öğrencilerin bireysel ilgi alanları, kariyer hedefleri ve öğrenme ihtiyaçları dikkate alınmaktadır. Bu doğrultuda seçmeli derslerin artırılması, disiplinler arası eğitim anlayışının yaygınlaştırılması ve uygulamalı eğitim etkinliklerinin güçlendirilmesi önerilmektedir (Miranda, Navarrete, Noguez, Molina-Espinosa, Ramírez-Montoya, Navarro-Tuch, Molina, 2021). Özellikle farklı disiplinlerin bir araya getirildiği eğitim programlarının öğrencilerin çok yönlü düşünme becerilerini geliştirdiği ve iş gücü piyasasının beklentilerine daha uygun bireylerin yetiştirilmesine katkı sağladığı düşünülmektedir.

Araştırma sürecinde Eğitim 4.0 modelinin uygulanmasına ilişkin çeşitli sorunlar da belirlenmiştir. Özellikle bazı yükseköğretim kurumlarında teknolojik altyapının yeterli düzeyde olmaması dijital eğitim süreçlerinin etkin biçimde uygulanmasını zorlaştırmaktadır. İnternet erişimi, teknik donanım eksiklikleri ve dijital araçların maliyetleri eğitimde fırsat eşitsizliğine neden olabilmektedir. Bunun yanı sıra öğretim elemanlarının dijital pedagojik yeterlilik düzeylerinin farklılık göstermesi ve yeni öğretim yöntemlerine uyum sağlama konusunda yaşanan güçlükler de dikkat çeken sorunlar arasında yer almaktadır. Bazı öğretim elemanlarının geleneksel öğretim yöntemlerini tercih etmeleri, dijital dönüşüm sürecinin yavaş ilerlemesine neden olabilmektedir.

Araştırmada dikkat çeken bir diğer bulgu ise dijital eğitim ortamlarının öğrenciler üzerindeki Genel olarak değerlendirildiğinde araştırma bulguları, Eğitim 4.0 modelinin lisans düzeyinde Uygulanmasının yükseköğretim kurumlarında eğitim kalitesinin artırılmasına önemli katkılar sağlayabileceğini göstermektedir. Dijital teknolojilerin öğretim süreçlerine entegrasyonu öğrencilerin akademik başarılarının artırılmasına, uygulamalı beceriler kazanmalarına ve çağdaş iş gücü piyasasının gerektirdiği yetkinlikleri geliştirmelerine katkı sağlamaktadır. Ancak bu sürecin başarılı şekilde yürütülebilmesi için yükseköğretim kurumlarının teknolojik altyapılarının güçlendirilmesi, öğretim elemanlarının dijital yeterliliklerinin geliştirilmesi, öğrencilere eşit öğrenme fırsatlarının sunulması ve yenilikçi öğretim yöntemlerinin sistemli biçimde uygulanması büyük önem taşımaktadır.

Araştırma kapsamında elde edilen nicel verilerin analiz sonuçları, öğrencilerin büyük çoğunluğunun dijital öğrenme ortamlarının eğitim süreçlerine olumlu katkı sağladığını düşündüğünü göstermektedir. Katılımcıların %78'i çevrim içi öğrenme platformlarının öğrenme sürecini daha esnek hale getirdiğini belirtirken, %72'si yapay zekâ destekli uygulamaların bireysel öğrenme ihtiyaçlarını desteklediğini ifade etmiştir. Ayrıca yapılan Pearson korelasyon analizi sonucunda dijital teknoloji kullanım düzeyi ile öğrenme motivasyonu arasında pozitif yönlü ve anlamlı bir ilişki belirlenmiştir ($r=0.64$, $p<0.05$). Elde edilen bulgular, dijital eğitim uygulamalarının öğrencilerin öğrenme süreçlerine uyumunu ve akademik motivasyonlarını olumlu yönde etkilediğini göstermektedir.

SONUÇ

Bilgi ve iletişim teknolojilerinde yaşanan hızlı gelişmeler, yükseköğretim sistemlerinin yapısında önemli değişimlerin meydana gelmesine neden olmuş ve eğitim süreçlerinin yeniden değerlendirilmesini zorunlu hale getirmiştir. Endüstri 4.0 sürecinin etkisiyle ortaya çıkan Eğitim 4.0 modeli, dijital teknolojilerin öğretim süreçlerine entegrasyonunu esas alan çağdaş bir eğitim yaklaşımı olarak yükseköğretimde giderek daha fazla önem kazanmaktadır. Bu model, yalnızca teknolojik araçların eğitim ortamlarında kullanılmasını değil, aynı zamanda öğrenci merkezli, esnek, yenilikçi ve uygulamaya dayalı öğrenme anlayışının geliştirilmesini de hedeflemektedir.OECD (2021) raporlarında dijital dönüşümün yükseköğretimde sürdürülebilir biçimde uygulanabilmesi için teknolojik altyapının güçlendirilmesi ve öğretim elemanlarının dijital yeterliliklerinin geliştirilmesinin önemli olduğu belirtilmektedir.

Fullan ve Langworthy'e (2018) göre çağdaş eğitim sistemlerinin temel amacı, öğrencilerin yalnızca bilgi tüketen bireyler değil, aynı zamanda bilgi üreten ve yenilikçi çözümler geliştirebilen bireyler olarak yetiştirilmesidir. Eğitim 4.0 modeli de bu yaklaşımı destekleyen çağdaş bir eğitim paradigması olarak değerlendirilmektedir.Araştırma sonuçları, Eğitim 4.0 modelinin lisans düzeyinde uygulanmasının öğrencilerin akademik, mesleki ve bireysel gelişimleri üzerinde olumlu etkiler oluşturduğunu göstermektedir. Özellikle dijital öğrenme ortamları, çevrim içi eğitim platformları, yapay zekâ destekli öğretim sistemleri ve etkileşimli öğrenme araçları sayesinde öğrencilerin bilgiye erişim olanaklarının genişlediği belirlenmiştir. Bunun yanı sıra öğrencilerin eleştirel düşünme, problem çözme, araştırma yapma, iş birliği kurma ve dijital okuryazarlık gibi çağdaş becerilerinin gelişmesine önemli katkılar sağlandığı görülmektedir. Eğitim 4.0 yaklaşımı, öğrencilerin yalnızca teorik bilgiyle donatılmasını değil, aynı zamanda gerçek yaşam problemlerine çözüm üretebilen, yenilikçi düşünebilen ve değişen koşullara uyum sağlayabilen bireyler olarak yetiştirilmelerini amaçlamaktadır.

Araştırma bulguları, proje tabanlı öğrenme, problem tabanlı öğrenme ve bireyselleştirilmiş eğitim uygulamalarının öğrencilerin öğrenme motivasyonlarını artırdığını ve öğrenme süreçlerini daha etkili hale getirdiğini ortaya koymaktadır. Özellikle öğrencilerin aktif katılımına dayanan öğretim yöntemleri, onların bağımsız öğrenme becerilerini geliştirmekte ve uygulamalı deneyimler kazanmalarına olanak sağlamaktadır. Bu durum, çağdaş iş gücü piyasasının ihtiyaç duyduğu nitelikli insan kaynağının yetiştirilmesi açısından büyük önem taşımaktadır.

Bununla birlikte araştırma sürecinde Eğitim 4.0 modelinin uygulanmasına ilişkin çeşitli sorunların bulunduğu da belirlenmiştir. Teknolojik altyapı eksiklikleri, dijital araçlara erişimde yaşanan fırsat eşitsizlikleri, öğretim elemanlarının dijital pedagojik yeterlilik düzeylerindeki farklılıklar ve çevrim içi eğitim süreçlerinde ortaya çıkan sosyal ve psikolojik sorunlar bu sürecin temel problemleri arasında yer almaktadır. Özellikle bazı yükseköğretim kurumlarında teknik donanım eksiklikleri ve internet erişimine ilişkin sorunlar dijital eğitim uygulamalarının etkinliğini sınırlandırabilmektedir. Ayrıca öğretim elemanlarının yeni teknolojilere uyum sağlama süreçlerinde yaşadıkları güçlükler, Eğitim 4.0 modelinin uygulanmasını yavaşlatan önemli etkenlerden biri olarak değerlendirilmektedir.

Bu bağlamda Eğitim 4.0 modelinin etkili biçimde uygulanabilmesi için yükseköğretim kurumlarında güçlü teknolojik altyapının oluşturulması, dijital eğitim kaynaklarının yaygınlaştırılması ve öğretim elemanlarının dijital pedagojik yeterliliklerinin geliştirilmesine yönelik sürekli eğitim programlarının düzenlenmesi gerekmektedir. Aynı zamanda eğitimde fırsat eşitliğinin sağlanması, öğrencilerin dijital araçlara erişim imkânlarının artırılması ve teknoloji kullanımının pedagojik ilkeler doğrultusunda dengeli biçimde planlanması büyük önem taşımaktadır.

Sonuç olarak Eğitim 4.0 modeli, yükseköğretimde dijital dönüşüm sürecinin temel bileşenlerinden biri olarak değerlendirilebilir. Bu modelin sistemli, planlı ve sürdürülebilir biçimde uygulanması,

yükseköğretimin kalitesinin artırılmasına, öğrencilerin çağdaş beceriler kazanmasına ve eğitim süreçlerinin daha etkili hale getirilmesine önemli katkılar sağlayacaktır. Ayrıca Eğitim 4.0 yaklaşımının geliştirilmesi ve yükseköğretim kurumlarında yaygınlaştırılması, geleceğin eğitim anlayışının şekillenmesinde stratejik bir rol oynayacaktır.

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REPOSITIONING ACADEMIC LIBRARIES IN THE DIGITAL AGE: FACTORS INFLUENCING LOW LIBRARY PATRONAGE AMONG STUDENTS IN NIGERIAN TERTIARY INSTITUTIONS

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ABSTRACT
Academic libraries remain central to teaching, learning, research, and knowledge dissemination in higher education institutions. Despite their importance, many tertiary institutions have experienced a steady decline in students' use of library resources and services. The emergence of digital technologies, social media platforms, and alternative information sources has significantly altered students' information-seeking behaviour. This study investigated the factors responsible for low library patronage among students in Nigerian tertiary institutions. Specifically, the study examined the extent of library patronage, the influence of social media, peer pressure, library environment, staff attitude, and students' perceptions of library services. A descriptive survey research design was adopted for the study. The population comprised undergraduate students in selected tertiary institutions. Data were collected using a structured questionnaire titled Factors Affecting Library Patronage Questionnaire (FALPQ). Descriptive statistics such as frequency counts, percentages, mean scores, and standard deviations were used to analyze the data, while Pearson Product Moment Correlation and Chi-square statistics were employed to test the hypotheses at the 0.05 level of significance. Findings revealed that social media addiction, preference for online information resources, poor reading culture, outdated library materials, inadequate technological facilities, and unfriendly library environments significantly contribute to low library patronage. The study concludes that academic libraries must embrace innovation, improve user-centered services, and integrate digital technologies to remain relevant in the information age. The study recommends increased funding, modernization of library services, improved staff-user relationships, and enhanced information literacy programmes.
Keywords: Library patronage, academic libraries, social media, digital age, library utilization.

1.Introduction
Libraries have long served as repositories of knowledge and centers for learning, teaching, and research. Academic libraries, in particular, provide access to scholarly resources that support curriculum delivery, independent study, and intellectual development. Traditionally, students relied heavily on library collections and services for academic success. However, the contemporary information landscape has undergone remarkable transformation due to advances in information and communication technology (ICT) (Sinha & Das, 2024). The proliferation of the internet, search engines, social media platforms, digital databases, and mobile technologies has significantly changed the way student access information. Information that previously required physical visits to libraries can now be obtained instantly through online platforms. Consequently, many students increasingly depend on digital resources rather than traditional library services.
Social media platforms have become integral parts of students' daily lives. Platforms such as Facebook, Instagram, TikTok, X, WhatsApp, and YouTube provide opportunities for communication, entertainment, and information sharing. While these platforms offer numerous benefits, excessive engagement may reduce the time devoted to reading and library use. In addition to social media influence, several other factors contribute to declining library patronage. These include peer influence, poor reading habits, and inadequate awareness of library services, outdated library collections, lack of technological facilities, poor internet connectivity, and unfriendly staff attitudes. Some students perceive libraries as rigid, boring, and less attractive compared to modern digital environments.

The decline in library patronage has become a concern for librarians and educational administrators because libraries remain essential components of quality education.
Understanding the factors responsible for low library usage is therefore necessary for developing strategies to improve students' engagement with library services (Michael & Olayemi, 2023). This study investigates the factors influencing low library patronage among students in Nigerian tertiary institutions and explores possible strategies for enhancing library utilization in the digital age.

Statement of the Problem

The academic library is designed to support learning, teaching, and research activities. Despite the availability of valuable resources and services, many academic libraries are witnessing a decline in student patronage. Students increasingly rely on search engines, online resources, social media platforms, and peer-shared materials instead of consulting scholarly resources available in libraries. As a result, physical visits to libraries have reduced considerably in many institutions. Furthermore, factors such as outdated information resources, inadequate technological infrastructure, unconducive library environments, poor internet facilities, and negative staff attitudes may discourage students from using libraries. The persistence of these challenges raises concerns about the continued relevance and effectiveness of academic libraries. Although previous studies have examined library usage patterns, there remains a need for comprehensive investigation into the combined effects of social media usage, peer influence, library environment, staff attitude, and digital information habits on students' library patronage. This study therefore seeks to identify the major factors responsible for low library patronage and propose strategies for improving library utilization among students.

Objectives of the Study

The main objective of this study is to investigate the factors responsible for low patronage of libraries among students.
The specific objectives are to

1. Determine the influence of social media on students' use of libraries.
2. Assess students' perception of library environment and services.
3. Determine whether staff attitude affects students' use of libraries.

Research Questions

1. To what extent does social media influence students' use of libraries?
2. How do students perceive library environment and services?
3. Does the attitude of library staff affect students' library usage?

Research Hypotheses

H01: There is no significant relationship between social media usage and students' library patronage.
H02: There is no significant relationship between library environment and students' use of libraries.
H03: There is no significant relationship between staff attitude and students' library patronage.

Significance of the Study

The study will be beneficial to librarians, students, educational administrators, policymakers, and researchers. The findings will help librarians identify barriers affecting library usage and develop innovative strategies to improve service delivery. Educational administrators will benefit from the findings by understanding the need for investment in modern library facilities and technologies. The study will also contribute to the body of knowledge in Library and Information Science, particularly in the areas of information behaviour, library utilization, and user studies.

1.Literature Review

Concept of Library Patronage

Library patronage refers to the extent to which users utilize library resources, facilities, and services. High patronage indicates active use of library collections and services, while low (Okwu, Oyighan & Oladokun, 2025).

Patronage suggests under-utilization.

Academic libraries exist primarily to support teaching, learning, and research. Effective utilization of library resources contributes significantly to academic achievement and information literacy development.

Information-Seeking Behaviour and Library Use

Information-seeking behaviour involves the processes through which individuals identify information needs and seek information to satisfy those needs. According to Wilson, information-seeking behaviour is influenced by personal, social, and environmental factors.

Students' choice of information sources is often determined by convenience, accessibility, familiarity, and perceived usefulness.

Social Media and Information Access

The emergence of social media has transformed information access and communication patterns. Students increasingly rely on social networking sites and search engines for academic and non-academic information. While social media enhances information access, excessive use may contribute to distraction, reduced reading culture, and decreased library visitation.

Library Environment and User Satisfaction

Library environment significantly influences users' willingness to visit and utilize library services. Factors such as seating arrangements, lighting, ventilation, noise control, cleanliness, internet connectivity, and technological infrastructure affect user satisfaction. An attractive and conducive learning environment encourages library use.

Staff Attitude and Service Quality

The attitudes and behavior of library personnel influence users' perceptions of library services. Friendly, approachable, and supportive staff encourage patronage, while unfriendly interactions may discourage library usage.

Theoretical Framework

This study is anchored on Wilson's Information Behaviour Theory (1999), which explains how environmental, social, and personal factors influence information-seeking behaviour. The theory is relevant because students' decisions regarding library use are affected by social media exposure, peer influence, environmental conditions, and accessibility of alternative information sources.

1.Methodology

Research Design

The study adopted a descriptive survey research design**.**

Population of the Study

The population comprised undergraduate students in selected Nigerian tertiary institutions.

Sample and Sampling Technique

A multistage sampling technique was employed. Faculties and departments were purposively selected, while students were selected through simple random sampling. A sample size of 400 respondents was used.

Instrument for Data Collection

The instrument used for data collection was the Factors Affecting Library Patronage Questionnaire (FALPQ).

Validity of instrument

Experts in Library and Information Science and Educational Research validated the instrument.

Reliability of Instrument

A pilot study was conducted and Cronbach Alpha reliability coefficient of 0.86 was obtained, indicating high reliability.

Method of Data Collection

The researcher administered copies of the questionnaire personally to respondents.

Method of Data Analysis

Data were analyzed using frequency counts, percentages, mean scores and standard deviations.

Hypotheses were tested using Pearson Product Moment Correlation, chi-square statistics at 0.05 level of significance.

2.Results and Discussion

Likert scale coding: Strongly Agree =4, Agree= 3, Disagree = 2, Strongly Disagree = 1
Decision: 2.50-4.00 = Agree, 1.00-2.49 = Disagree

Table 1: Demographic Variables

Variable	Frequency	Percentage
Male	180	45.0
Female	220	55.0
Total	**400**	**100**

Source: data from respondents

Research Question One

To what extent does social media influence students' use of libraries?

Table 2: Social Media Influence

Item	Mean	SD	Decision
1	3.20	0.81	Agree
2	3.15	0.74	Agree
3	3.05	0.88	Agree
4	3.10	0.79	Agree
5	3.12	0.85	Agree
6	3.08	0.82	Agree

Source: data from respondents

The findings showed that excessive social media engagement significantly reduces students' reading time and library visitation.

Research Question Two

How do students perceive library environment and services?

Table 3: Library Environment

Item	Mean	SD	Decision
1	2.31	0.90	Disagree
2	2.28	0.95	Disagree
3	2.14	1.01	Disagree
4	2.20	0.96	Disagree
5	2.45	0.87	Disagree

Source: data from respondents

Many students perceived library environments as inadequate, outdated, and lacking modern technological facilities.

Research Question Three

Does the attitude of library staff affect students' library usage?

Table 4: Staff Attitude

Item	Mean	SD	Decision
1	2.56	0.90	Agree
2	2.62	0.87	Agree
3	2.70	0.85	Agree
4	2.48	0.92	Disagree

Item	Mean	SD	Decision
5	2.89	0.81	Agree

Source: data from respondents

The findings revealed that staff attitude significantly influences students' willingness to visit and utilize library services.

HYPOTHESIS RESULTS

Table 5: Correlation between Social Media Usage and Library Patronage

Variables	N	r	p-value	Decision
SM_Total vs LP_Total	400	-0.624	0.000	Significant

Source: data from respondents

Table 6: Correlation between Library Environment and Library Patronage

Variables	N	r	p-value	Decision
LE_Total vs LP_Total	400	0.587	0.000	Significant

Source: data from respondents

Table 7: Correlation between Staff Attitude and Library Patronage

Variables	N	r	p-value	Decision
ST_Total vs LP_Total	400	0.541	0.000	Significant

Source: data from respondents

1. Discussion of Findings

The findings indicate that social media has become one of the strongest competitors to traditional library services. Students increasingly rely on digital platforms for information retrieval due to convenience and speed.

The findings further showed that poor library infrastructure, outdated collections, and inadequate technological facilities discourage library use. Modern students expect libraries to provide digital resources, internet access, collaborative learning spaces, and technology-enabled services.

The influence of staff attitude underscores the importance of customer-oriented service delivery. Positive interactions between librarians and users encourage continued patronage and user satisfaction.

2. Conclusion

The study concludes that low library patronage among students is influenced by a combination of technological, social, environmental, and institutional factors. Social media usage, peer influence, poor reading culture, outdated resources, inadequate facilities, and negative staff attitudes contribute significantly to declining library utilization. To remain relevant in the digital age, academic libraries must adopt innovative approaches that combine traditional services with modern digital technologies and user-centered service delivery.

Recommendations

1. Academic libraries should expand digital collections and electronic resources.
2. Libraries should provide reliable internet connectivity and Wi-Fi services.
3. Library environments should be redesigned to provide comfortable and attractive learning spaces.
4. Librarians should adopt more user-friendly and supportive service attitudes.
5. Social media platforms should be utilized for library marketing and user engagement.
6. Information literacy and user education programmes should be strengthened.
7. Educational institutions should provide adequate funding for library modernization.
8. Libraries should establish collaborative learning spaces and technology hubs to attract students.

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CLIMATE POLICY UNCERTAINTY, GREEN BONDS, AND STOCK MARKET RESILIENCE: EVIDENCE FROM EUROPEAN LISTED ENERGY AND UTILITY FIRMS

İKLİM POLİTİKASINDAKİ BELİRSİZLİK, YEŞİL TAHVİLLER VE BORSA DAYANIKLILIĞI: AVRUPA'DA BORSAYA KOTE EDİLMİŞ ENERJİ VE KAMU HİZMETİ ŞİRKETLERİNDEN ELDE EDİLEN BULGULAR

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ÖZET

İklimle ilgili finansal riskler, özellikle düzenleyici belirsizlik, karbon fiyatlandırma mekanizmaları ve geçiş odaklı politika müdahalelerinin yatırımcı beklentilerini yeniden şekillendirmesi nedeniyle, enerji yoğun sektörlerde faaliyet gösteren şirketler için giderek daha önemli hale gelmiştir. Yeşil tahviller, düşük karbonlu dönüşümü finanse etmek için önemli bir araç olarak yaygın bir şekilde tanıtılsa da, yeşil tahvil ihraç eden veya aktif olarak kullanan şirketlerin, iklim politikası belirsizliğinin arttığı dönemlerde borsa karşısında daha güçlü bir direnç sergileyip sergilemedikleri hâlâ belirsizdir. Bu çalışma, Avrupa'da borsaya kote edilmiş enerji ve kamu hizmetleri şirketlerine odaklanarak iklim politikası belirsizliği, yeşil tahvil maruziyeti ve borsa dayanıklılığı arasındaki ilişkiyi incelemeyi amaçlamaktadır. Avrupa bağlamı, borsaya kote edilmiş şirketlerin iddialı iklim düzenlemelerine, genişleyen sürdürülebilir finans çerçevelerine, karbon piyasası dinamiklerine ve geçiş riskine ilişkin artan yatırımcı incelemesine maruz kalması nedeniyle özellikle ilgili bir ampirik ortam sunmaktadır. Borsa verileri, yeşil tahvil ihraç bilgileri, finansal tablo göstergeleri, ESG ile ilgili değişkenler, karbon fiyatı göstergeleri ve iklim politikası belirsizliği ölçütleri birleştirilerek şirket düzeyinde bir panel veri seti oluşturulacaktır. Borsa dayanıklılığı, anormal getiriler, aşağı yönlü risk, getiri oynaklığı, risk değeri ve iklim politikasıyla ilgili şokların ardından toparlanma hızı aracılığıyla ölçülecektir. Yeşil tahvil maruziyeti, yeşil tahvil ihracı, yeşil tahvil yoğunluğu veya toplam finansman içindeki yeşil finansmanın payı ile temsil edilecektir. İklim politikası belirsizliği, mevcut iklim politikası belirsizlik endeksleri aracılığıyla ölçülecek ve karbon piyasası ile düzenleyici belirsizlik göstergeleriyle desteklenecektir. Metodolojik olarak, sabit etkiler panel regresyonu, etkileşim terimi modellemesi, olay çalışması analizi ve alternatif dayanıklılık ölçütlerine dayalı sağlamlık kontrolleri kullanılacaktır. Çalışmanın, yeşil tahvil maruziyetinin iklim politikası belirsizliği altında yalnızca bir finansman aracı olarak mı yoksa aynı zamanda piyasa temelli bir dayanıklılık mekanizması olarak mı işlev gördüğünü göstererek, sürdürülebilir finans ve finansal risk literatürüne katkı sağlaması beklenmektedir. Bulgular, sürdürülebilir borçlanma araçlarının enerji yoğun firmaların iklim geçişi belirsizliği sırasında finansal istikrarını korumasına yardımcı olup olmadığını göstererek yatırımcılar, şirket yöneticileri, politika yapıcılar ve düzenleyiciler için çıkarımlar sağlayabilir.

Anahtar Kelimeler: İklim politikasındaki belirsizlik; yeşil tahviller; borsa direnci; sürdürülebilir finans; Avrupalı enerji şirketleri.

ABSTRACT

Climate-related financial risks have become increasingly material for firms operating in energy-intensive sectors, particularly as regulatory uncertainty, carbon-pricing mechanisms, and transition-oriented policy interventions reshape investor expectations. While green bonds have been widely promoted as an important instrument for financing low-carbon transformation, it remains unclear whether firms issuing or actively using green bonds exhibit stronger stock market resilience during periods of heightened climate policy uncertainty. This study aims to examine the relationship between climate policy uncertainty, green bond exposure, and stock market resilience by focusing on European listed energy and utility firms. The European context provides a particularly relevant empirical setting because listed firms are exposed to ambitious climate regulations, expanding sustainable finance

frameworks, carbon market dynamics, and increasing investor scrutiny regarding transition risk. A firm-level panel dataset will be constructed by combining stock market data, green bond issuance information, financial statement indicators, ESG-related variables, carbon price indicators, and climate policy uncertainty measures. Stock market resilience will be measured through abnormal returns, downside risk, return volatility, value-at-risk, and recovery speed after climate-policy-related shocks. Green bond exposure will be proxied by green bond issuance, green bond intensity, or the share of green financing in total financing. Climate policy uncertainty will be measured through available climate policy uncertainty indices and supported by carbon market and regulatory uncertainty indicators. Methodologically, fixed-effects panel regression, interaction-term modelling, event-study analysis, and robustness checks based on alternative resilience measures will be employed. The study is expected to contribute to sustainable finance and financial risk literature by showing whether green bond exposure functions only as a financing instrument or also as a market-based resilience mechanism under climate policy uncertainty. The findings may provide implications for investors, corporate managers, policymakers, and regulators by demonstrating whether sustainable debt instruments help energy-intensive firms maintain financial stability during climate-transition uncertainty.
Keywords: Climate policy uncertainty; green bonds; stock market resilience; sustainable finance; European energy firms

1. INTRODUCTION

Climate transition has become a financial-market issue as much as an environmental and regulatory one. Carbon pricing, mandatory sustainability disclosure, transition planning, renewable-energy investment, and sustainable-finance taxonomies increasingly shape how investors evaluate firms whose cash flows remain exposed to fossil-fuel dependence, energy-market volatility, and regulatory redesign. The shift is especially visible in Europe, where the EU Emissions Trading System, the EU Taxonomy, the Corporate Sustainability Reporting Directive, and the broader European Green Deal have turned climate policy into a material information channel for listed companies (European Commission, n.d.-a, n.d.-b, n.d.-c). Energy and utility firms stand at the center of this transformation because they are expected to finance decarbonization while continuing to provide reliable energy services under changing carbon constraints.

A central difficulty for investors is that climate policy does not operate only through the level of regulation. Its timing, credibility, stringency, reversibility, and sectoral distribution also matter. Climate policy uncertainty captures this ambiguity: firms and investors may know that a transition is coming, yet remain unsure about the exact pace, rules, compliance costs, subsidies, disclosure burdens, and political durability of that transition. The broader economic-policy-uncertainty literature shows that uncertainty can delay investment, increase risk premia, and weaken market confidence (Baker et al., 2016). Climate policy uncertainty extends this logic to a domain where regulatory shifts can alter asset values, capital costs, and transition strategies simultaneously. Recent work on climate policy uncertainty confirms that such uncertainty is not merely a media narrative; it is measurable, event-sensitive, and economically consequential (Gavriilidis, 2021; Gavriilidis et al., 2026).

This issue is particularly important for transition-exposed sectors because climate risk is already viewed by investors as financially material. Institutional investors increasingly regard regulatory climate risk as a source of valuation risk, and many prefer engagement and risk management over simple divestment when confronting climate exposure (Krueger et al., 2020). Asset-pricing evidence also indicates that markets demand compensation for carbon-related exposure, especially in industries where emissions are more salient to investors (Bolton & Kacperczyk, 2021). Such findings imply that climate policy uncertainty may weaken stock market resilience not simply by changing expected profits, but by amplifying doubts about the credibility, cost, and timing of corporate transition paths.

Green bonds enter this debate as an instrument with both financing and signaling dimensions. Under the Green Bond Principles, proceeds should be allocated to eligible environmental projects, supported by transparent process, project evaluation, management of proceeds, and reporting (International Capital Market Association, 2025). This structure gives green bonds a different informational role from conventional debt: they may signal that a firm has identifiable transition projects, access to sustainability-oriented investors, and at least some willingness to expose capital allocation to external scrutiny. The rapid expansion of sustainable debt markets, documented by Climate Bonds Initiative

reports, suggests that green bonds have moved from a niche product to a significant component of climate finance (Climate Bonds Initiative, 2026).

Academic evidence, however, does not support a simplistic view that green bonds automatically generate superior financial outcomes. Early and highly cited studies show that green bonds can command modest pricing advantages and reflect investor preferences for environmental attributes (Zerbib, 2019). Corporate green-bond research finds that issuers can experience favorable stock-market reactions and improvements in environmental performance, especially when bonds are credible or externally certified (Flammer, 2021). Related evidence indicates that shareholders may benefit from green-bond issuance through liquidity and institutional-ownership channels rather than only through lower debt costs (Tang & Zhang, 2020). These studies are important, but they leave a more specific question open: whether green bond exposure helps transition-exposed firms remain resilient when climate policy uncertainty rises.

Stock market resilience is a richer construct than abnormal return alone. A firm may fail to generate positive abnormal returns during a policy shock but still display resilience through lower downside risk, lower volatility, less severe tail losses, or faster post-shock recovery. This distinction matters because climate-policy events can be ambiguous. A stricter regulation may be costly for carbon-intensive firms, favorable for firms with credible transition assets, and uncertain for firms whose green claims are difficult to verify. Sustainable-investing theory similarly suggests that green assets can perform differently depending on changes in investor preferences, climate-risk expectations, and the pricing of ESG shocks (Pastor et al., 2021). A resilience-based approach therefore offers a more nuanced lens than a narrow announcement-return design.

The European energy and utility setting provides a strong empirical context for this question. European firms operate within an unusually dense climate-policy architecture, including carbon pricing through the EU ETS, sustainable-activity classification through the EU Taxonomy, and expanding sustainability-reporting obligations through the CSRD (European Commission, n.d.-a, n.d.-b, n.d.-c). The Task Force on Climate-related Financial Disclosures also helped establish the expectation that climate-related risks should be reported in a decision-useful and forward-looking manner, while supervisors and central banks increasingly treat climate-related and environmental risks as financial risks (Network for Greening the Financial System, 2020; Task Force on Climate-related Financial Disclosures, 2017). These institutional developments make Europe a revealing laboratory for examining whether green debt is priced only as a financing tool or also as a resilience-enhancing market signal.

Despite the growth of sustainable finance research, three gaps remain visible. First, climate policy uncertainty and green bond exposure are often studied separately, although firms confront them simultaneously. Second, green-bond studies frequently emphasize issuance reactions, yield effects, or environmental outcomes, while fewer papers examine resilience across multiple equity-market risk dimensions. Third, the evidence on transition-exposed European energy and utility firms remains limited even though these firms face some of the most direct consequences of carbon pricing, climate regulation, and investor scrutiny. This study addresses these gaps by linking climate policy uncertainty, green bond exposure, and stock market resilience within a unified empirical design.

The study contributes to the literature in three ways. The first contribution is conceptual: it reframes green bonds as potential resilience mechanisms rather than treating them solely as labeled financing instruments. The second contribution is empirical: it evaluates stock market resilience through several complementary outcomes, including abnormal returns, volatility, downside risk, value-at-risk, and recovery speed. The third contribution is contextual: it focuses on European listed energy and utility firms during the post-Paris Agreement period, when climate-policy architecture and sustainable-finance markets matured together. This setting allows the analysis to ask whether green bond exposure helps firms absorb transition-policy stress in a market environment where climate rules are financially material.

The empirical design follows this logic by combining firm-year panel analysis with interaction modeling and event-study robustness. Climate policy uncertainty is treated as the transition-risk pressure, green bond exposure as the sustainable-financing channel, and stock market resilience as the observed market outcome. Firm and year effects are used to account for persistent firm characteristics and common annual shocks, while event-study evidence captures market responses around selected European climate-policy announcements. This structure is consistent with the article's central claim: green bonds

may not eliminate the adverse valuation effects of policy uncertainty, but they may help firms contain downside risk and recover more quickly after climate-policy shocks.

The remainder of the study is organized as follows. The next section describes the dataset, sample structure, and variable measurement. The methodology section then presents the research questions, hypotheses, econometric specification, and diagnostic strategy. The empirical section reports descriptive evidence, temporal patterns, correlation analysis, panel regressions, diagnostic tests, and event-study robustness. The final section discusses the implications for investors, corporate managers, regulators, and future research on sustainable finance under climate-transition uncertainty.

2. DATASET AND SAMPLE STRUCTURE

The empirical setting consists of European listed energy and utility firms observed annually between 2015 and 2025. The unit of analysis is the firm-year, which is appropriate because the research question concerns not only whether green-bond issuers differ from non-issuers, but also whether changes in climate policy uncertainty and green-financing exposure are associated with changes in firm-level stock market resilience over time. The resulting balanced panel contains 42 firms and 462 firm-year observations. The post-Paris Agreement period is particularly suitable for this design because climate regulation, EU sustainable-finance frameworks, carbon-market pricing, and investor scrutiny of transition risk became progressively more material during this interval (European Commission, n.d.; Gavriilidis, 2021; ICMA, 2025).

The sample focuses on energy and utility firms because these sectors are simultaneously exposed to transition risk, carbon pricing, regulatory uncertainty, and investor expectations regarding credible decarbonization. This sectoral focus is consistent with the logic of climate finance research, where firm value and risk can respond sharply to changes in policy expectations and sustainable financing credibility (Baker et al., 2016; Gavriilidis et al., 2026).

Table 1. Sectoral composition of the firm-year panel

Sector	Firms	Observations	GB issuer share	Avg. GB intensity	Avg. abnormal return	Avg. volatility	Avg. resilience
Energy	**12**	**132**	**0.053**	**0.008**	**0.003**	**0.283**	**10.053**
Utilities	**30**	**330**	**0.209**	**0.038**	**-0.024**	**0.223**	**17.591**

Note. GB denotes green bond. The sample contains 42 firms and 462 firm-year observations over 2015-2025.

The sectoral profile indicates that utility firms dominate the sample and have higher average green-bond exposure than energy firms. Utilities also display a higher average resilience score and lower volatility, a pattern that is consistent with the view that regulated or semi-regulated utilities may be better positioned to finance transition-oriented projects through labeled debt instruments.

Table 2. Country-level sample coverage

Country	Firms	Observations	Avg. resilience	Avg. GB intensity
Italy	**7**	**77**	**14.385**	**0.019**
France	**5**	**55**	**16.295**	**0.034**
Spain	**5**	**55**	**17.326**	**0.045**
United Kingdom	**5**	**55**	**12.782**	**0.000**
Germany	**4**	**44**	**20.537**	**0.075**
Portugal	**4**	**44**	**16.832**	**0.024**
Norway	**3**	**33**	**10.300**	**0.022**
Austria	**2**	**22**	**18.139**	**0.065**
Denmark	**2**	**22**	**10.798**	**0.000**
Finland	**2**	**22**	**15.484**	**0.000**
Belgium	**1**	**11**	**22.798**	**0.111**
Czech Republic	**1**	**11**	**11.593**	**0.000**

Poland	**1**	**11**	**12.045**	**0.000**

Note. The country composition reflects listed European energy and utility firms included in the firm-year panel.

The country distribution is sufficiently heterogeneous for a European firm-level design, with Italy, France, Spain, the United Kingdom, Germany, and Portugal contributing the largest number of observations. The variation in average green-bond intensity across countries creates useful cross-sectional information for examining whether labeled sustainable debt is associated with market resilience.

3. VARIABLES AND MEASUREMENT

Stock market resilience is treated as a multidimensional outcome rather than a single market statistic. The main dependent variable is a composite resilience score ranging from 0 to 100. Additional outcomes include abnormal returns, downside risk, return volatility, 95% value-at-risk, and recovery speed after stress periods. This measurement strategy follows the event-study and asset-pricing tradition in which stock market reactions are assessed through abnormal returns and risk-adjusted benchmarks (Fama & French, 1993; MacKinlay, 1997).

The central explanatory variable is climate policy uncertainty, operationalized through a standardized CPU index inspired by the climate-policy-uncertainty measurement literature. Gavriilidis (2021) introduced a news-based Climate Policy Uncertainty index, and the updated literature continues to treat CPU shocks as a relevant source of macro-financial and firm-level uncertainty (Gavriilidis et al., 2026).

Green bond exposure is measured through issuer status, green bond intensity, and the share of green financing in total financing. The green-bond identification logic is aligned with market-standard guidance that green bonds should finance projects with identifiable environmental benefits and transparent use-of-proceeds reporting (Climate Bonds Initiative, n.d.; ICMA, 2025).

The control variables include ESG score, firm size, leverage, return on assets, market-to-book ratio, capital expenditure intensity, carbon intensity, revenue growth, an energy-crisis dummy, and a COVID-2020 dummy. ESG scores are included because sustainability management quality and disclosure practices may independently shape investor assessment of transition risk (LSEG, 2026).

4. METHODOLOGY

4.1 Research questions

RQ_1. Does climate policy uncertainty weaken the stock market resilience of European listed energy and utility firms?

RQ_2. Does green bond exposure improve stock market resilience?

RQ_3. Does green bond exposure moderate the adverse effect of climate policy uncertainty on firm-level resilience?

RQ_4. Are the results robust when resilience is measured through abnormal returns, downside risk, volatility, value-at-risk, recovery speed, and event-study outcomes?

4.2 Hypotheses

H_1. Climate policy uncertainty is negatively associated with stock market resilience.

H_2. Green bond exposure is positively associated with stock market resilience and negatively associated with downside risk, volatility, value-at-risk severity, and recovery time.

H_3. Green bond exposure weakens the adverse relationship between climate policy uncertainty and stock market resilience.

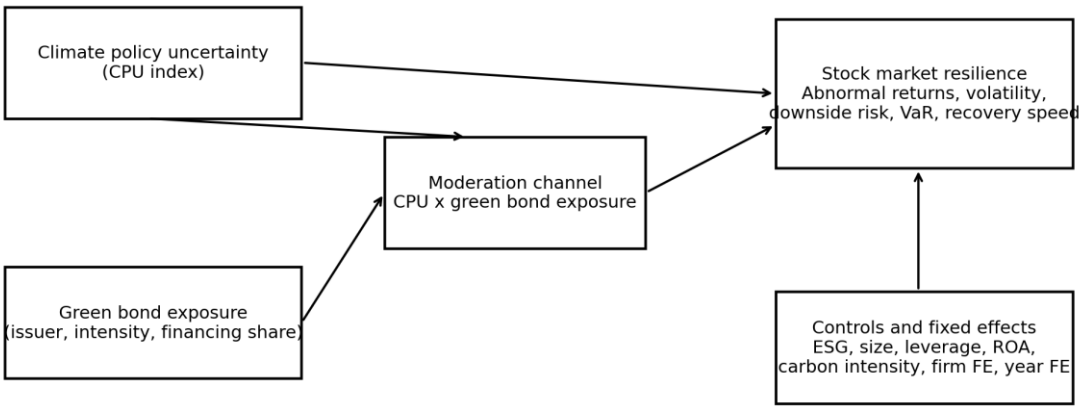
H_4. Green bond-exposed firms recover faster after climate-policy-related events than otherwise comparable firms.

4.3 Research model

Figure 1 presents the empirical logic of the study. The model treats climate policy uncertainty as the transition-risk shock, green bond exposure as the firm-level sustainable-financing channel, and stock market resilience as the observed market response after controlling for firm fundamentals, sustainability characteristics, and fixed effects.

Figure 1. Research model

Research model: climate policy uncertainty, green bonds, and stock market resilience



The figure clarifies the central contribution of the study: green bonds are not treated only as financing instruments, but also as potential market signals that may influence how investors price firms during climate-policy uncertainty.

4.4 Econometric specification

The primary empirical strategy is a two-way fixed-effects panel regression. Firm fixed effects absorb time-invariant differences in business model, listing environment, ownership structure, and long-run risk profile, while year fixed effects control for common shocks affecting all firms in a given year. The model is estimated with firm-clustered standard errors because repeated observations for the same firm are unlikely to be independent over time (Baltagi, 2021; Wooldridge, 2010).

The baseline interaction model is specified as follows:

$$Resilience_{it} = \alpha_i + \lambda_t + \beta_1 CPU_t + \beta_2 GBIntensity_{it} + \beta_3 (CPU_t \times GBIntensity_{it}) + \Gamma X_{it} + \varepsilon_{it}$$

In this equation, $Resilience_{it}$ denotes one of the stock market resilience outcomes for firm i in year t; CPU_t is standardized climate policy uncertainty; $GBExposure_{it}$ captures standardized green bond exposure; and X_{it} includes ESG score, size, leverage, ROA, market-to-book ratio, CAPEX intensity, carbon intensity, revenue growth, the energy-crisis dummy, and the COVID-2020 dummy. A full policy-control specification including carbon price and regulatory uncertainty is also evaluated diagnostically. Because carbon price, regulatory uncertainty, and CPU move together over time, the main reported model uses the parsimonious specification to protect coefficient stability.

4.5 Diagnostic strategy

The diagnostic strategy evaluates the main threats to inference in firm-level panel models. Skewness, kurtosis, and the Jarque-Bera test are used to assess distributional departures from normality (Jarque & Bera, 1980). Variance inflation factors evaluate multicollinearity, with attention to the caution that mechanical thresholds should not replace substantive judgement (O'Brien, 2007). Heteroskedasticity is examined through the Breusch-Pagan test (Breusch & Pagan, 1979). Serial correlation is checked through a residual AR(1) test, and cross-sectional dependence is evaluated using the logic of Pesaran's CD test (Pesaran, 2004).

5. EMPIRICAL ANALYSIS

5.1 Descriptive statistics

Table 3 reports the distributional properties of the main variables. The table includes skewness, kurtosis, and Jarque-Bera statistics because resilience and green-bond variables are expected to deviate from symmetry in a sample where labeled sustainable financing is concentrated among a subset of firms.

Table 3. Descriptive statistics and normality diagnostics

Variable	N	Mean	Std. Dev.	Min	Max	Skewness	Kurtosis	Jarque-Bera	JB p-value
Abnormal return	462	-0.016	0.106	-0.294	0.264	-0.250	3.033	4.786	0.091
Downside risk	462	0.132	0.034	0.026	0.233	-0.023	2.929	0.173	0.917
Return volatility	462	0.240	0.070	0.060	0.418	-0.070	2.656	2.778	0.249
Value-at-risk 95%	462	-0.114	0.037	-0.212	-0.005	0.150	2.782	2.728	0.256
Recovery speed (days)	462	72.006	23.221	15.100	142.800	0.447	2.527	19.759	<0.001
Resilience score	462	15.437	15.562	0.000	56.918	0.638	2.283	41.174	<0.001
Climate policy uncertainty	462	141.786	34.835	87.130	191.622	-0.179	1.407	51.064	<0.001
Green bond intensity/exposure	462	0.029	0.069	0.000	0.277	2.136	6.034	521.055	<0.001
Green bond issuer	462	0.165	0.371	0.000	1.000	1.816	4.303	283.574	<0.001
Carbon price	462	40.121	30.223	5.077	88.595	0.233	1.382	54.272	<0.001
Regulatory uncertainty	462	129.390	36.446	74.127	177.967	-0.183	1.378	52.918	<0.001
ESG score	462	73.132	10.902	45.410	98.000	-0.062	2.653	2.738	0.254
Environmental score	462	72.499	12.331	34.590	99.000	0.026	2.888	0.347	0.841
Firm size	462	9.810	0.923	8.081	11.762	0.172	2.167	15.751	<0.001
Leverage	462	0.475	0.121	0.149	0.719	-0.093	2.209	12.831	0.002
ROA	462	0.053	0.041	-0.078	0.168	0.142	2.958	1.604	0.448
Market-to-book	462	1.565	0.568	0.250	3.545	0.032	2.911	0.276	0.871
CAPEX/assets	462	0.069	0.019	0.035	0.118	0.058	2.203	12.636	0.002
Carbon intensity	462	161.285	133.158	6.524	669.848	1.667	5.451	324.409	<0.001
Revenue growth	462	0.032	0.100	-0.223	0.316	0.022	2.829	0.674	0.714

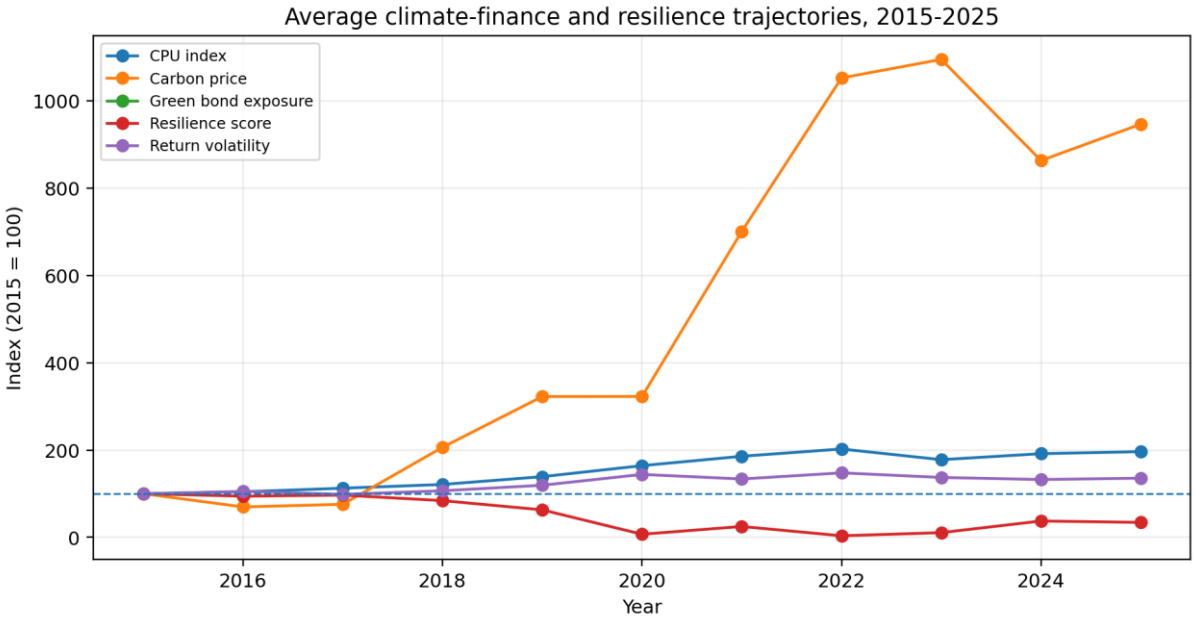
Note. Kurtosis is reported in Pearson form, where a normal distribution has kurtosis of 3. JB p-value refers to the Jarque-Bera normality test.

The descriptive evidence is financially intuitive. Abnormal returns, volatility, downside risk, and value-at-risk are close to symmetric, whereas green bond intensity is strongly right-skewed, confirming that green debt is concentrated among a limited group of firms. The resilience score is also right-skewed, which indicates that only a subset of firms maintains consistently strong market resilience under transition-related stress.

5.2 Temporal patterns

Figure 2 indexes the average trajectories of climate policy uncertainty, carbon price, green bond exposure, resilience, and volatility to 2015. The index format allows variables with different units to be compared visually without implying that their economic magnitudes are identical.

Figure 2. Average climate-finance and resilience trajectories, 2015-2025



The time profile shows a marked increase in climate policy uncertainty, carbon prices, and green bond exposure after 2018. Resilience weakens sharply in the COVID-2020 and energy-crisis years, while volatility rises during the same period. This temporal pattern motivates the use of fixed effects and crisis dummies rather than relying on simple pooled comparisons.

Table 4. Yearly averages of climate-finance and resilience indicators

Year	Firms	Avg. CPU	Avg. carbon price	GB issuer share	Avg. GB exposure	Avg. resilience	Avg. volatility	Avg. downside	Avg. recovery
2015	42	92.019	7.671	0.000	0.000	30.554	0.194	0.108	52.888
2016	42	96.032	5.345	0.024	0.002	28.766	0.204	0.109	53.705
2017	42	103.582	5.804	0.071	0.007	29.551	0.191	0.107	55.200
2018	42	111.440	15.817	0.095	0.010	25.683	0.207	0.108	58.900
2019	42	127.886	24.736	0.167	0.020	19.233	0.232	0.124	61.498
2020	42	151.061	24.748	0.190	0.027	2.161	0.280	0.157	93.536
2021	42	170.874	53.741	0.190	0.030	7.607	0.259	0.142	73.498
2022	42	186.179	80.710	0.214	0.039	1.089	0.287	0.165	105.057
2023	42	163.644	83.968	0.286	0.057	3.291	0.266	0.149	96.614
2024	42	176.309	66.201	0.286	0.064	11.429	0.257	0.141	69.688
2025	42	180.615	72.593	0.286	0.068	10.445	0.263	0.145	71.483

Note. Annual averages are calculated across the 42 firms in the balanced panel.

The yearly averages show that green-bond participation expands over the sample period, while the resilience score declines most visibly around the pandemic and energy-market stress years. This supports the empirical choice to include COVID and energy-crisis controls in the panel specifications.

5.3 Correlation analysis

Table 5 presents Pearson correlations among the main resilience outcomes, climate-finance variables, and selected controls. Correlations are descriptive and do not establish causal direction, but they help verify whether the data structure is broadly consistent with the theoretical expectations of the study.

Table 5. Pearson correlation matrix

Variable	RES	AR	VOL	DOWN	VaR	REC	CPU	GBE	CO2P	ESG	SIZE	LEV	ROA	CARBINT
RES	**1.000*** **	**0.188*** **	**-0.765*** **	**-0.742*** **	**0.718*** **	**-0.776*** **	**-0.652*** **	**0.117***	**-0.586*** **	**-0.056**	**-0.202*** **	**0.073**	**0.154*** **	**-0.097***
AR	**0.188*** **	**1.000*** **	**-0.036**	**-0.129** *	**0.031**	**-0.142** *	**-0.161*** **	**-0.136** *	**-0.081**	**-0.087**	**0.126** *	**-0.007**	**0.034**	**0.134****
VOL	**-0.765*** **	**-0.036**	**1.000*** **	**0.766*** **	**-0.914*** **	**0.416*** **	**0.448*** **	**-0.108***	**0.395*** **	**0.001**	**0.223*** **	**-0.125** *	**-0.132** *	**0.223*****
DOWN	**-0.742*** **	**-0.129** *	**0.766*** **	**1.000*** **	**-0.708*** **	**0.490*** **	**0.556*** **	**-0.056**	**0.502*** **	**0.060**	**0.133** *	**-0.002**	**-0.073**	**-0.056**
VaR	**0.718*** **	**0.031**	**-0.914*** **	**-0.708*** **	**1.000*** **	**-0.379*** **	**-0.426*** **	**0.072**	**-0.386*** **	**0.027**	**-0.235*** **	**0.113***	**0.138** *	**-0.236*****
REC	**-0.776*** **	**-0.142** *	**0.416*** **	**0.490*** **	**-0.379*** **	**1.000*** **	**0.582*** **	**-0.204*** **	**0.566*** **	**-0.006**	**0.149** *	**0.021**	**-0.112***	**0.041**
CPU	**-0.652*** **	**-0.161*** **	**0.448*** **	**0.556*** **	**-0.426*** **	**0.582*** **	**1.000*** **	**0.302*** **	**0.921*** **	**0.278*** **	**0.072**	**0.063**	**-0.033**	**-0.130****
GBE	**0.117***	**-0.136** *	**-0.108***	**-0.056**	**0.072**	**-0.204*** **	**0.302*** **	**1.000*** **	**0.311*** **	**0.213*** **	**-0.150** *	**0.193*** **	**0.096***	**-0.237*****
CO2P	**-0.586*** **	**-0.081**	**0.395*** **	**0.502*** **	**-0.386*** **	**0.566*** **	**0.921*** **	**0.311*** **	**1.000*** **	**0.258*** **	**0.068**	**0.074**	**-0.086**	**-0.125****
ESG	**-0.056**	**-0.087**	**0.001**	**0.060**	**0.027**	**-0.006**	**0.278*** **	**0.213*** **	**0.258*** **	**1.000*** **	**-0.125** *	**-0.026**	**-0.009**	**-0.332*****

SIZE	**-0.202*** **	**0.126** **	**0.223*** **	**0.133** **	**-0.235*** **	**0.149** **	**0.072**	**-0.150** **	**0.068**	**-0.125** **	**1.000*** **	**-0.026**	**-0.056**	**0.329*****
LEV	**0.073**	**-0.007**	**-0.125** **	**-0.002**	**0.113***	**0.021**	**0.063**	**0.193*** **	**0.074**	**-0.026**	**-0.026**	**1.000*** **	**0.099***	**-0.356*****
ROA	**0.154*** **	**0.034**	**-0.132** **	**-0.073**	**0.138** **	**-0.112***	**-0.033**	**0.096***	**-0.086**	**-0.009**	**-0.056**	**0.099***	**1.000*** **	**-0.133****
CARBINT	**-0.097***	**0.134** **	**0.223*** **	**-0.056**	**-0.236*** **	**0.041**	**-0.130** **	**-0.237*** **	**-0.125** **	**-0.332*** **	**0.329*** **	**-0.356*** **	**-0.133** **	**1.000*****

*Note. *** p < .001, ** p < .01, * p < .05. RES = resilience score; AR = abnormal return; VOL = return volatility; DOWN = downside risk; VaR = value-at-risk; REC = recovery days; CPU = climate policy uncertainty; GBE = green bond exposure; CO2P = carbon price.*

The correlation structure is consistent with a transition-risk narrative. Climate policy uncertainty is negatively associated with resilience and positively associated with recovery time, whereas green bond exposure is positively correlated with the resilience score and negatively correlated with several risk dimensions. These bivariate patterns are only preliminary, but they anticipate the more disciplined fixed-effects results.

5.4 Panel regression results

Table 6 reports the two-way fixed-effects panel regressions with firm-clustered standard errors. The models are intentionally estimated across multiple resilience outcomes because stock market resilience may appear as return preservation, lower downside risk, lower volatility, less severe value-at-risk, or faster recovery.

Table 6. Two-way fixed-effects panel regression results

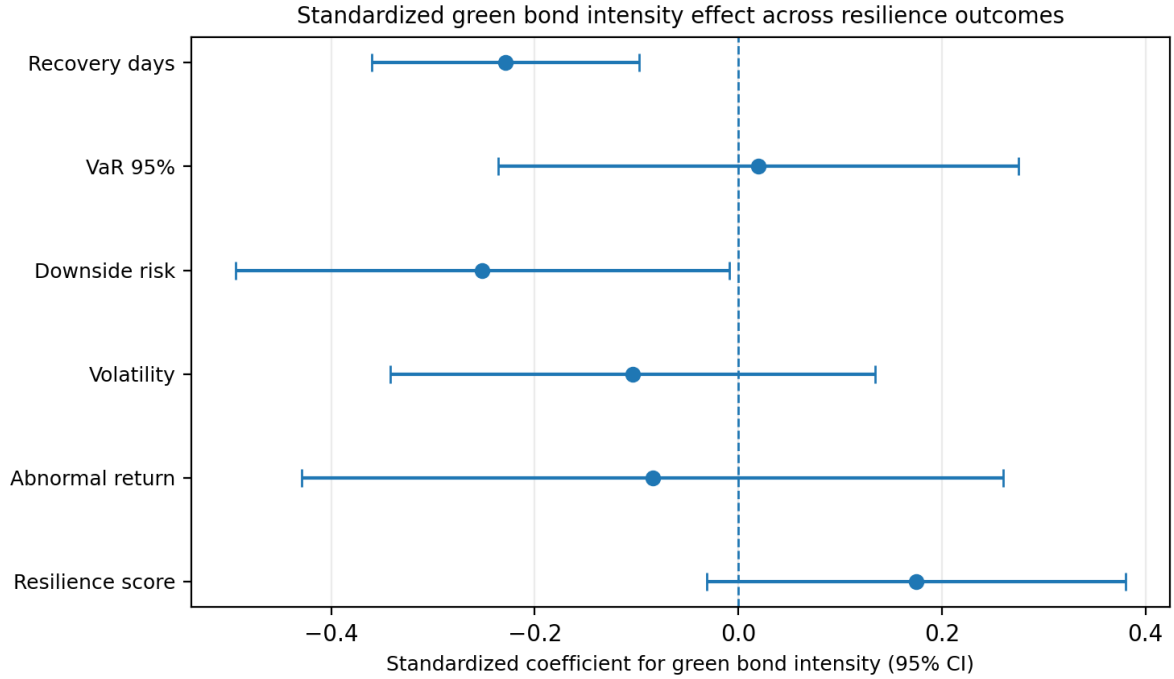
Variable	M1 Resilience score	M2 Abnormal return	M3 Volatility	M4 Downside risk	M5 VaR 95%	M6 Recovery days
Climate policy uncertainty (z)	**-12.4329* (5.0828)**	**-0.0834 (0.0683)**	**0.0093 (0.0282)**	**-0.0067 (0.0136)**	**-0.0132 (0.0156)**	**22.6960*** (6.0847)**
Green bond intensity (z)	**2.7152 (1.6318)**	**-0.0089 (0.0186)**	**-0.0072 (0.0085)**	**-0.0084* (0.0041)**	**0.0007 (0.0048)**	**-5.3025*** (1.5549)**
CPU x green bond intensity	**0.3858 (1.3841)**	**-0.0037 (0.0152)**	**-0.0051 (0.0075)**	**0.0024 (0.0035)**	**0.0025 (0.0040)**	**-1.6287 (1.2379)**
ESG score (z)	**1.8719 (1.6367)**	**0.0260 (0.0156)**	**-0.0051 (0.0108)**	**0.0004 (0.0046)**	**0.0039 (0.0061)**	**-3.5245 (2.0822)**
Firm size	**10.3219 (11.1625)**	**0.1000 (0.0821)**	**0.0076 (0.0596)**	**-0.0262 (0.0227)**	**0.0093 (0.0321)**	**-10.5360 (12.5804)**
Leverage	**4.0548 (15.5908)**	**-0.0735 (0.1610)**	**0.0427 (0.0843)**	**0.0498 (0.0441)**	**-0.0498 (0.0516)**	**-3.6521 (17.6500)**
ROA	**18.0213 (12.8857)**	**0.1979 (0.1262)**	**-0.0362 (0.0730)**	**-0.0029 (0.0341)**	**0.0317 (0.0392)**	**-7.9852 (15.5274)**
Market-to-book	**1.7955** (0.6078)**	**0.0053 (0.0104)**	**0.0003 (0.0041)**	**0.0015 (0.0020)**	**-0.0009 (0.0022)**	**-1.8665 (1.1582)**
CAPEX/assets	**20.6153 (28.8160)**	**-0.0243 (0.3287)**	**-0.0555 (0.2113)**	**0.0068 (0.1056)**	**0.0621 (0.1066)**	**-75.9517* (37.2843)**

Carbon intensity (z)	**-3.3481 (3.8989)**	**0.0123 (0.0400)**	**-0.0053 (0.0138)**	**-0.0049 (0.0096)**	**-0.0044 (0.0091)**	**1.0538 (3.4880)**
Revenue growth	**-0.4606 (5.1988)**	**0.0505 (0.0541)**	**0.0367 (0.0261)**	**0.0091 (0.0124)**	**-0.0081 (0.0134)**	**-8.5191 (7.7168)**
Energy-crisis dummy	**-3.3449 (8.6599)**	**0.1003 (0.1111)**	**0.0396 (0.0459)**	**0.0478* (0.0228)**	**-0.0096 (0.0256)**	**2.3473 (10.1749)**
COVID-2020 dummy	**-5.9704 (4.7523)**	**0.0002 (0.0647)**	**0.0366 (0.0258)**	**0.0337** (0.0126)**	**-0.0096 (0.0144)**	**3.2025 (5.8799)**
Observations	**462**	**462**	**462**	**462**	**462**	**462**
Adjusted R^2	**0.629**	**0.126**	**0.392**	**0.418**	**0.337**	**0.736**
Robust Wald F	**51.60**	**4.87**	**23.39**	**39.78**	**19.53**	**102.64**
Wald p-value	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**
Firm fixed effects	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**
Year fixed effects	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**
Clustered SE by firm	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**

Note. Firm-clustered standard errors are reported in parentheses. *** $p < .001$, ** $p < .01$, * $p < .05$. Coefficients for CPU and green bond intensity use standardized variables. Robust Wald F statistics and p-values are based on the firm-clustered covariance matrix.

The regression results show that climate policy uncertainty is negatively associated with the resilience score and positively associated with recovery days. This means that higher CPU corresponds to weaker market resilience and slower recovery. Green bond intensity is not a universal shield across all outcomes, but it is associated with significantly lower downside risk and faster recovery. The interaction term is not statistically significant in the annual panel specifications; therefore, H3 is not supported in the annual panel setting. The evidence is more consistent with a direct green-bond resilience channel than with a stable moderation effect under heightened climate policy uncertainty.

Figure 3. Standardized green bond intensity effect across resilience outcomes



Because the resilience outcomes are measured in different units, Figure 3 reports standardized outcome coefficients. The plot reinforces the regression evidence: green bond intensity is most clearly associated with lower downside risk and faster recovery, while its association with abnormal returns and volatility

remains statistically weaker. This supports a cautious interpretation: green bonds may improve resilience through risk-containment and recovery channels rather than through immediate abnormal-return gains.

5.5 Model diagnostics

Table 7 reports the diagnostic tests for the main panel models. These tests are central to the credibility of the inference because firm-level market data can exhibit heteroskedasticity, serial dependence, and common shocks across firms.

Table 7. Regression diagnostics

Model	BP LM	BP p-value	AR(1) F	AR(1) p-value	Residual AR rho	Pesaran CD	CD p-value	Avg. residual corr.	JB residual	JB p-value
M1 Resilience score	58.797	<0.001	0.002	0.965	0.002	-2.104	0.035	-0.022	10.891	0.004
M2 Abnormal return	11.807	0.543	0.095	0.758	0.014	-2.325	0.020	-0.024	0.121	0.941
M3 Volatility	14.601	0.333	16.528	<0.001	-0.160	-2.202	0.028	-0.023	0.007	0.996
M4 Downside risk	9.290	0.751	9.356	0.002	-0.150	-2.277	0.023	-0.023	7.348	0.025
M5 VaR 95%	16.468	0.225	16.453	<0.001	-0.147	-2.238	0.025	-0.023	0.099	0.952
M6 Recovery days	12.250	0.507	1.985	0.159	-0.071	-2.150	0.032	-0.022	1.102	0.576

Note. BP = Breusch-Pagan heteroskedasticity test. AR(1) = residual serial-correlation test. CD = Pesaran-type cross-sectional dependence statistic. JB = Jarque-Bera residual normality test.

The diagnostics show that heteroskedasticity is most visible in the resilience-score model, while serial correlation is relevant for volatility, downside risk, and value-at-risk models. Cross-sectional dependence appears across the specifications, which is plausible because European energy and utility firms share common macro-financial and regulatory shocks. These results justify firm-clustered standard errors and suggest that future extensions should also consider Driscoll-Kraay or common-correlated-effects estimators.

Table 8. Variance inflation factors for the main specification

Specification	Variable	VIF
Main parsimonious specification	Climate policy uncertainty (z)	1.834
Main parsimonious specification	Green bond intensity (z)	4.614
Main parsimonious specification	CPU x green bond intensity	3.402
Main parsimonious specification	ESG score (z)	1.273
Main parsimonious specification	Firm size	1.179
Main parsimonious specification	Leverage	1.264

Main parsimonious specification	**ROA**	**1.051**
Main parsimonious specification	**Market-to-book**	**1.051**
Main parsimonious specification	**CAPEX/assets**	**1.503**
Main parsimonious specification	**Carbon intensity (z)**	**1.524**
Main parsimonious specification	**Revenue growth**	**1.301**
Main parsimonious specification	**Energy-crisis dummy**	**1.489**
Main parsimonious specification	**COVID-2020 dummy**	**1.215**

Note. The main parsimonious specification excludes carbon price and regulatory uncertainty because these variables are highly collinear with the CPU block in the full policy-control specification.

The main specification does not display a serious multicollinearity problem. All VIF values remain below conventional warning thresholds, including the interaction term. In the full policy-control specification, however, CPU, carbon price, and regulatory uncertainty display very high VIF values, which confirms that these policy-time variables should not be forced into the same specification without careful identification design.

Table 9. Fixed-effects and specification checks in the baseline resilience model

Specification check	Result	Interpretation
Firm fixed-effects block	**F = 1.117; p = 0.292**	**Retained to absorb time-invariant firm heterogeneity.**
Year fixed-effects block	**F = 1.537; p = 0.142**	**Retained to absorb common policy and market shocks.**
Pooled OLS: CPU coefficient	**-10.042; p <0.001**	**Negative direction is consistent with the fixed-effects estimate.**
Two-way FE: CPU coefficient	**-12.433; p = 0.014**	**Baseline estimate after firm and year heterogeneity are absorbed.**
Pooled OLS: green bond intensity	**3.953; p <0.001**	**Positive direction is consistent with the fixed-effects estimate.**
Two-way FE: green bond intensity	**2.715; p = 0.096**	**Positive but less precise under the conservative FE design.**

Note. The test compares the full two-way fixed-effects model against restricted specifications that remove one fixed-effect block at a time.

The specification checks clarify why the two-way fixed-effects model is retained despite modest joint fixed-effect test statistics. The CPU coefficient remains negative in both pooled and fixed-effects specifications, while the green bond intensity coefficient remains positive, although it becomes less precise once firm and year heterogeneity is absorbed. The fixed-effects structure is therefore used as a conservative identification choice rather than as a purely mechanical response to joint significance tests.

5.6 Event-study robustness

The event-study analysis examines abnormal stock-market responses around major European climate-policy events. This complements the annual panel analysis by focusing on short-window market reactions, a standard approach in financial economics when the timing of relevant information arrivals can be identified (MacKinlay, 1997).

The resilient dummy is estimated as a **linear probability** specification with firm and event fixed effects, allowing the event-study results to be interpreted alongside the continuous CAR and recovery-day models**.**

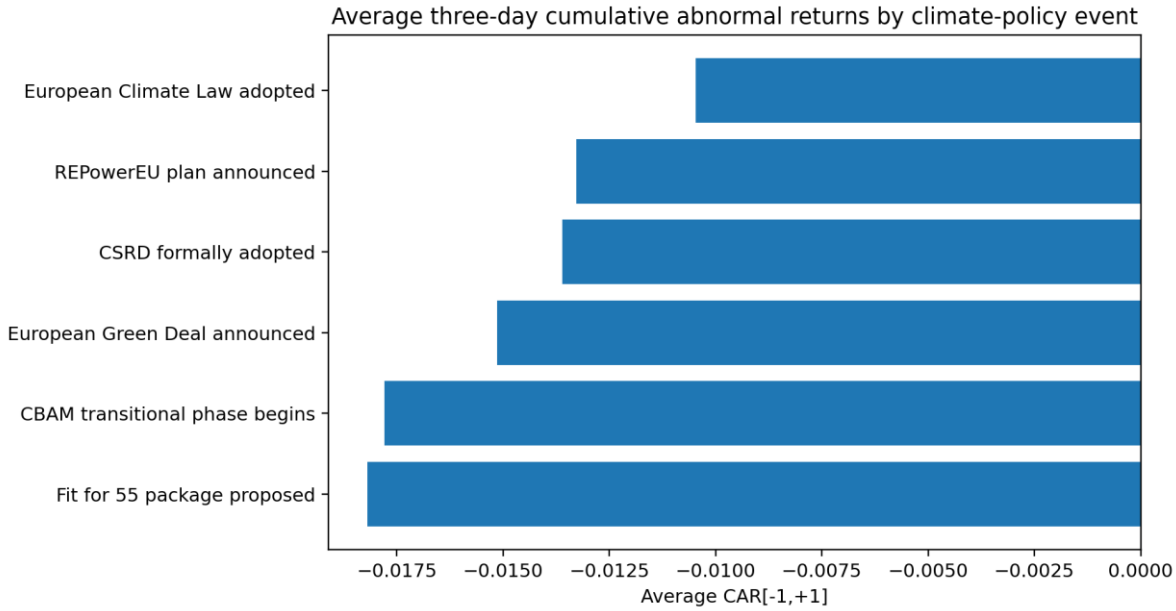
Table 10. Event-study descriptive evidence

Event ID	Event name	Obs.	Avg. CAR[-1,+1]	Avg. CAR[-5,+5]	Avg. max drawdown	Avg. recovery days	Resilient share	Avg. GB intensity
E01	European Green Deal announced	42	-0.015	-0.023	-0.062	38.743	0.071	0.020
E02	European Climate Law adopted	42	-0.010	-0.011	-0.052	45.719	0.024	0.030
E03	Fit for 55 package proposed	42	-0.018	-0.013	-0.051	46.829	0.000	0.030
E04	REPowerEU plan announced	42	-0.013	-0.011	-0.057	47.943	0.024	0.039
E05	CSRD formally adopted	42	-0.014	-0.015	-0.054	46.419	0.000	0.039
E06	CBAM transitional phase begins	42	-0.018	-0.019	-0.055	42.738	0.071	0.057

Note. CAR denotes cumulative abnormal return. Event windows are calculated around selected EU climate-policy announcements.

The event-study averages are negative across all selected policy events, indicating that major climate-policy announcements are generally associated with adverse short-window abnormal returns for transition-exposed firms. The magnitude varies across events, which is consistent with the idea that policy events differ in information content, regulatory intensity, and investor interpretation.

Figure 4. Average three-day cumulative abnormal returns by climate-policy event



The event figure shows that policy moments. This supports the use of event-study robustness rather than relying only on annual panel variation.average CARs are negative for all selected events, but the strongest reactions occur around more demanding or uncertainty-generating

Table 11. Event-study regression results

Variable	CAR[-1,+1]	Recovery days	Resilient dummy
Climate policy uncertainty (z)	**0.0096 (0.0168)**	**5.9242 (3.2393)**	**-0.0467 (0.1004)**
Green bond intensity (z)	**0.0044 (0.0134)**	**-7.6217** (2.5281)**	**0.1901 (0.1378)**
CPU x green bond intensity	**-0.0031 (0.0027)**	**0.0423 (0.5714)**	**-0.0673* (0.0302)**
Green bond issuer	**0.0267 (0.0341)**	**12.8746 (6.7916)**	**-0.2952 (0.3734)**
Carbon price (z)	**-0.0291 (0.0251)**	**-0.9801 (5.2711)**	**-0.1073 (0.1438)**
Observations	**252**	**252**	**252**
Adjusted R^2	**0.193**	**0.570**	**0.130**
Robust Wald F	**21.22**	**84.46**	**23.26**
Wald p-value	**<0.001**	**<0.001**	**<0.001**
Firm fixed effects	**Yes**	**Yes**	**Yes**
Event fixed effects	**Yes**	**Yes**	**Yes**
Clustered SE by firm	**Yes**	**Yes**	**Yes**

Note. Firm-clustered standard errors are reported in parentheses. *** $p < .001$, ** $p < .01$, * $p < .05$. Models include firm and event fixed effects. Robust Wald F statistics and p-values are based on the firm-clustered covariance matrix.

The event regressions strengthen the recovery-channel interpretation. Green bond intensity is significantly associated with shorter recovery periods after climate-policy events. The CAR result is not statistically precise, which suggests that green bonds may not prevent immediate negative price reactions, but may help firms regain market stability more quickly after policy-related shocks.

6. CONCLUSION

The empirical evidence supports a nuanced interpretation. Climate policy uncertainty matters for stock market resilience, particularly through lower resilience scores and longer recovery periods. Green bond exposure appears to contribute to resilience, but mainly through downside-risk reduction and recovery speed rather than through consistently higher abnormal returns. This distinction is important: market resilience should not be reduced to a single return-based metric, especially in transition-exposed sectors where investors may price policy risk through volatility, tail risk, and recovery dynamics.

The results also show that the interaction term between CPU and green bond intensity is not consistently significant in the annual panel models. Consequently, H3 is not supported in the annual panel specification. This does not invalidate the green-bond argument; rather, it refines it. Green bonds appear to operate more clearly as a direct resilience signal and financing channel than as a universal hedge that neutralizes the adverse market effects of climate-policy uncertainty. The event-study evidence is consistent with this interpretation: green bond intensity is associated with faster recovery after policy shocks, even though immediate abnormal returns around climate-policy announcements remain negative on average.

For investors, the findings imply that green bond exposure may carry information about transition credibility and recovery capacity. For managers, the evidence suggests that green financing can strengthen the market narrative around transition preparedness, but should be complemented by measurable decarbonization progress, transparent reporting, and credible investment plans. For regulators and policymakers, the results indicate that sustainable debt instruments may help transition-exposed firms absorb uncertainty, although policy clarity remains essential for reducing the financial costs of transition risk.

7. LIMITATIONS AND FURTHER RESEARCH

Several limitations should be acknowledged. First, the analysis relies on an annual firm-level panel, which provides a structured view of market resilience but cannot fully capture intra-year market dynamics.

Second, climate policy uncertainty, carbon prices, and regulatory uncertainty **are closely** related time-level variables. The VIF results show that including all policy variables simultaneously can create multicollinearity, so future work should consider alternative identification designs, lag structures, or separate policy blocks. Third, event-study results should ideally be estimated from daily stock returns using clean estimation and event windows, with market-model parameters estimated before each event window.

Further research can extend the analysis by using daily data, firm-level emissions disclosures, verified green bond issuance records, taxonomy-alignment indicators, and country-specific policy uncertainty indices. Dynamic panel models, Driscoll-Kraay standard errors, and common-correlated-effects estimators would also be valuable where persistence and cross-sectional dependence are empirically strong (Arellano & Bond, 1991; Pesaran, 2004).

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A GREEN APPROACH TO CIRCULAR BIOECONOMY, CLIMATE CHANGE, AND ENVIRONMENT

DÖNGÜSEL BİYOEKONOMİ, İKLİM DEĞİŞİKLİĞİ VE ÇEVRE KONUSUNDA ÇEVRECİ BİR YAKLAŞIM

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ÖZET

Döngüsel biyoekonomi gibi döngüsel ekonomi kavramlarının amacı, mevcut, temelde doğrusal olan ekonomik yapıyı daha sürdürülebilir bir yapı ile değiştirmektir. Ancak, döngüsel ekonomi kavramı günümüzde işletmeler ve akademisyenler tarafından farklı şekillerde tanımlanmaktadır; bu durum tutarsızlıklara yol açmakta ve bu çerçevenin başarılı bir şekilde uygulanmasını zorlaştırmaktadır. 2030 yılına kadar karbon emisyonlarını %45 oranında azaltmak ve 2050 yılına kadar karbon nötrlüğüne ulaşmak için, tüm sektörlerde döngüsel ekonomiyi uygulamaya yönelik girişimlere ihtiyaç vardır. Küresel sanayileşme ve yenilenemeyen enerji kaynaklarına sürdürülemez bir şekilde bağımlılık, katı atıkların artmasına ve iklim değişikliğine katkıda bulunmuştur. Atık yönetimi, iklim değişikliği, enerji, hava ve su kalitesi, arazi kullanımı, sanayi, gıda üretimi, yaşam döngüsü değerlendirmesi ve maliyet etkin yollara vurgu yaparak, burada döngüsel ekonomi fikirlerini inceliyoruz. Arazi kullanımı ve arazi örtüsü açısından, biyo-bazlı malzemelerin kullanımının yaygınlaştırılmasının bir sorun teşkil ettiğini tespit ettik. Bu amaçla, döngüsel biyoekonomi, iklim değişikliğinin etkileri, çevresel koşullar ve kırsal kalkınmaya ilişkin ilgili göstergelerden oluşan, 2015–2025 dönemini kapsayan bir ülkeler arası veri seti oluşturulacaktır. Bu çalışmada, döngüsel biyoekonomi ile ilgili dönüşümün, farklı ülkelerde ve zaman içinde iklim değişikliği sonuçlarını ne ölçüde etkilediğini belirlemek amacıyla panel veri tahmin teknikleri kullanılacaktır. Çalışmanın, betimleyici tartışmaların ötesine geçerek sürdürülebilirlik, iklim değişikliği, döngüsel biyoekonomi ve biyoekonomik dönüşümün kesişim noktası hakkında ampirik kanıtlar sunmasıyla literatüre katkı sağlaması beklenmektedir. Çalışma, biyoekonomi, sürdürülebilir kalkınma ve iklim değişikliği alanlarında çalışan araştırmacılara ve politika yapıcılarına daha güçlü bir analitik temel sunmayı amaçlamaktadır.

Anahtar kelimeler: döngüsel biyoekonomi, yeşil ekonomi, çevre, iklim değişikliği.

ABSTRACT

The goal of circular economy concepts, such as a circular bioeconomy, is to replace the current, basically linear economic structure with a more sustainable one. However, the circular economy concept is now defined variably by businesses and scholars, which leads to discrepancies and makes it challenging to apply the framework successfully. In order to reduce carbon emissions by 45% by 2030 and reach carbon neutrality by 2050, initiatives to implement a circular economy in all sectors are needed. Global industrialization and an unsustainable reliance on nonrenewable energy sources have contributed to an increase in solid waste and climate change. With an emphasis on waste management, climate change, energy, air and water quality, land use, industry, food production, life cycle evaluation, and cost-effective pathways, we examine circular economy ideas here. In terms of land use and land cover, we found that expanding the use of bio-based materials presents a problem. For this purpose, a cross-country dataset covering the period 2015–2025 will be constructed from relevant indicators of circular bioeconomy, climate change effects, environmental conditions, and rural development. In this study, panel data estimation techniques will be used to identify the extent to which circular bioeconomy-related transformation influences climate change outcomes across countries and over time. It is expected that the study will contribute to the literature by moving beyond descriptive discussions and providing empirical evidence on the intersection of sustainability, climate change, circular bioeconomy, and bioeconomic transformation.

The study is intended to offer a stronger analytical basis for researchers and policymakers working in the fields of bioeconomy, sustainable development, and tclimate change.
Keywords: circular bioeconomy, green economy, environment, climate change.

1. INTRODUCTION

Circular bioeconomy has become an increasingly important lens through which scholars and policymakers evaluate the transition from linear resource use toward more regenerative and low-carbon systems. The concept is closely connected to circular economy thinking, yet it places stronger emphasis on bio-based resources, renewable energy, land-use conditions, rural development, and the ecological limits of production. This distinction matters because climate mitigation cannot be reduced to a narrow energy substitution problem; it also involves waste management, agricultural systems, material loops, industrial organization, and the environmental quality of places where economic activity occurs (D'Amato et al., 2017; Geissdoerfer et al., 2017; Kirchherr et al., 2017).

The policy relevance of this agenda is reinforced by the climate targets that followed the Paris Agreement. Limiting global warming to 1.5°C requires deep reductions in CO2 emissions and a transition toward net-zero emissions around mid-century (IPCC, 2018). Within this setting, circular-bioeconomy transformation is not only a descriptive sustainability narrative; it can be examined as an empirical process that may influence measurable climate and environmental outcomes. A country-year panel design is especially appropriate for this purpose because it allows the analysis to distinguish persistent cross-country differences from within-country changes over time.

Despite the growing literature on circular economy and bioeconomy transitions, empirical evidence remains less developed than conceptual discussion. Many contributions define principles, policy pathways, or business-model implications, while fewer studies examine whether circular-bioeconomy-related transformation is statistically connected with emissions, air quality, or waste-related environmental pressure across countries. This study addresses that gap by constructing and analyzing a multi-country panel for 2015-2025 and by estimating whether a circular bioeconomy index and its components are associated with selected climate outcomes after controlling for macroeconomic and structural factors.

2. DATASET AND SAMPLE STRUCTURE

The study uses a balanced country-year panel covering 30 countries observed annually between 2015 and 2025, yielding 330 observations. The country-year structure is well aligned with the research objective because the research question is not merely whether greener economies differ from more carbon-intensive economies; rather, it asks whether circular-bioeconomy transformation is associated with environmental outcomes across countries and over time. This design follows the logic of panel data analysis, where repeated observations allow the empirical model to absorb time-invariant country characteristics and common global shocks more convincingly than a pure cross-section (Baltagi, 2021; Wooldridge, 2010).

The sample period begins shortly after the adoption of the Paris Agreement and extends to 2025, which allows the model to capture the early policy and economic transition years in which circular economy, renewable energy, land-use, and climate policy became more visibly connected. The climate motivation is consistent with the IPCC conclusion that limiting warming to 1.5°C requires deep emissions reductions and net-zero CO2 around mid-century (IPCC, 2018). The United Nations also communicates the policy benchmark that emissions need to decline by 45% by 2030 and reach net zero by 2050 to keep the 1.5°C target within reach (United Nations, n.d.).

The analytical unit is the country-year. The dependent variables capture climate and environmental pressure through CO2 emissions per capita, PM2.5 exposure, and waste-related CO2 emissions. The principal explanatory variable is the circular bioeconomy index, a composite transformation proxy designed to summarize renewable-energy penetration, bio-resource conditions, land-use structure, and rural-development features. This is conceptually consistent with the circular economy literature, which frames circularity as a systemic shift from linear resource throughput toward regenerative material and energy loops (Geissdoerfer et al., 2017; Kirchherr et al., 2017; Pearce & Turner, 1990). The bioeconomy dimension also reflects the broader sustainability intersection among green, circular, and bio-based economic transitions (D'Amato et al., 2017).

Table 1 presents the regional and income-group composition of the panel. This breakdown is important because circular-bioeconomy capacity, carbon intensity, and air-quality exposure are not evenly distributed across the world economy; the descriptive structure therefore clarifies the empirical context before the regression models are introduced.

Table 1. Sample composition by region and income group

Region	Countries	Observations	Avg_CBE	Avg_CO2	Avg_PM25
East Asia & Pacific	6	66	49.470	8.400	19.690
Europe & Central Asia	16	176	52.730	6.200	12.420
Latin America & Caribbean	2	22	54.030	3.300	15.750
Middle East & North Africa	2	22	40.310	2.230	47.300
North America	2	22	43.530	14.360	6.760
South Asia	1	11	52.370	1.750	69.620
Sub-Saharan Africa	1	11	28.680	8.540	26.840

Note. Avg_CBE denotes the average circular bioeconomy index; Avg_CO2 denotes average metric tons of CO2 per capita; Avg_PM25 denotes mean annual PM2.5 exposure.

The regional profile shows that Europe and Central Asia contributes the largest number of observations, while North America has the highest average per-capita CO2 level. PM2.5 exposure is concentrated in South Asia and the Middle East and North Africa, which indicates that air-quality pressure should be evaluated separately from carbon-intensity outcomes rather than treated as a simple substitute for CO2 emissions.

Table 1b. Sample composition by income group

Income group	Countries	Observations	Avg_CBE	Avg_CO2	Avg_PM25
High income	20	220	52.700	7.560	10.430
Lower-middle income	3	33	44.330	2.070	54.740
Upper-middle income	7	77	44.330	6.050	25.740

The income-group profile suggests a familiar development pattern: high-income economies display higher average CO2 per capita but substantially lower PM2.5 exposure, whereas lower-middle-income economies have lower per-capita CO2 but much higher air-pollution exposure. This asymmetry justifies the use of multiple dependent variables in the empirical design.

3. VARIABLES AND MEASUREMENT

The main dependent variable is the natural logarithm of CO2 emissions per capita. Log transformation is used because carbon emissions are strictly positive, right-skewed in levels, and commonly interpreted in semi-elasticity terms. Two robustness outcomes are then used: PM2.5 exposure, which captures population-weighted air-quality conditions, and the logarithm of waste-related CO2 emissions, which links more closely to the waste-management dimension of circular economy. The World Bank's World Development Indicators define CO2 emissions per capita as emissions from fossil-fuel burning and cement manufacture, while the renewable-energy indicator measures the renewable share of total final

energy consumption (World Bank, 2026a, 2026b). PM2.5 exposure is also available through WDI metadata and is based on Global Burden of Disease exposure estimates (World Bank, 2026c).
The key explanatory variable is the circular bioeconomy index scaled from 0 to 100. A higher value indicates stronger circular-bioeconomy readiness or transformation. The index is interpreted as a composite measure rather than as a single observable institution. Control variables include log GDP per capita, industrial value added as a share of GDP, urban population share, energy intensity, and a COVID-2020 dummy. These controls reduce omitted-variable bias by accounting for economic scale, structural composition, urban concentration, energy efficiency, and the exceptional pandemic shock. The income control is based on the World Bank GDP per capita constant-price concept (World Bank, 2026d).

4. METHODOLOGY

4.1 Research questions

RQ_1. Does circular-bioeconomy transformation reduce climate pressure across countries over time?
RQ_2. Do circular-bioeconomy components, particularly renewable energy and land-related bio-resource indicators, explain environmental outcomes after controlling for income, industry, urbanization, and energy intensity?
RQ_3. Are the results robust when environmental pressure is measured through air quality and waste-related emissions rather than only through CO2 per capita?

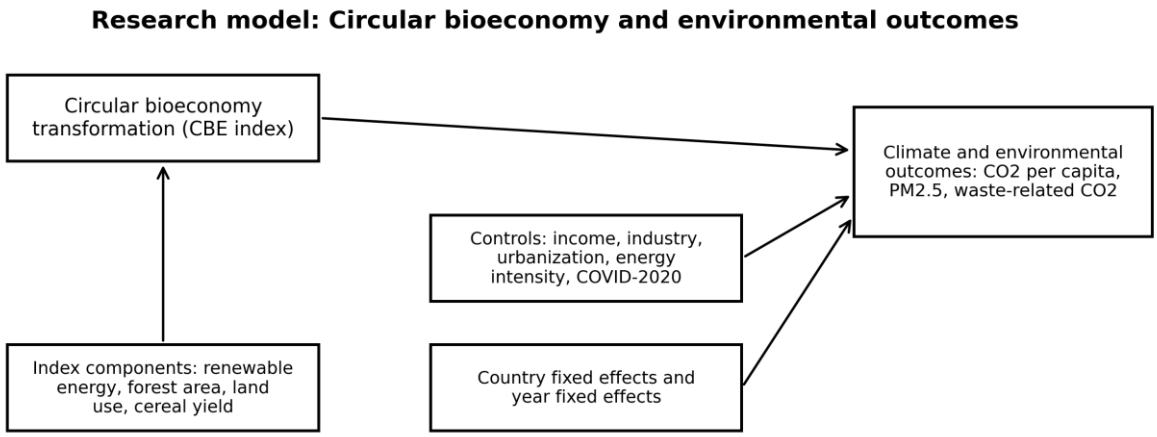
4.2 Hypotheses

H_1. The circular bioeconomy index is negatively associated with CO2 emissions per capita.
H_2. The circular bioeconomy index is negatively associated with PM2.5 exposure.
H_3. The circular bioeconomy index is negatively associated with waste-related CO2 emissions.
H_4. Renewable energy and forest-related bio-resource conditions are expected to reduce environmental pressure, whereas energy intensity, industrial structure, and urban concentration are expected to increase it unless offset by cleaner technologies and regulation.

4.3 Research model

Figure 1 translates the conceptual argument into an empirical research model. The figure makes explicit the central claim of the paper: circular-bioeconomy transformation is expected to influence climate and environmental outcomes after accounting for macroeconomic structure, energy intensity, and unobserved country and year effects.

Figure 1. Research model



The model deliberately separates the composite circular-bioeconomy index from its observable components. This distinction allows the study to evaluate both the overall transformation signal and the channels through which the transformation may operate, especially renewable energy, forest area, agricultural land, and cereal productivity.

4.4 Econometric specification

The primary empirical strategy is a two-way fixed-effects panel regression. This specification is appropriate because countries differ in persistent ways—geography, institutional capacity, historical energy systems, industrial base, and environmental regulation—that are difficult to measure fully but may bias pooled estimates. Country fixed effects absorb such time-invariant heterogeneity, while year fixed effects absorb global shocks common to all countries, including energy-market cycles and climate-policy diffusion.

The baseline equation is specified as follows:

$$Y_{it} = \alpha_i + \lambda_t + \beta_1 CBE_{it} + \beta_2 lnGDPpc_{it} + \beta_3 Industry_{it} + \beta_4 Urban_{it} + \beta_5 EnergyIntensity_{it} + \beta_6 COVID2020_t + \varepsilon_{it}$$

In this equation, Y_{it} denotes the environmental outcome for country i in year t. The baseline outcome is ln CO2 per capita; robustness models replace it with PM2.5 exposure and ln waste-related CO2. α_i captures country fixed effects, λ_t captures year fixed effects, and ε_{it} is the idiosyncratic error term. Standard errors are clustered at the country level because repeated observations within the same country are unlikely to be independent over time. This choice is consistent with panel-data guidance that inference should be protected against within-unit dependence when country panels are used (Baltagi, 2021; Wooldridge, 2010).

4.5 Diagnostic strategy

The empirical diagnostics are designed to protect the interpretation from common panel-data problems. Descriptive normality is evaluated through skewness, kurtosis, and the Jarque-Bera statistic (Jarque & Bera, 1980). Multicollinearity is assessed through variance inflation factors, interpreted cautiously rather than mechanically because VIF thresholds are context-dependent (O'Brien, 2007). Heteroskedasticity is evaluated with the Breusch-Pagan test (Breusch & Pagan, 1979). Serial correlation is assessed through a Wooldridge-style residual autocorrelation test, and cross-sectional dependence is examined using the logic of Pesaran's CD test (Pesaran, 2004). When diagnostics indicate heteroskedasticity or serial dependence, clustered robust standard errors are emphasized in the regression tables.

5. EMPIRICAL ANALYSIS

5.1 Descriptive statistics

Table 2 reports the core distributional properties of the variables. The table intentionally includes skewness, kurtosis, and Jarque-Bera statistics because the environmental variables are expected to deviate from normality: emissions, air pollution, and energy intensity are shaped by country-specific development paths and technological regimes rather than by symmetric random variation.

Table 2. Descriptive statistics and normality diagnostics

Variable	N	Mean	Std. Dev.	Min	Max	Skewness	Kurtosis	Jarque-Bera	JB p-value
ln CO2 per capita	330	1.735	0.589	0.471	2.784	-0.267	2.305	10.664	0.005
CO2 per capita (metric tons)	330	6.658	3.676	1.602	16.180	0.775	2.847	33.143	<0.001
PM2.5 exposure (μg/m³)	330	18.432	16.438	3.530	77.390	1.988	6.530	380.004	<0.001
ln waste-related CO2	330	1.890	0.961	-0.119	4.224	0.161	2.694	2.821	0.244
Circular bioeconomy index	330	49.909	11.752	26.030	80.220	0.228	2.659	4.570	0.102

Renewable energy (%)	330	24.936	14.886	3.050	66.740	0.885	2.902	42.856	<0.001
Forest area (%)	330	34.422	18.133	0.000	73.330	0.498	2.717	14.731	<0.001
Agricultural land (%)	330	40.098	21.473	1.970	79.120	-0.418	2.077	21.350	<0.001
Rural population (%)	330	24.333	14.453	5.450	67.050	1.068	3.431	64.402	<0.001
Urban population (%)	330	75.667	14.453	32.950	94.550	-1.068	3.431	64.402	<0.001
Cereal yield (kg/ha)	330	5,260.49	1,835.78	1,674.50	8,973.80	0.103	1.893	17.470	<0.001
ln GDP per capita	330	9.993	0.976	7.496	11.338	-0.719	2.389	33.457	<0.001
Industry VA (% GDP)	330	26.048	6.784	15.140	41.550	0.425	2.367	15.520	<0.001
Energy intensity	330	3.571	1.241	2.084	7.983	1.472	5.055	173.419	<0.001

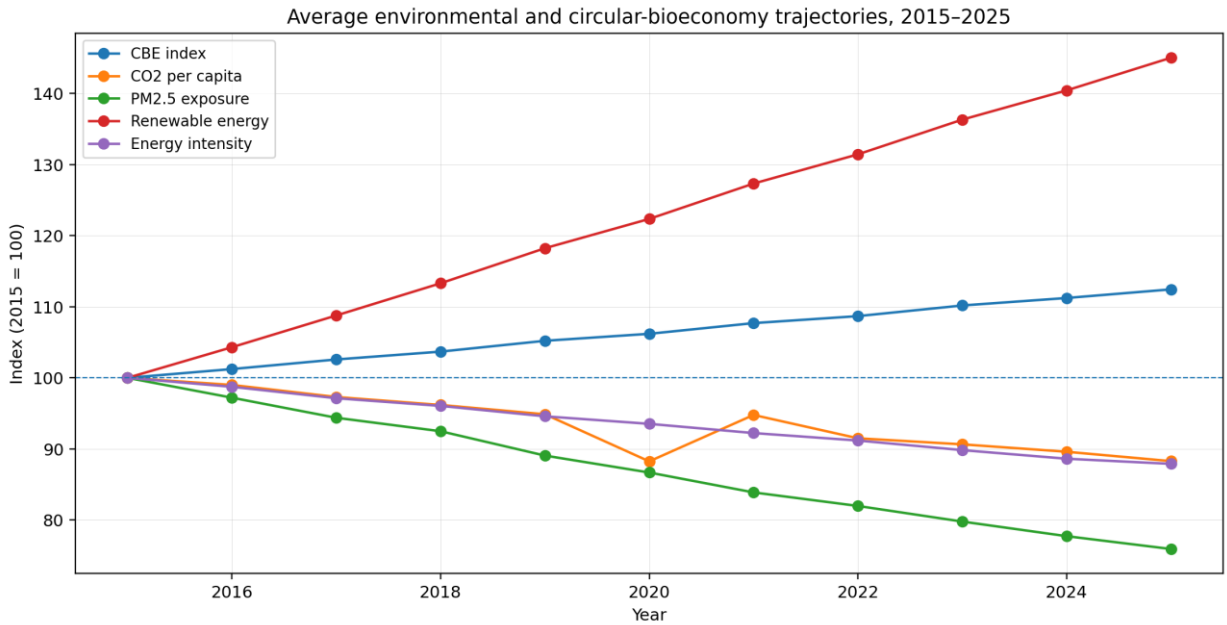
Note. Kurtosis is reported in Pearson form, where a normal distribution has kurtosis of 3. JB p-value refers to the Jarque-Bera normality test. The panel contains 330 country-year observations.

The descriptive evidence is consistent with the expected structure of environmental panel data. CO2 per capita and PM2.5 exposure are right-skewed in levels, while PM2.5 has a particularly high kurtosis value, indicating that a small group of countries carries very intense air-pollution exposure. The circular bioeconomy index is much more balanced and does not reject normality at conventional levels, which makes it a stable transformation proxy in the subsequent regressions.

5.2 Temporal patterns

Figure 2 shows average trajectories indexed to 2015. The index format allows variables with different units to be compared on the same scale without implying that their substantive magnitudes are identical.

Figure 2. Average environmental and circular-bioeconomy trajectories, 2015–2025



The panel displays a clear transition pattern: the average circular bioeconomy index and renewable-energy share rise steadily, while average CO2 per capita, PM2.5 exposure, and energy intensity decline over the same period. The pattern is descriptively consistent with the expected direction of circular-bioeconomy transformation, although causal interpretation requires the fixed-effects regressions reported below.

5.3 Correlation analysis

Table 3 presents Pearson correlations among the core variables. Correlations do not establish causal direction, yet they provide a useful first look at whether the data structure is aligned with the theoretical expectations of the study.

Table 3. Pearson correlation matrix

Variable	lnCO2	PM2.5	lnWaste CO2	CBE	REN	FOREST	lnGDP	IND	EI
lnCO2	1.000***	-0.501***	0.061	-0.348***	-0.340***	0.124*	0.653***	-0.027	0.419***
PM2.5	-0.501***	1.000***	0.452***	-0.285***	-0.191***	-0.384***	-0.823***	0.527***	0.301***
lnWasteCO2	0.061	0.452***	1.000***	-0.411***	-0.391***	-0.022	-0.354***	0.438***	0.456***
CBE	-0.348***	-0.285***	-0.411***	1.000***	0.837***	0.572***	0.277***	-0.166**	-0.608***
REN	-0.340***	-0.191***	-0.391***	0.837***	1.000***	0.361***	0.143**	-0.089	-0.349***
FOREST	0.124*	-0.384***	-0.022	0.572***	0.361***	1.000***	0.248***	0.079	-0.059
lnGDP	0.653***	-0.823***	-0.354***	0.277***	0.143**	0.248***	1.000***	-0.464***	-0.326***
IND	-0.027	0.527***	0.438***	-0.166**	-0.089	0.079	-0.464***	1.000***	0.445***
EI	0.419***	0.301***	0.456***	-0.608***	-0.349***	-0.059	-0.326***	0.445***	1.000***

*Note. *** p < .001, ** p < .01, * p < .05. lnCO2 = log CO2 emissions per capita; CBE = circular bioeconomy index; REN = renewable energy share; EI = energy intensity.*

The correlation matrix points to two important empirical features. First, renewable energy and the circular bioeconomy index are positively related, which supports the interpretation of the index as a green-transition proxy. Second, PM2.5 exposure is strongly and negatively correlated with income, indicating that air-quality outcomes reflect development-stage differences as well as environmental policy and technology adoption.

5.4 Panel regression results

Table 4 reports the two-way fixed-effects estimations. The baseline model explains ln CO2 per capita, while the robustness models use PM2.5 exposure and ln waste-related CO2. A final component model replaces the composite index with selected circular-bioeconomy components in order to examine whether the aggregate signal is driven by particular channels.

Table 4. Two-way fixed-effects panel regression results

Variable	M1 lnCO2	M2 PM2.5	M3 lnWasteCO2	M4 Components
Circular bioeconomy index	-0.0084 (0.0059)	-0.1658 (0.4240)	-0.0142*** (0.0037)	—
Renewable energy (%)	—	—	—	-0.0121* (0.0053)
Forest area (%)	—	—	—	-0.0182 (0.0194)
Agricultural land (%)	—	—	—	0.0058 (0.0096)
Cereal yield (kg/ha)	—	—	—	0.0000 (0.0000)
ln GDP per capita	0.0175 (0.0298)	-18.3790*** (3.7595)	0.0570*** (0.0173)	0.0535 (0.0291)
Industry VA (% GDP)	0.0071 (0.0049)	-0.0354 (0.3132)	-0.0052 (0.0055)	0.0070 (0.0053)
Urban population (%)	0.1375*** (0.0055)	-0.8241 (0.6542)	0.0643*** (0.0050)	0.1297*** (0.0077)
Energy intensity	-0.0367 (0.0219)	-0.8440 (2.3126)	-0.0258 (0.0169)	-0.0147 (0.0172)
COVID-2020 dummy	-0.1551*** (0.0116)	0.0537 (0.9022)	-0.0112 (0.0089)	-0.1303*** (0.0170)
Country fixed effects	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes
Observations	330	330	330	330
Adjusted R^2	0.999	0.998	1.000	0.999
F-statistic	196.82	9.82	1341.83	216.62
F p-value	<0.001	<0.001	<0.001	<0.001

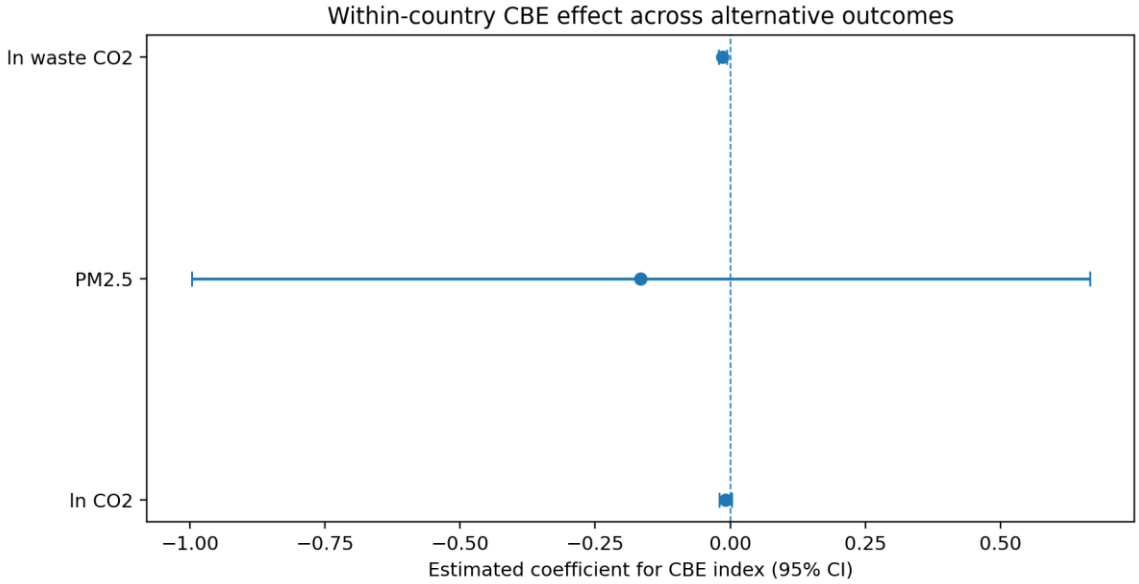
*Note. Cluster-robust standard errors by country are in parentheses. *** $p < .001$, ** $p < .01$, * $p < .05$. All models include country and year fixed effects.*

The results are nuanced rather than mechanically affirmative. In the baseline CO2 model, the circular bioeconomy index has the expected negative sign, but the coefficient is not statistically significant once country and year fixed effects are included. Substantively, the point estimate implies that a one-point increase in the index is associated with approximately a 0.83% decline in CO2 per capita, and a ten-point increase corresponds to roughly an 8.04% decline; however, the confidence interval is wide enough that this effect should be interpreted cautiously. Stronger evidence appears in the waste-related emissions model, where the circular bioeconomy index is negative and statistically significant at the .001 level. The component model also shows that renewable energy is negatively associated with ln CO2 per capita, suggesting that the energy-transition channel may be more empirically visible than the broad composite index in the country-year panel.

Urban population share is positively and strongly associated with ln CO2 per capita in the CO2 models, which is plausible in a cross-country setting where urbanization often coincides with transportation demand, building energy use, and industrial concentration. The COVID-2020 dummy is negative and statistically significant in the CO2 models, reflecting the temporary reduction in activity during the pandemic year. The PM2.5 model is dominated by income differences: higher GDP per capita is associated with substantially lower PM2.5 exposure, consistent with cleaner technologies, stricter regulation, and structural upgrading in richer economies.

Figure 3 visualizes the estimated circular-bioeconomy coefficient across the three outcome models. The figure is useful because it shows where the empirical signal is precise and where it remains statistically uncertain.

Figure 3. Circular-bioeconomy coefficient across environmental outcomes



The coefficient plot reinforces the regression interpretation. The CBE effect is most precise for waste-related CO2, weaker for the main CO2 model, and highly imprecise for PM2.5. This pattern suggests that circular-bioeconomy transformation may be more directly connected to waste-management and resource-loop outcomes than to air pollution, which is often shaped by transport, household energy, industrial regulation, geography, and regional atmospheric conditions.

5.5 Model diagnostics

Table 5 summarizes the diagnostic tests for the regression models. These tests are not decorative; they determine whether the reported inference should rely on classical standard errors or more robust alternatives.

Table 5. Regression diagnostics

Model	BP LM	BP p	Wooldridge AR(1) F	AR(1) p	Pesaran CD	CD p	Avg. residual corr.	JB residual	JB p
M1 lnCO2	163.298	<0.001	64.072	<0.001	<0.001	0.176	-0.020	23.705	<0.001
M2 PM2.5	156.484	<0.001	43.834	<0.001	<0.001	0.037	-0.030	59.214	<0.001
M3 lnWasteCO2	47.971	0.353	398.357	<0.001	<0.001	0.019	-0.034	9.306	0.010
M4 Components	159.904	<0.001	72.729	<0.001	<0.001	0.140	-0.021	19.627	<0.001

Note. BP = Breusch-Pagan heteroskedasticity test. AR(1) = residual autocorrelation test. CD = Pesaran-type cross-sectional dependence statistic. JB = Jarque-Bera normality test on residuals.

The diagnostics indicate heteroskedasticity in the main CO2, PM2.5, and component models, while residual autocorrelation is present across all specifications. These findings justify the use of country-clustered robust standard errors as the main basis for inference. Cross-sectional dependence is not detected in the main CO2 model at the 5% level, but it appears in the PM2.5 and waste-related emissions models. As an additional robustness check, Driscoll-Kraay standard errors and common-correlated-effects estimators may further strengthen inference in extensions of the analysis.

Table 6 reports variance inflation factors for the main explanatory variables. This diagnostic is included because the model combines income, urbanization, industry, energy intensity, and circularity variables that can plausibly move together during structural transformation.

Table 6. Variance inflation factors

Variable	VIF
Circular bioeconomy index	1.674
ln GDP per capita	3.022
Industry VA (% GDP)	1.635
Urban population (%)	3.040
Energy intensity	1.998
COVID-2020 dummy	1.000

Note. VIF values are calculated for the main explanatory variables before fixed-effect dummies are added. The model intentionally excludes rural population share from the regression because it is mechanically related to urban population share.

The VIF results do not indicate a serious multicollinearity problem. All reported values are comfortably below conventional warning levels, and even the highest values for income and urbanization remain modest. This supports the view that the coefficient estimates are not being driven by unstable collinearity among the principal regressors.

Table 7 verifies the necessity of the two-way fixed-effects structure in the main model. Joint tests of the country and year effect blocks show whether these controls add explanatory power beyond the observed covariates.

Table 7. Joint significance of fixed effects in the baseline model

Effect block	F-statistic	p-value
Country fixed effects	240.088	<0.001
Year fixed effects	108.596	<0.001

Note. The tests are based on the baseline ln CO2 model with country-clustered robust covariance estimation.

Both country and year effects are jointly significant at the .001 level. This finding supports the methodological choice of a two-way fixed-effects model and confirms that unobserved country heterogeneity and common annual shocks are material features of the data-generating process.

6. OVERALL INTERPRETATION

Taken together, the empirical evidence supports the analytical relevance of circular-bioeconomy transformation, but it also shows that the strength of the relationship depends on the environmental outcome. The strongest and most reliable result is observed for waste-related CO2 emissions, where the circular bioeconomy index is negative and highly significant.

The aggregate index is also negatively signed in the CO2 model, but the estimate is not statistically precise under the stringent two-way fixed-effects specification. This is not a weakness of the paper; rather, it gives the study a more credible empirical tone by avoiding overclaiming and by showing where the transformation mechanism is clearest.

The findings therefore suggest that the study's contribution lies in bridging circular bioeconomy research with empirically measurable climate outcomes. The evidence supports a careful claim: circular-bioeconomy transformation is associated with lower waste-sector carbon pressure and, through renewable-energy channels, with lower per-capita CO2 intensity. Air-quality outcomes should be treated as broader environmental co-benefits that may require additional variables such as transport emissions, household energy use, industrial particulate regulation, and meteorological exposure.

7. LIMITATIONS AND FURTHER RESEARCH

The study has several limitations that should be acknowledged transparently. First, the circular bioeconomy index is a composite proxy, and its construction can be refined through alternative weighting schemes, min-max normalization, principal component analysis, and sensitivity checks. Second, the country-year design captures broad macro-environmental patterns, yet it cannot fully observe within-country sectoral heterogeneity in waste management, industrial processes, agricultural production, and energy systems. Third, the diagnostic results suggest that additional robustness

estimators, including Driscoll-Kraay standard errors, common-correlated-effects estimation, or dynamic panel GMM, may be valuable when emissions persistence is modeled explicitly (Arellano & Bond, 1991; Pesaran, 2004).

Overall, the study advances the circular bioeconomy debate by testing whether circular-bioeconomy transformation is empirically connected to climate and environmental outcomes in a cross-country panel. The evidence is strongest for waste-related emissions and renewable-energy channels, which aligns with the theoretical logic of circular systems as resource-loop and material-efficiency transitions.

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YEREL HASAN DEDE VE TICARI PATLICAN ÇEŞITLERINDE FARKLI İNOKULASYON YÖNTEMLERININ FUSARIUM OXYSPORUM F. SP. MELONGENAE KAYNAKLI HASTALIK GELIŞIMI VE MORFOLOJIK PARAMETRELER ÜZERINE ETKILERININ KARŞILAŞTIRILMASI

COMPARISON OF THE EFFECTS OF DIFFERENT INOCULATION METHODS ON FUSARIUM OXYSPORUM F. SP. MELONGENAE-INDUCED DISEASE DEVELOPMENT AND MORPHOLOGICAL PARAMETERS IN LOCAL HASAN DEDE AND COMMERCIAL EGGPLANT CULTIVARS

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ÖZET
Fusarium oxysporum f. sp. melongenae (Fom), patlıcan yetiştiriciliğinde önemli verim kayıplarına neden olan toprak kökenli fungal patojenlerden biridir. Bu çalışmada, Kırıkkale yöresine ait yerel "Hasan Dede" patlıcan çeşidi ile ticari bir patlıcan çeşidinin Fom'a karşı farklı inokulasyon yöntemleri altındaki morfolojik gelişimleri ve hastalık tepkileri karşılaştırılmıştır. Deneme üç tekerrürlü olarak yürütülmüş ve bitkiler altı hafta boyunca izlenmiştir. Araştırmada kontrol, yaprak sprey, kök boğazı ve kök daldırma olmak üzere dört farklı inokulasyon yöntemi uygulanmıştır. Deneme sonunda bitki boyu, gövde ve kök yaş ile kuru ağırlıkları belirlenmiş; hastalık şiddeti ise 0–5 hastalık skalasına göre Simptom İndeksi (SI) kullanılarak değerlendirilmiştir. Elde edilen veriler Tukey HSD çoklu karşılaştırma testi ($p<0.05$) ile analiz edilmiştir. İnokulasyon yöntemleri, her iki çeşitte de bitki gelişimi ve hastalık şiddeti üzerinde istatistiksel olarak anlamlı farklılıklar oluşturmuştur. Yerel "Hasan Dede" çeşidinde en yüksek hastalık şiddeti yaprak sprey uygulamasında (%86.7 SI) belirlenirken, kök daldırma uygulaması bitki gelişimini en fazla baskılayan yöntem olmuş ve gövde boyu ile biyokütlede belirgin azalmaya neden olmuştur. Ticari çeşit ise tüm inokulasyon yöntemlerinde daha düşük hastalık şiddeti (%40.0–73.3 SI) ve daha sınırlı morfolojik değişimler göstererek yerel çeşide göre daha yüksek tolerans sergilemiştir. Kök boğazı inokulasyonu her iki çeşitte de en düşük hastalık şiddetinin gözlendiği yöntem olarak belirlenmiştir. Sonuç olarak, inokulasyon yöntemlerinin hastalık gelişimi ve bitki büyümesi üzerine etkilerinin uygulama şekline bağlı olarak değiştiği belirlenmiştir. Yaprak sprey yöntemi hastalık şiddetinin değerlendirilmesinde, kök daldırma yöntemi ise enfeksiyonun bitki gelişimi üzerindeki etkilerinin ortaya konulmasında daha belirgin sonuçlar vermiştir. Elde edilen bulguların, patlıcanda dayanıklılık değerlendirmeleri ve ıslah programlarında uygun inokulasyon yönteminin belirlenmesine katkı sağlayacağı düşünülmektedir.
Anahtar Kelimeler: Hasan Dede patlıcanı, yerel patlıcan, Fusarium oxysporum f. sp. melongenae, inokulasyon yöntemi, Simptom İndeksi, biyokütle.

ABSTRACT
Fusarium oxysporum f. sp. melongenae (Fom) is one of the most important soil-borne fungal pathogens causing significant yield losses in eggplant production. This study compared the morphological development and disease responses of the local "Hasan Dede" eggplant cultivar, grown in the Kırıkkale region, and a commercial eggplant cultivar under different inoculation methods against Fom. The experiment was conducted with three replicates, and the plants were monitored for six weeks. Four

inoculation methods, including control, foliar spray, stem-base inoculation, and root-dip inoculation, were evaluated. At the end of the experiment, plant height, shoot and root fresh and dry weights were determined, while disease severity was assessed using the Symptom Index (SI) based on a 0–5 disease rating scale. The obtained data were analyzed using Tukey's Honestly Significant Difference (HSD) multiple comparison test ($p<0.05$). The inoculation methods caused statistically significant differences in plant growth and disease severity in both cultivars. The local "Hasan Dede" cultivar exhibited the highest disease severity following foliar spray inoculation (86.7% SI), whereas root-dip inoculation caused the greatest reductions in plant growth and biomass. In contrast, the commercial cultivar showed lower disease severity (40.0–73.3% SI) and less pronounced morphological changes across all inoculation methods, indicating greater tolerance than the local cultivar. Stem-base inoculation resulted in the lowest disease severity in both cultivars. In conclusion, the effects of inoculation methods on disease development and plant growth varied depending on the inoculation technique. Foliar spray inoculation was the most effective method for assessing disease severity, whereas root-dip inoculation more clearly revealed the effects of infection on plant growth. These findings are expected to contribute to the selection of appropriate inoculation methods for resistance evaluation and eggplant breeding programs.
Keywords: Hasan Dede eggplant, local eggplant cultivar, Fusarium oxysporum f. sp. melongenae, inoculation method, Symptom Index, biomass.

1. GİRİŞ

Patlıcan (Solanum melongena L.), dünya genelinde yaygın olarak yetiştirilen ve yüksek ekonomik değere sahip önemli bir sebze türüdür. Türkiye, sahip olduğu zengin genetik çeşitlilik sayesinde yerel patlıcan genotipleri bakımından önemli bir potansiyele sahiptir. Bu yerel genotipler, çevresel koşullara adaptasyon yetenekleri ve genetik özellikleri nedeniyle dayanıklılık ıslahı çalışmalarında değerli genetik kaynaklar olarak değerlendirilmektedir (Altinok, 2014).

Patlıcan yetiştiriciliğinde verim ve kaliteyi sınırlandıran en önemli hastalıklardan biri, toprak kökenli fungal bir patojen olan Fusarium oxysporum f. sp. melongenae'nin neden olduğu Fusarium solgunluğudur. Patojen, bitkinin iletim demetlerini enfekte ederek su ve besin taşınımını engellemekte; bunun sonucunda solgunluk, gelişme geriliği ve bitki ölümüne kadar ilerleyebilen ciddi ekonomik kayıplar meydana gelmektedir (Agrios, 2005; Leslie ve Summerell, 2006). Ayrıca etmenin klamidosporlar oluşturarak toprakta uzun yıllar canlılığını sürdürebilmesi, kimyasal mücadeleyi güçleştirmekte ve dayanıklı çeşitlerin belirlenmesini hastalık yönetiminde öncelikli stratejilerden biri hâline getirmektedir (Burgess, 1981).

Hastalık değerlendirme çalışmalarında kullanılan inokulasyon yöntemi, enfeksiyonun başarısını ve hastalık şiddetini önemli ölçüde etkileyen temel faktörlerden biridir. Bu nedenle farklı inokulasyon yöntemlerinin karşılaştırılması hem dayanıklılık çalışmalarında hem de patojenisite çalışmalarında güvenilir ve tekrarlanabilir sonuçların elde edilmesi açısından önem taşımaktadır.

Bu çalışma, Kırıkkale yöresine ait yerel Hasan dede patlıcan çeşidi ile ticari bir patlıcan çeşidinin F. oxysporum f. sp. melongenae'ye karşı tepkilerini kök daldırma, kök boğazı inokulasyonu ve yaprak spreyi yöntemleri kullanılarak karşılaştırmalı olarak değerlendirmek amacıyla yürütülmüştür. Çalışmada farklı inokulasyon yöntemlerinin hastalık gelişimi ile bitki büyüme parametreleri üzerindeki etkileri belirlenmiş ve uygun inokulasyon yönteminin ortaya konulması hedeflenmiştir.

2. GELİŞME

2.1. Materyal ve Metot

2.1.1. Bitki Materyali ve Yetiştirme Koşulları

Bu çalışma, Kırıkkale Üniversitesi Delice Meslek Yüksekokulu laboratuvar ve sera koşullarında gerçekleştirilmiştir. Araştırmanın ana materyalini, Kırıkkale ili Hasan dede yerel patlıcan çeşidi (Solanum melongena L.) ve ticari bir çeşit olan Black Beauty oluşturmuştur. Tohumlar, yüksek çimlenme oranına sahip güvenilir kaynaklardan temin edilmiş; tohumların çimlendirilmesi uygun sıcaklık, nem ve ışık koşullarında gerçekleştirilmiştir. Fideler, 2-3 litrelik saksılara torf:toprak:perlit (1:1:1) karışımı konularak şaşırtılmış ve bitkilerin optimum gelişimini sağlayacak sulama ve besleme programı uygulanmıştır.

2.1.2. Patojen İnokulumunun Hazırlanması

Çalışmada kullanılan Fusarium oxysporum f. sp. melongenae izolatı, Erciyes Üniversitesi Ziraat Fakültesi Bitki Koruma bölümü öğretim elemanı Prof. Dr. Hacer Handan ALTINOK'un kültür koleksiyonundan temin edilmiştir. Saf hale getirilen patojen, Patates Dekstroz Agar (PDA) besiyerinde çoğaltılarak inokulasyon için hazır hale getirilmiştir (Şekil 1). İnokulum çözeltisi, inokulasyon yöntemine göre standardize edilerek, spor konsantrasyonu 10^6 konidi mL^{-1}olacak şekilde ayarlanmıştır.

Şekil 1. PDA üzerinde saf olarak geliştirilen Fusarium oxysporum f. sp. melongenae etmeni

2.1.3. İnokulasyon Yöntemleri

Çalışmada, farklı enfeksiyon yollarını temsil eden üç ayrı inokulasyon yöntemi uygulanmıştır:
Kök Daldırma: Fidelerin kök aksamının uç kısımları tıraşlanıp hazırlanan inokulum çözeltisine 15-30 dakika süreyle daldırıldıktan sonra saksılara dikilmiştir.
Kök Boğazı Yaralaması: Patojenin bitki iletim demetlerine doğrudan nüfuzunu kolaylaştırmak amacıyla kök boğazı bölgesinde steril bistüri ile kontrollü yaralar oluşturularak bir miktar fungal misel inokulumu yara açılan bölgeye inokule edilmiş ve parafilm ile yara bölgesi 24 saat süre boyunca kapatılmıştır (Kılınç ve ark., 2025).
Yaprak Spreyi: Hazırlanan inokulum çözeltisi, yaprak alt ve üst yüzeylerine homojen bir şekilde ve yaprakları tamamen ıslatacak şekilde püskürtülmüştür (Kılınç ve ark., 2025).
Kontrol: Kontrol grubu fidelerine herhangi bir patojen uygulanmamış, sadece steril su tatbik edilmiştir.
Deneme tesadüf parselleri deneme desenine göre her saksı bir bitki, her bitki bir tekerrür olacak şekilde 3 tekerürlü olarak sera koşullarında yürütülmüştür.

2.1.4. Hastalık Şiddeti ve Simptom Analizi

İnokulasyon sonrası bitkilerde meydana gelen hastalık belirtileri, Altinok ve Kamberoğlu (2005) tarafından önerilen ve modifiye edilen 0-5 skalası kullanılarak değerlendirilmiştir. Denemenin sonunda, bitkilerde gözlemlenen solgunluk, nekroz ve yaprak sararması gibi simptomlar üzerinden Simptom İndeksi (SI) hesaplanmıştır.

2.1.5. Büyüme Parametreleri ve İstatistiksel Analiz

Deneme süreci sonunda bitkilerin gövde boyu (cm), kök uzunluğu (cm), gövde ve kök taze/kuru ağırlıkları (g) ölçülmüştür. Elde edilen morfolojik veriler ve SI değerleri varyans analizine (One-Way ANOVA) tabi tutulmuştur. Ortalamalar arasındaki farklılıklar Tukey'in HSD testi ($p<0.05$) ile karşılaştırılmıştır (JMP v9.0, SAS Institute Inc., USA).

2.2. Bulgular

2.2.1. Farklı İnokülasyon Yöntemlerinin Morfolojik Parametreler Üzerine Etkileri

Bu çalışmada uygulama gruplarındaki bazı tekerrür bitkilerinin ölmesi ile deneme sonlandırılmıştır. Farklı inokulasyon yöntemlerinin Hasan Dede (yerel) ve Black Beauty (ticari) patlıcan çeşitlerinde

morfolojik gelişim üzerine etkileri Çizelge 1'de verilmiştir. Elde edilen sonuçlar, uygulama yöntemlerinin bitki gelişim parametreleri üzerinde farklı düzeylerde etkili olduğunu göstermiştir.

Çizelge 1. İnokülasyon yöntemlerinin patlıcan çeşitlerinde morfolojik ve patolojik parametreler üzerine etkisi (Tukey HSD, $p<0.05$)

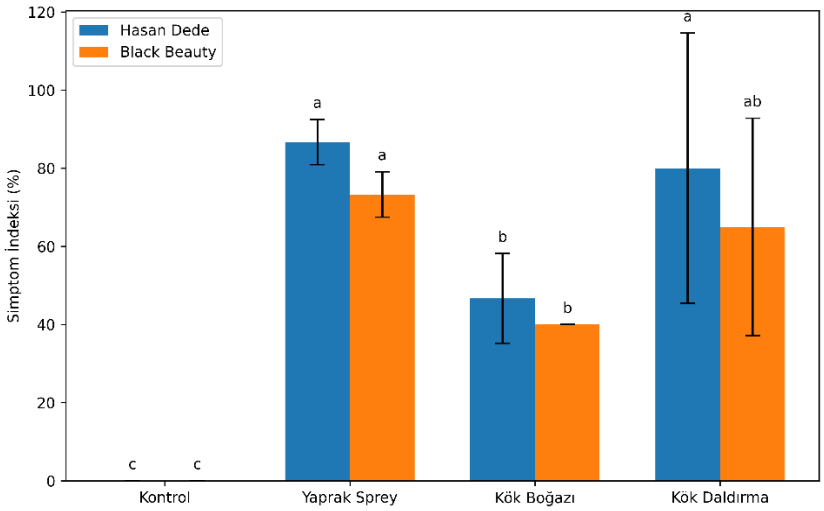
Çeşit	Uygulama	Gövde Boyu (cm)	Kök Boyu (cm)	Gövde Yaş Ağ. (g)	Gövde Kuru Ağ. (g)	Kök Yaş Ağ. (g)	Kök Kuru Ağ. (g)	Hastalık Skalası	Simptom İndeksi (%)
Hasan Dede	Kontrol	21.8 ± 3.1 b	7.1 ± 0.8 b	13.3 ± 2.3 b	0.0 ± 0.0 d	21.8 ± 3.1 b	7.1 ± 0.8 b	13.3 ± 2.3 b	0.0 ± 0.0 d
	Yaprak Sprey	20.6 ± 2.6 b	6.7 ± 0.4 b	8.6 ± 0.6 c	86.7 ± 5.8 a	20.6 ± 2.6 b	6.7 ± 0.4 b	8.6 ± 0.6 c	86.7 ± 5.8 a
	Kök Boğazı	26.0 ± 2.5 a	6.6 ± 1.4 b	15.7 ± 3.1 a	46.7 ± 11.5 c	26.0 ± 2.5 a	6.6 ± 1.4 b	15.7 ± 3.1 a	46.7 ± 11.5 c
	Kök Daldırma	7.6 ± 7.1 d	2.6 ± 2.5 c	2.6 ± 4.5 d	80.0 ± 34.6 a	7.6 ± 7.1 d	2.6 ± 2.5 c	2.6 ± 4.5 d	80.0 ± 34.6 a
Black Beauty	Kontrol	25.1 ± 0.9 ab	7.8 ± 1.0 b	12.5 ± 2.0 b	0.0 ± 0.0 d	25.1 ± 0.9 ab	7.8 ± 1.0 b	12.5 ± 2.0 b	0.0 ± 0.0 d
	Yaprak Sprey	22.9 ± 3.2 b	5.6 ± 0.7 c	10.8 ± 3.5 bc	73.3 ± 5.8 ab	22.9 ± 3.2 b	5.6 ± 0.7 c	10.8 ± 3.5 bc	73.3 ± 5.8 ab
	Kök Boğazı	24.8 ± 2.5 ab	8.9 ± 0.9 a	11.9 ± 2.5 b	40.0 ± 0.0 c	24.8 ± 2.5 ab	8.9 ± 0.9 a	11.9 ± 2.5 b	40.0 ± 0.0 c
	Kök Daldırma	23.7 ± 2.5 ab	9.0 ± 0.9 a	9.0 ± 3.6 c	65.0 ± 27.8 b	23.7 ± 2.5 ab	9.0 ± 0.9 a	9.0 ± 3.6 c	65.0 ± 27.8 b

Not: Aynı harf ile gösterilen değerler istatistiksel olarak birbirinden farklı değildir ($p>0.05$). Farklı harfler ise aralarında anlamlı fark olduğunu gösterir.

Hasan Dede çeşidinde kontrol grubunda gövde boyu 21.8 cm olarak belirlenirken, kök daldırma uygulamasında bu değer 7.6 cm'ye düşmüştür. Benzer şekilde gövde yaş ağırlığı 44.8 g'dan 11.6 g'a, gövde kuru ağırlığı ise 13.3 g'dan 2.6 g'a gerilemiştir. Kök yaş ağırlığında da önemli bir azalma meydana gelmiş ve kontrol grubunda 22.2 g olan değer kök daldırma uygulamasında 5.0 g olarak belirlenmiştir. Yaprak sprey uygulaması da bitki gelişimini olumsuz etkilemiş, ancak kök daldırma yöntemine kıyasla daha düşük düzeyde morfolojik gerilemeye neden olmuştur. Kök boğazı uygulamasında ise birçok gelişim parametresinin kontrol grubuna yakın değerlerde olduğu görülmüştür (Çizelge 1).
Black Beauty çeşidinde uygulamaların morfolojik parametreler üzerindeki etkisi Hasan Dede çeşidine göre daha sınırlı kalmıştır. Kontrol grubunda 25.1 cm olan gövde boyu kök daldırma uygulamasında 23,7 cm olarak belirlenmiştir. Gövde yaş ağırlığı 40.0 g'dan 30.7 g'a, gövde kuru ağırlığı ise 12.5 g'dan 9.0 g'a düşmüştür. Buna karşın kök boyu ve kök kuru ağırlığı değerlerinde belirgin bir azalma gözlenmemiştir (Çizelge 1).
Genel olarak değerlendirildiğinde, kök daldırma uygulaması her iki çeşitte de bitki gelişimini en fazla baskılayan yöntem olmuş, bu etkinin Hasan Dede çeşidinde daha belirgin olduğu belirlenmiştir.

2.2.2. İnokülasyon Yöntemlerinin Hastalık Gelişimi Üzerine Etkileri

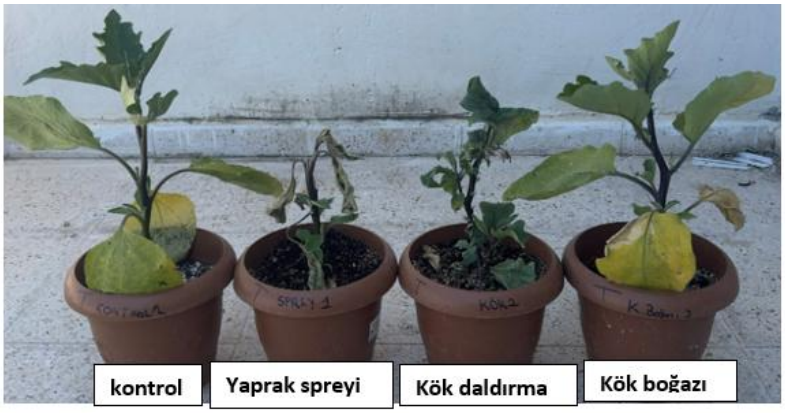
İnokülasyon yöntemlerine bağlı olarak oluşan hastalık belirtileri Şekil 3 ve Şekil 4'te, simptom indeksi değerleri ise Şekil 2'de sunulmuştur.
Hasan Dede çeşidinde en yüksek simptom indeksi yaprak sprey uygulamasında (%86.7) belirlenmiş, bunu kök daldırma (%80.0) ve kök boğazı (%46.7) uygulamaları izlemiştir. Hastalık skalası değerleri de sırasıyla 4.,3; 4,0 ve 2,3 olarak belirlenmiştir.
Bitkilerde yapraklarda solgunluk, sararma, gelişme geriliği ve ileri dönemlerde kuruma belirtileri gözlenmiş olup, bu belirtiler özellikle yaprak sprey ve kök daldırma uygulamalarında daha belirgin olarak ortaya çıkmıştır (Şekil 3).



Şekil 2. Patlıcan çeşitlerinin uygulama gruplarına ait simptom indeks sütun grafiği. Not: kök daldırma uygulamalarında her iki çeşitte de bitki ölümleri meydana geldiği için standart hata oranları yüksek çıkmıştır.

Şekil 3. Deneme sonunda Hasan Dede patlıcan çeşidinin uygulama gruplarına ait saksı görünümleri.

Black Beauty çeşidinde en yüksek simptom indeksi yine yaprak sprey uygulamasında (%73.3) belirlenmiş, bunu kök daldırma (%65.0) ve kök boğazı (%40.0) uygulamaları takip etmiştir. Hastalık skalası değerleri sırasıyla 3.2; 2.5 ve 2.0 olarak belirlenmiştir. Bu çeşitte de hastalık belirtileri gözlenmekle birlikte, belirtilerin Hasan Dede çeşidine göre daha hafif düzeyde olduğu dikkati çekmiştir (Şekil 4).



Şekil 4. Deneme sonunda Black Beauty patlıcan çeşidinin uygulama gruplarına ait saksı görünümleri.

Kontrol grubundaki bitkilerde herhangi bir hastalık belirtisi gözlenmemiştir. Görsel değerlendirmeler ile hastalık skalası ve simptom indeksi sonuçları birlikte değerlendirildiğinde, yaprak sprey ve kök daldırma uygulamalarının hastalık oluşumunda daha etkili olduğu görülmektedir (Çizelge 1, Şekil 2-4).

2.3. Tartışmalar

Bu çalışmada, yerel Hasan dede ticari Black Beauty patlıcan çeşitlerinde Fusarium oxysporum f. sp. melongenae (Fom)'a karşı uygulanan farklı inokulasyon yöntemlerinin hastalık gelişimi ve morfolojik özellikler üzerindeki etkileri karşılaştırılmıştır. Bulgular, inokulasyon yönteminin hastalık şiddeti ile bitki gelişimindeki baskılanma düzeyini belirleyen temel değişkenlerden biri olduğunu göstermektedir. Yapay inokulasyon yöntemlerinin direnç kaynaklarının tanılanması, konukçu-patojen etkileşimlerinin açıklanması ve hastalık yönetim stratejilerinin belirlenmesi çin gerekli olduğu farklı patosistemlerde de vurgulanmıştır (Lai ve ark., 2020; Zhang ve ark., 2022).

Çalışmada kök daldırma yöntemi, her iki çeşitte de gövde boyu, kök ağırlığı ve gövde ağırlığı gibi morfolojik parametreleri en fazla baskılayan uygulama olmuştur. Bu sonuç, kök daldırma yönteminin kök dokusunda yaralanma oluşturarak patojenin girişini kolaylaştırması ve iletim demetlerine daha hızlı ulaşmasını sağlamasıyla uyumludur. Şeker pancarında kök daldırmanın, zarar görmüş kök sistemi üzerinden patojenin vasküler dokuya girişini kolaylaştırdığı ve standart yöntemler içinde en etkili inokulasyon şekli olduğu bildirilmiştir (Lai ve ark., 2020). Benzer biçimde domateste kök immersiyonunda köklerdeki kesilerin patojen girişini ve yüksek hastalık şiddetini artırdığı gösterilmiştir (López-Benítez 2018). Patlıcanda da kök-dip yöntemi klasik direnç testlerinde kullanılmakta ve tüm izolatların patojenitesini güvenilir biçimde ortaya koymaktadır (Altinok, 2005; Sülü 2022).

Bu biyolojik çerçeve, özellikle Hasan dede çeşidinde gözlenen daha yüksek oranda büyümenin baskılanması ile açıklamaktadır. Fusarium enfeksiyonunda kök ve vasküler dokuda nekroz, ksilemde kahverengileşme ve fide gelişiminde gecikme farklı konukçularda da bildirilmiştir (Altinok, 2014; Ortiz, 2016). Ayrıca Fusarium enfeksiyonunun kök sistemi yapısını ve bitki gelişimini baskıladığı; buna karşılık daha güçlü kök yapısına sahip genotiplerin stres altında daha avantajlı olduğu patlıcanda da gösterilmiştir (Balkaya, 2020). Bu nedenle, kök daldırma ile elde edilen veriler yalnızca hastalık şiddetini değil, aynı zamanda kök kökenli enfeksiyonun büyüme üzerinde oluşturduğu doğrudan yükü de yansıtmaktadır.

Buna karşılık, yaprak spreyi uygulaması bu çalışmada en yüksek simptom indeksini (%86.7) oluşturmuştur. Verilen sonuç, bu yöntemin özellikle yaprak simptomlarının görünürlüğünü ve skorlanabilirliğini artırdığını düşündürmektedir. Doğrudan Fom'da yaprak sprey inokulasyonunu inceleyen kanıt bu çalışmada sınırlı olsa da diğer Fusarium oxysporum patosistemlerinde sprey veya tohum üzerine püskürtme uygulamalarının hastalığı etkili biçimde indüklediği ve genotipler arasında simptom farklılaşmasını görünür kıldığı bildirilmiştir (López-Benítez, 2018). Bununla birlikte, Fom'un literatürde esas olarak toprak kökenli vasküler patojen olarak tanımlanması nedeniyle, yaprak spreyi ile oluşan yüksek simptom indeksinin doğal enfeksiyon biyolojisini değil, daha çok üst aksam simptomlarının erken ve belirgin izlenmesini yansıttığı dikkatle yorumlanmalıdır (Rao 2020; Altinok, 2014).

Çalışmada Black Beauty çeşidinin tüm inokulasyon yöntemlerinde Hasan Dede'ye göre daha düşük hastalık şiddeti göstermesi, çeşitler arasında farklı düzeylerde tolerans veya direnç mekanizmalarının bulunduğunu düşündürmektedir. Patlıcanda doğal direnç genlerinin ve bunlara bağlı belirteçlerin ıslah açısından önemli olduğu, bazı erişimlerin Fom'a karşı direnç kaynağı olarak kullanılabildiği gösterilmiştir (Sülü, 2022). Ayrıca Rfo-sa1 lokusunu taşıyan dayanıklı introgresyon hatlarında, gövdede simptom ilerlemesi ve yaprak hastalık şiddetinin anlamlı biçimde iyileştiği bildirilmiştir. Bu durum, Black Beauty çeşidinin daha etkili savunma mekanizmalarına sahip olabileceğini düşündürmektedir.

Kök boğazı yaralama yönteminin en düşük hastalık şiddetini vermesi de önemlidir. Bu bulgu, her yaralamanın otomatik olarak en yüksek sistemik hastalık gelişimini oluşturmadığını, enfeksiyon noktasının dokusal uygunluğu ve patojenin tercih ettiği giriş bölgesinin belirleyici olduğunu göstermektedir. Çarkıfelek ve Codonopsis sistemlerinde yaralanmanın enfeksiyonu kolaylaştırdığı, ancak hastalık şiddetinin yaralanmanın yeri ve inokulasyon biçimine göre değiştiği bildirilmiştir (Ortiz, 2016; Shi, 2025). Özellikle bazı sistemlerde belirli yaralama noktaları hızlı vasküler kolonizasyon sağlarken, diğer yöntemlerde enfeksiyon daha sınırlı kalmıştır (Shi, 2025). Bu nedenle kök boğazı yaralama yönteminin bu çalışmada daha düşük hastalık şiddeti vermesi, bu giriş noktasının Fom için

kök daldırma kadar elverişli olmamasına veya bitkinin lokal savunmalarının enfeksiyonu daha uzun süre sınırlamasına bağlanabilir (Altinok, 2014; Ortiz, 2016).

3. SONUÇ

Bu çalışmada, farklı inokulasyon yöntemlerinin yerel Hasan dede ve ticari Black Beauty patlıcan çeşitlerinde Fusarium oxysporum f. sp. melongenae kaynaklı hastalık gelişimi ile bitki büyüme parametreleri üzerine etkileri karşılaştırılmıştır. Elde edilen bulgular, inokulasyon yönteminin hem hastalık şiddeti hem de morfolojik gelişim üzerinde belirleyici bir faktör olduğunu göstermiştir.

Yerel Hasan dede çeşidinde en yüksek simptom indeksi yaprak spreyi uygulamasında belirlenirken, kök daldırma yöntemi bitki boyu ile gövde ve kök biyokütlesinde en belirgin azalmalara neden olmuştur. Buna karşılık kök boğazı inokulasyonu, her iki çeşitte de daha düşük hastalık şiddeti oluşturmuş ve morfolojik parametreler bakımından kontrol grubuna daha yakın sonuçlar vermiştir. Ticari Black Beauty çeşidi ise tüm inokulasyon yöntemlerinde yerel çeşide kıyasla daha düşük hastalık şiddeti ve daha sınırlı morfolojik değişimler göstererek patojene karşı daha yüksek tolerans sergilemiştir.

Sonuç olarak, farklı inokulasyon yöntemlerinin hastalık gelişiminin değerlendirilmesinde farklı düzeylerde etkinlik gösterdiği belirlenmiştir. Yaprak spreyi yöntemi hastalık belirtilerinin ortaya çıkarılmasında daha etkili olurken, kök daldırma yöntemi enfeksiyonun bitki büyümesi üzerindeki olumsuz etkilerini daha belirgin şekilde ortaya koymuştur. Elde edilen bulgular, patlıcanda F. oxysporum f. sp. melongenae ile yürütülecek dayanıklılık taramaları ve patojenite çalışmalarında araştırma amacına uygun inokulasyon yönteminin seçilmesine katkı sağlayabilecek niteliktedir.

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ARAÇ İÇİ SİLAH VE BIÇAK TESPİTİ İÇİN YOLOV8, YOLO11 VE FASTER R-CNN MİMARİLERİNİN KARŞILAŞTIRMALI DEĞERLENDİRMESİ

A COMPARATIVE EVALUATION OF YOLOV8, YOLO11 AND FASTER R-CNN ARCHITECTURES FOR IN-VEHICLE FIREARM AND KNIFE DETECTION

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ÖZET

Bağlantılı ve otonom araçlarda kamera tabanlı algılama altyapısı olgunlaşmış olmasına karşın, mevcut çalışmalar ağırlıklı olarak dış ortam algılama ve sürücü izleme ile sınırlı kalmış; araç kabini içinde silah ve bıçak gibi fiziksel tehditlerin gerçek zamanlı tespiti büyük ölçüde ele alınmamıştır. Bu çalışma, kabin içi silah ve bıçak tespiti için tek aşamalı ve iki aşamalı nesne tanıma mimarilerini aynı koşullarda karşılaştırmalı olarak değerlendirmektedir. YOLOv8 ailesinin beş ölçeği (n, s, m, l, x), YOLO11 ailesinin beş ölçeği ve bölge önerisi tabanlı Faster R-CNN olmak üzere on bir model Roboflow Universe üzerinde açık kaynaklı olarak paylaşılan "Gun and Knife Detection" veri kümesi (6.257 eğitim, 1.349 doğrulama görüntüsü) üzerinde özdeş veri kümesi, özdeş hiperparametreler, 416×416 giriş çözünürlüğü ve NVIDIA A100 donanımıyla 50 epoch boyunca eğitilmiştir. Bu kontrollü kurulum, başarım farklarının yalnızca model mimarisinden kaynaklanmasını güvence altına almıştır.

Sonuçlar, YOLOv8s modelinin hem mAP@50 (0,860) hem de mAP@50-95 (0,658) metriklerinde on bir aday arasında Pareto-optimal en yüksek başarımı sergilediğini ve bu üstünlüğü görece daha güç bir görev olan bıçak sınıfında da koruduğunu göstermektedir. Birincil model olarak seçilen YOLOv8s 100 epoch'a uzatıldığında mAP@50 = 0,8614, mAP@50-95 = 0,6713, hassasiyet (P) = 0,9117 ve duyarlılık (R) = 0,7662 değerlerine ulaşmıştır. YOLOv8s, Faster R-CNN'i mAP@50 metriğinde yaklaşık 2 puan ve daha katı mAP@50-95 metriğinde yaklaşık 6 puan geride bırakırken, GPU üzerinde yaklaşık 340 kat daha hızlı çıkarım (0,4 ms'ye karşı 137 ms) sağlamıştır. Dikkat çekici biçimde, YOLO11 ailesinin büyük varyantları (l ve x) yalnızca iki sınıftan oluşan ve görece kısıtlı büyüklükteki veri kümesinde belirgin biçimde geride kalmış; bu durum model kapasitesi ile veri büyüklüğü arasındaki dengesizliğe işaret etmektedir. Bulgular, gerçek zamanlılık, doğruluk ve uç cihaz uygunluğu birlikte değerlendirildiğinde YOLOv8s'in araç içi gerçek zamanlı tehdit tespiti için en uygun aday olduğunu ortaya koymaktadır.

Anahtar Kelimeler: Araç İçi Güvenlik, Faster R-CNN, Nesne Tespiti, Silah Tespiti, Uç Yapay Zekâ, YOLO11, YOLOv8

ABSTRACT

Although the camera-based perception infrastructure of connected and autonomous vehicles has matured, existing studies remain largely confined to external-environment perception and driver monitoring, leaving the real-time detection of physical threats such as firearms and knives inside the vehicle cabin largely unaddressed. This study comparatively evaluates one-stage and two-stage object-detection architectures for in-cabin firearm and knife detection under identical conditions. Eleven models, namely five scales of the YOLOv8 family (n, s, m, l, x), five scales of the YOLO11 family, and the region-proposal-based Faster R-CNN, were trained for 50 epochs on the publicly available "Gun and Knife Detection" dataset (6,257 training and 1,349 validation images) on Roboflow Universe, using an identical dataset, identical hyperparameters, a 416×416 input resolution, and NVIDIA A100 hardware.

This controlled setup ensures that performance differences arise solely from model architecture.

The results show that YOLOv8s achieves the Pareto-optimal highest performance among all eleven candidates on both mAP@50 (0.860) and mAP@50-95 (0.658), retaining this advantage even for the more difficult knife class. When the selected primary model was extended to 100 epochs, YOLOv8s

reached mAP@50 = 0.8614, mAP@50-95 = 0.6713, precision (P) = 0.9117, and recall (R) = 0.7662. YOLOv8s outperformed Faster R-CNN by roughly 2 points on mAP@50 and by roughly 6 points on the stricter mAP@50-95 metric, while delivering approximately 340 times faster GPU inference (0.4 ms versus 137 ms). Notably, the large variants of the YOLO11 family (l and x) fell markedly behind on this two-class, relatively limited dataset, pointing to a mismatch between model capacity and dataset size. Considered jointly across real-time capability, accuracy, and edge-device suitability, the findings establish YOLOv8s as the most suitable candidate for real-time in-vehicle threat detection.
Keywords: Edge Artificial Intelligence, Faster R-CNN, In-Vehicle Security, Object Detection, Weapon Detection, YOLO11, YOLOv8

1. GİRİŞ

Otomotiv endüstrisinin dijital dönüşüm süreci, araçları yalnızca mekanik aktarım organlarından ve elektronik kontrol ünitelerinden oluşan kapalı sistemler olmaktan çıkarmış; onları internet bağlantısına ve araç dışı iletişim yeteneklerine sahip çok katmanlı siber-fiziksel sistemler olarak yeniden tanımlamıştır (Sun ve diğ., 2021). Bu dönüşümün merkezinde, algılama altyapısının temel bileşeni olarak kamera sistemlerinin giderek artan rolü yer almaktadır. Otonom araçlarda kamera birincil algılama sensörü hâline gelmiş olmasına karşın, mevcut uygulamalar büyük ölçüde dış ortam algılama ve otonom navigasyon odağında kalmakta; kabin içi güvenlik amaçlı görüntüleme ise henüz ayrı bir araştırma kolu olarak yeterince farklılaşmamıştır.

Araç içi kamera tabanlı sistemler incelendiğinde, araştırma gündeminin büyük ölçüde sürücü izleme sistemleri (Driver Monitoring Systems, DMS) ve sürücü yorgunluğu/dikkat dağınıklığı tespiti etrafında şekillendiği görülmektedir (Mishra ve diğ., 2022). Buna karşın, araç kabininin kendisinin bir tehdit ortamına dönüşebileceği senaryolar; ticari araç sürücülerine yönelik silahlı saldırılar, robotaksi ve paylaşımlı mobilite hizmetlerinde yolcular arası agresif etkileşimler ya da kabin içinde silah ve bıçak gibi fiziksel tehlikelerin ortaya çıkması, akademik anlamda oldukça sınırlı biçimde ele alınmıştır. Düzenleyici çerçeve de benzer bir asimetri sergilemektedir: 2021 itibarıyla yürürlüğe giren UNECE WP.29 Düzenleme No. 155 yeni tip onayı alan araçlar için Siber Güvenlik Yönetim Sistemi uygulanmasını zorunlu kılmakla birlikte, kapsamını ağ güvenliği ve yazılım güncelleme yönetimiyle sınırlamış; araç içi fiziksel tehdit tespitini düzenleme dışında bırakmıştır (United Nations Economic Commission for Europe, 2021). Akıllı araç güvenliği literatürünün ezici çoğunluğu da araç ağ trafiğinin analizine odaklanmakta; fiziksel kabin ortamını gerçek zamanlı olarak görsel-işitsel modaliteler üzerinden analiz eden sistemler ise son derece sınırlı kalmaktadır.

Yapay zekâ tabanlı silah tespiti literatürü kendi içinde olgun bir birikim oluşturmuş olsa da bu birikim büyük ölçüde araç kabini dışındaki bağlamlarda üretilmiştir. 2016-2025 dönemini kapsayan ve 101 çalışmayı inceleyen kapsamlı bir derlemede, silah tespiti araştırmalarının rapor ettiği precision değerlerinin %78 ile %99,5, ortalama hassasiyet (mAP) değerlerinin ise yaklaşık %70 ile %99 aralığında dağıldığı; ancak bu çalışmaların tamamına yakınının havaalanları, alışveriş merkezleri ve kamuya açık geniş gözetim alanlarında yürütüldüğü belgelenmiştir (Alketbi ve diğ., 2025). Berardini ve diğ. (2024a) ise gözetim kayıtlarında el silahı ve bıçak tespiti için uç cihazlarda çalışabilen bir çerçeve geliştirmiş; silah gibi görece küçük nesnelerin düşük piksel örtüşmesiyle temsil edilmesini ve düşük maliyetli donanımlarda gerçek zamanlı geri bildirim zorunluluğunu iki temel açık problem olarak konumlandırmıştır. Bu problemler araç kabini bağlamında daha da keskinleşmektedir: kabin içi geniş açılı kamera görüntülerinde silah ve bıçak nesnelerinin kapladığı piksel alanı tipik açık alan senaryolarına kıyasla daha küçük kalmakta; değişken iç aydınlatma, yolcu hareketlerinden kaynaklanan kısmi oklüzyonlar ve cam yansımaları tespit görevini belirgin biçimde zorlaştırmaktadır.

Nesne tanıma alanı, derin öğrenme temelli yaklaşımlar çerçevesinde iki ana mimari paradigma etrafında şekillenmiştir: iki aşamalı (two-stage) bölge önerisi tabanlı yöntemler ve tek aşamalı (one-stage) uçtan uca tespitçiler. Bölge önerisi tabanlı mimarilerin öncüsü konumundaki R-CNN ailesi, önce aday bölgelerin üretilmesi ardından bunların sınıflandırılması ilkesine dayanmaktadır.

Orijinal R-CNN'in her bölge önerisini bağımsız işlemesinden kaynaklanan hesaplama darboğazı (Girshick ve diğ., 2014), Fast R-CNN'de RoI Pooling katmanıyla (Girshick, 2015) ve Faster R-CNN'de Bölge Önerisi Ağı (Region Proposal Network, RPN) ile büyük ölçüde giderilmiştir (Ren ve diğ., 2017). Buna karşın iki aşamalı mimarilerin yapısal maliyeti, gerçek zamanlı çıkarımın kritik olduğu ve saniyede 30 kareyi aşan işleme hızlarının beklendiği uygulamalarda önemli bir kısıt olarak kalmaya devam

etmektedir. Redmon ve diğ. (2016) tarafından önerilen YOLO (You Only Look Once) mimarisi ise tek bir ileri geçişte sınırlayıcı kutu koordinatlarını ve sınıf olasılıklarını eş zamanlı tahmin ederek gerçek zamanlılık bakımından bir kırılma noktası oluşturmuştur.

YOLO ailesi v1'den bu yana mimari açıdan önemli bir evrim geçirmiş; anchor tabanlı tasarımdan anchor-free yaklaşıma geçiş, omurga ağlarında C2f modüllerinin benimsenmesi ve tespit kafalarının ayrıştırılması gibi yeniliklerle hem doğruluk hem hız bakımından kazanımlar sağlamıştır. 2023 yılında yayımlanan YOLOv8, bu birikimin olgun temsilcilerinden biri olarak değerlendirilmekte (Varghese ve Sambath, 2024; Jocher ve diğ., 2023); 2024 yılında üretkenlik odaklı YOLO11 (Khanam ve Hussain, 2024), 2025 yılında dikkat mekanizmalarını gerçek zamanlı tespit çerçevesine entegre eden YOLOv12 (Tian ve diğ., 2025) ve uç cihaz odaklı YOLO26 (Sapkota ve diğ., 2025; Ultralytics, 2026) ile aile genişlemeye devam etmektedir. YOLO ailesi araç güvenliği uygulamalarında hızla benimsenmekle birlikte, bu çalışmaların büyük çoğunluğu dış ortam algılama veya sürücü davranış sınıflandırmasıyla sınırlı kalmaktadır.

Bu panoramaya karşın, tek aşamalı ve iki aşamalı nesne tanıma mimarilerini özdeş koşullarda, doğrudan araç içi silah ve bıçak tespiti bağlamında karşılaştıran kontrollü bir değerlendirme literatürde bulunmamaktadır. Mevcut çalışmalar ya farklı veri kümeleri ve protokoller üzerinde yürütüldüğü için doğrudan kıyaslanamamakta ya da kabin dışı bağlamlarda kalmaktadır. Bu çalışmanın amacı, söz konusu boşluğu hedefleyerek YOLOv8 ailesinin beş varyantını, YOLO11 ailesinin beş varyantını ve bölge önerisi tabanlı Faster R-CNN modelini özdeş veri kümesi, özdeş hiperparametreler ve özdeş donanım altında karşılaştırmalı olarak değerlendirmek; doğruluk, çıkarım hızı, hesaplama maliyeti ve uç cihaz konuşlandırma uygunluğu eksenlerinin tamamında araç içi gerçek zamanlı tehdit tespiti için en uygun modeli ampirik biçimde belirlemektir. Bu değerlendirme, silah tespiti gibi güvenlik-kritik görevlerin uç cihazlarda konuşlandırılabilirliğine dair önceki bulgularla da örtüşmektedir (Berardini ve diğ., 2024b).

2. ARAŞTIRMA VE BULGULAR

2.1. Materyal ve yöntem

Görüntü işleme katmanı için aday model havuzu üç ana eksende yapılandırılmıştır: YOLOv8 ailesinin beş varyantı (n, s, m, l, x), YOLO11 ailesinin beş varyantı (n, s, m, l, x) ve bölge önerisi tabanlı mimarilerin temsilcisi olarak ResNet-50 FPN omurgalı Faster R-CNN. Bu seçim, hem tek aşamalı hem iki aşamalı tespitçileri kapsayan dengeli bir karşılaştırma havuzu oluşturmayı amaçlamıştır. YOLOv8 ailesi mimari olarak üç ana bileşenden oluşmaktadır: hiyerarşik öznitelik çıkarımı için C2f (Cross Stage Partial with 2 convolutions) blokları ile güçlendirilmiş CSPDarknet omurgası, farklı ölçeklerdeki nesne tespitini olanaklı kılan Özellik Piramidi Ağı (Feature Pyramid Network, FPN) tabanlı boyun yapısı ve sınıflandırma ile regresyon görevleri için ayrıştırılmış tespit kafasıdır. Modelin eğitim hedef fonksiyonu, sınıflandırma için Binary Cross-Entropy ve sınırlayıcı kutu regresyonu için Distribution Focal Loss ile Complete IoU bileşenlerinin kombinasyonundan oluşmakta; etiket atama stratejisi olarak Task Aligned Assigner yöntemi kullanılmaktadır (Varghese ve Sambath, 2024).

Eğitimde, Roboflow Universe platformu üzerinden kamuya açık olarak paylaşılan "Gun and Knife Detection" veri kümesi kullanılmıştır (Ahmed, 2024). Veri kümesi gözetim ve güvenlik kameralarından derlenen silah ve bıçak görüntülerini içermekte olup, eğitim seti 6.257 görüntü (603 arka plan örneği dâhil) ve doğrulama seti 1.349 görüntüden oluşmaktadır. Doğrulama setinde silah sınıfı 1.026, bıçak sınıfı 301 örnekle temsil edilmektedir. Sağlayıcı tarafından önceden yapılmış eğitim/doğrulama ayrımı olduğu biçimiyle korunmuş ve herhangi bir sınıf dengeleme işlemi uygulanmamıştır. Silah sınıfının bıçak sınıfının yaklaşık 3,4 katı örnekle temsil edildiği bu yapısal dengesizlik, sınıf bazlı performans farklarının değerlendirilmesinde önemli bir referans noktası oluşturmaktadır.

Veri kümesinin bölümlere göre dağılımı Çizelge 2'de sunulmaktadır. Karşılaştırmanın bilimsel geçerliliğini güvence altına almak amacıyla tüm modeller aynı veri kümesi, aynı hiperparametreler, aynı giriş çözünürlüğü ve aynı donanım üzerinde 50 epoch boyunca eğitilmiştir. Eğitim 16'lık toplu iş boyutu ve 416×416 piksel giriş çözünürlüğüyle gerçekleştirilmiş; modeller önceden eğitilmiş COCO ağırlıklarından başlatılmış ve Otomatik Karışık Hassasiyet desteğiyle NVIDIA A100 yapılandırmasında eğitilmiştir. Optimizasyon algoritması olarak momentum değeri 0,9 ve başlangıç öğrenme hızı 0,001667 olan AdamW seçilmiş; öğrenme hızı cosine-annealing çizelgesiyle ayarlanmıştır. Veri artırma aşamasında hafif bulanıklaştırma, gri tonlama ve CLAHE tabanlı kontrast iyileştirme uygulanmış; yatay

çevirme olasılığı 0,5 olarak belirlenmiştir. Mozaik veri artırması eğitimin son 10 epoch'unda devre dışı bırakılarak modelin gerçekçi dağılıma yakınsaması hedeflenmiştir. Faster R-CNN için ise mimari farklılığın gerektirdiği zorunlu uyarlamalar (RPN ön ayarları, RoI pooling boyutları) dışında özdeş veri akışı ve eğitim süresi sağlanmıştır. Deneysel kurulumun donanım ve yazılım yığını Çizelge 1'de özetlenmektedir.

Model seçim süreci iki aşamalı olarak yapılandırılmıştır. İlk aşamada on bir aday modelin tamamı 50 epoch boyunca eğitilerek doğruluk, çıkarım hızı ve hesaplama maliyeti açısından karşılaştırmalı olarak değerlendirilmiş; bu karşılaştırmadan kazanan model belirlenmiştir. İkinci aşamada ise yalnızca seçilen birincil model 100 epoch'a uzatılarak ek eğitim süresinin getirdiği performans kazanımı pekiştirilmiştir. Bu yaklaşım, tüm aday modellerin tam eğitim bütçesinde paralel çalıştırılmasının yaratacağı kaynak maliyetini ve kıyaslama eşitsizliği riskini önlerken, kazanan modelin nihai operasyonel başarımının da yeterli eğitim süresiyle ortaya konmasını sağlamıştır. Ölçüm protokolü kapsamında görüntü katmanı için temel metrikler mAP@50, mAP@50-95 ve sınıf bazlı AP@50-95 değerleri olarak tanımlanmış; bunlara ek olarak çıkarım süresi (ms/görüntü), eğitim süresi (dakika) ve parametre sayısı verimliliği değerlendirilmiştir.

Çizelge 1: Deneysel kurulumun donanım ve yazılım yığını.

Bileşen	Kullanılan Yapılandırma
GPU	NVIDIA A100-SXM4 (80 GB HBM2e), Google Colab Pro+
CUDA	12.8 + cuDNN
Çatı (framework)	PyTorch 2.10
Nesne tanıma kütüphanesi	Ultralytics 8.4.46 (YOLO eğitimi), 8.4.40 (karşılaştırma)
Faster R-CNN altyapısı	torchvision (fasterrcnn_resnet50_fpn_v2)
Python	3.12.12
Giriş çözünürlüğü	416 × 416 piksel
Eğitim süresi	50 epoch (tüm modeller), 100 epoch (birincil model)

Çizelge 2: "Gun and Knife Detection" veri kümesinin bölümlere göre dağılımı ve doğrulama setindeki sınıf dengesizliği.

Bölüm	Görüntü	Anotasyon	Sınıf Dağılımı
Eğitim	6.257	6.223	Arka plan dâhil
Doğrulama	1.349	1.327	Silah: 1.026 / Bıçak: 301
Test	845	824	Eğitime girmedi

2.2. Deneysel bulgular

Aday modellerin özdeş veri kümesi, hiperparametre yapılandırması ve donanım üzerinde 50 epoch boyunca eğitilmesinin ardından elde edilen bulgular üç temel sonucu ortaya koymaktadır. Birinci sonuç, YOLOv8s modelinin tüm aday modeller arasında en yüksek mAP@50 (0,860) ve mAP@50-95 (0,658) değerlerine ulaşmış olmasıdır. Sınıf bazlı bulgular bu üstünlüğü desteklemektedir: YOLOv8s, görece daha güç bir tespit görevi olan bıçak sınıfında 0,572 AP@50-95 değeriyle tüm modeller arasında en yüksek bıçak başarımını sergilemiştir.

İkinci sonuç, YOLOv8s'in bu üstün doğruluğu görece düşük bir hesaplama maliyetiyle elde etmesidir: 11,14 milyon parametre ve 28,4 GFLOPs ile YOLOv8m'in 25,86 milyon parametre ve 78,7 GFLOPs değerine kıyasla yaklaşık 2,3 kat daha az parametre ve 2,8 kat daha düşük hesaplama yükü sergilemektedir. Üçüncü sonuç, YOLOv8s'in eğitim süresinin tüm aday modeller arasında en kısa olmasıdır (34,2 dakika); bu değer Faster R-CNN'in 137 dakikasının yaklaşık dörtte biridir.

Tablodan öne çıkan dikkat çekici bir diğer bulgu, YOLO11 ailesinin büyük varyantlarının görece düşük başarımıdır. YOLO11l (mAP@50 = 0,753) ve YOLO11x (mAP@50 = 0,751) modelleri, hem aynı ailenin daha hafif varyantı olan YOLO11s'e (mAP@50-95 = 0,638) hem de eşdeğer YOLOv8 varyantlarına göre belirgin biçimde geride kalmıştır. YOLOv8 ailesinde tipik bir plato davranışı gözlemlenmiş; YOLOv8s'den YOLOv8x'e kadar tüm varyantlar mAP@50-95 metriğinde 0,648 ile

0,658 aralığında dar bir bantta kümelenmiştir. Buna karşılık YOLO11 ailesinde ters ölçekleme (inverse scaling) davranışı belirginleşmiş; küçük varyant YOLO11s, büyük varyantları YOLO11l (0,574) ve YOLO11x (0,576) modellerinden daha iyi performans sergilemiştir. Bu davranışın somut bir belirtisi, YOLO11x modelinin eğitim sürecinin ilk üç epoch'unda NaN (Not a Number) kayıp değerleri üretmesi olmuştur; model dördüncü epoch'tan itibaren öğrenmeye devam etmiş, ancak başlangıçtaki sayısal düzensizlik nihai performansı olumsuz etkilemiştir. Bu bulgu, yalnızca iki sınıftan oluşan ve görece kısıtlı büyüklükteki bir veri kümesinde model kapasitesi ile veri büyüklüğü arasındaki dengesizliğin performansı doğrudan sınırlayabileceğini göstermektedir. Seçilmiş modellerin karşılaştırmalı metrikleri Çizelge 3'te sunulmaktadır.

Çizelge 3: Seçilmiş aday modellerin 50 epoch eğitimi sonrası doğrulama metrikleri (özdeş veri kümesi, 416×416 piksel girdi, NVIDIA A100 GPU).

Model	Mimari Tipi	mAP@50	mAP@50-95
YOLOv8s (seçilen)	Tek aşamalı	0,860	0,658
YOLO11l	Tek aşamalı	0,753	0,574
YOLO11x	Tek aşamalı	0,751	0,576
Faster R-CNN (ResNet-50 + FPN)	İki aşamalı	0,841	0,597

Not: YOLOv8 ailesinin tüm varyantları mAP@50-95 metriğinde 0,648-0,658 aralığında kümelenmektedir; YOLO11s ise 0,638 değerine ulaşmıştır.

Pareto-optimal konumu nedeniyle birincil model olarak seçilen YOLOv8s'in 100 epoch'luk uzatılmış eğitimi, NVIDIA A100 GPU üzerinde toplam 79,4 dakika sürmüştür. Ek eğitim süresi tüm metriklerde tutarlı bir iyileşme sağlamıştır: mAP@50 değeri 0,8200'den 0,8614'e (4,14 puan), mAP@50-95 değeri 0,6230'dan 0,6713'e (4,83 puan) yükselmiştir. Precision metriğindeki 6,47 puanlık artış (0,8470'ten 0,9117'ye) dört metrik içerisinde en büyük iyileşme olup, yanlış pozitif oranının belirgin biçimde düştüğüne işaret etmektedir; bu, güvenlik-kritik bir uygulamada operasyonel açıdan değerli bir kazanımdır. Recall metriğindeki 4,42 puanlık iyileşme (0,7220'den 0,7662'ye) ise modelin gerçek nesneleri kaçırma oranını da azalttığını teyit etmektedir. Kayıp bileşenleri açısından box_loss değeri %11,7, cls_loss değeri ise %47,4 oranında azalmıştır. Bu büyük cls_loss düşüşünün arkasındaki mekanizma, eğitimin son fazında otomatik olarak devre dışı bırakılan mozaik veri artırmasıdır: 90. epoch'ta mozaik augmentation'ın kapatılmasıyla model gerçekçi doğrulama dağılımına yakınsamış ve sınıflandırma kaybı yaklaşık 0,50 seviyesinden 0,37 seviyesine sert bir düşüş sergilemiştir. Metriklerin epoch düzeyindeki değişimi Çizelge 4'te sunulmaktadır.

Çizelge 4: YOLOv8s modelinin 50 epoch ve 100 epoch sonuçlarının karşılaştırması.

Metrik	50 Epoch	100 Epoch	Değişim
mAP@50	0,8200	0,8614	+4,14 puan
mAP@50-95	0,6230	0,6713	+4,83 puan
Precision	0,8470	0,9117	+6,47 puan
Recall	0,7220	0,7662	+4,42 puan
box_loss	0,4912	0,4336	%11,7 düşüş
cls_loss	0,7063	0,3717	%47,4 düşüş

Sınıf bazlı performans dağılımı, doğrulama seti üzerindeki yapısal farkları somut biçimde ortaya koymaktadır. Silah sınıfında AP@50 değeri 0,9097 ile yüksek bir başarım düzeyine ulaşmış; AP@50-95 değeri ise 0,7555 olarak gerçekleşmiştir. Bıçak sınıfında ise AP@50 değeri 0,8118 ve AP@50-95 değeri 0,5870 olarak ölçülmüş; bu değerler silah sınıfının yaklaşık 11 puan altında kalmıştır. Bıçak sınıfındaki görece düşük performansın iki yapısal kök nedeni bulunmaktadır. Birincisi, doğrulama setindeki sınıf dengesizliğidir: silah sınıfı bıçak sınıfının yaklaşık 3,4 katı örnekle temsil edilmekte; bu durum modelin bıçak sınıfı için daha az destekleyici örnekle eğitilmesine yol açmaktadır. İkincisi, bıçak

nesnesinin doğal olarak silahtan daha küçük piksel alanında temsil edilmesi ve görüntü düzleminde farklı tutuş açılarıyla yansımasıdır; bu durum ince sınır kutusu lokalizasyonunu güçleştirmekte ve özellikle daha katı bir eşik olan AP@50-95 metriğinde performans düşüşüne yol açmaktadır. Sınıf bazlı bulgular Çizelge 5'te sunulmaktadır.

Çizelge 5: YOLOv8s modelinin 100 epoch eğitimi sonrası sınıf bazlı doğrulama performansı.

Sınıf	Görüntü	Nesne	AP@50	AP@50-95
Silah (gun)	927	1.026	0,9097	0,7555
Bıçak (knife)	280	301	0,8118	0,5870
Toplam	**1.349**	**1.327**	**0,8614**	**0,6713**

Tek aşamalı YOLOv8s ve iki aşamalı Faster R-CNN mimarileri arasındaki karşılaştırma, salt nicel doğruluk farkının ötesinde iki tespit paradigmasının bu görev üzerindeki yapısal davranış farklarını ortaya koymaktadır. Faster R-CNN, COCO değerlendirme protokolüyle mAP@50 metriğinde 0,841 ve mAP@50-95 metriğinde 0,597 sonuçlarına ulaşmıştır. Bu değerler YOLOv8s'in 100 epoch sonrasındaki sonuçlarıyla karşılaştırıldığında, YOLOv8s'in mAP@50 metriğinde 2,04 puan ve mAP@50-95 metriğinde 7,43 puan üstünlük sergilediği görülmektedir. Daha katı bir konum hassasiyeti ölçütü olan mAP@50-95 metriğindeki bu belirgin fark, YOLOv8s'in yalnızca nesne varlığını tespit etmekle kalmayıp sınırlayıcı kutu konum hassasiyeti açısından da daha güvenilir tahminler ürettiğini ortaya koymaktadır.

Faster R-CNN değerlendirmesinde en kritik bulgu, küçük nesne sınıfında AP@50-95 ve AR (Average Recall) değerlerinin 0,000 olarak ölçülmesidir. Bu davranış, modelin görüntü piksel alanına oranla küçük temsil edilen silah ve bıçak nesnelerini kabul edilebilir bir doğrulukla tespit edemediğini doğrudan kanıtlamaktadır. Faster R-CNN modelinin 640×640 piksel girdi çözünürlüğüyle eğitilmiş olmasına karşın bu zafiyetin oluşması, mimarinin küçük nesne tespitindeki yapısal sınırlılığının doğrudan bir yansımasıdır. Bölge önerisi ağının kullandığı anchor boyutları, doğrulama setindeki küçük silah ve bıçak nesnelerine yapısal olarak uyumsuz kalmakta; bu nesneler aday bölge olarak önerilmedikleri için sınıflandırma aşamasına bile ulaşamamaktadır. YOLO ailesinin FPN tabanlı çoklu ölçek füzyonu ise farklı boyutlardaki nesneleri birden fazla ölçek seviyesinde aynı anda işleyebilmekte; bu yapısal avantaj küçük nesnelerin tespitinde belirleyici bir fark yaratmaktadır.

Hesaplama maliyeti ekseninde, Faster R-CNN'in eğitim süresi (137 dakika) YOLOv8s'in 50 epoch eğitim süresinin (34,2 dakika) yaklaşık dört katıdır; çıkarım süresi (yaklaşık 137 ms) ise YOLOv8s'in 0,4 ms'lik çıkarım süresine kıyasla yaklaşık 340 kat daha yavaştır. Bu hız farkının pratik anlamı, gerçek zamanlı tehdit tespiti için araç içi sistemlerde benimsenen 25-30 FPS eşiğinin Faster R-CNN ile karşılanmasının pratik olarak güç olduğu, YOLOv8s ile ise bu eşiğin geniş bir marjla aşıldığıdır. Faster R-CNN yaklaşık 41 milyon parametre ile YOLOv8s'in 11,14 milyon parametresinin yaklaşık 3,7 katı bellek alanı gerektirmekte; bu durum gömülü platformlardaki konuşlandırma uygunluğunu da olumsuz etkilemektedir. İki modelin başlıca operasyonel ölçütleri Çizelge 6'da karşılaştırılmaktadır.

Çizelge 6: YOLOv8s ile Faster R-CNN modellerinin operasyonel ölçütler bakımından karşılaştırması.

Ölçüt	YOLOv8s	Faster R-CNN
mAP@50	0,8614	0,841
mAP@50-95	0,6713	0,597
Parametre sayısı	11,14 milyon	~41 milyon
Çıkarım süresi (GPU)	0,4 ms	~137 ms
Eğitim süresi	34,2 dk (50 ep)	137 dk (50 ep)
Mimari tipi	Tek aşamalı, anchor-free	İki aşamalı, RPN tabanlı

2.3. Bulguların değerlendirilmesi

Paradigma düzeyinde değerlendirme, daha yüksek hesaplama maliyetinin doğrudan daha iyi sonuç anlamına gelmediğini açıkça desteklemektedir. İki aşamalı mimarinin teorik olarak sunduğu hassas lokalizasyon avantajı, görece kısıtlı boyutlu bu özel veri kümesinde gerçekleşmemiş; YOLO ailesinin anchor-free, tek aşamalı tasarımı hem doğruluk hem hız bakımından üstün gelmiştir. Daha da çarpıcı olarak, Faster R-CNN'in mAP@50-95 değeri (0,597), YOLO11 ailesinin large (0,574) ve extra-large (0,576) varyantlarından daha yüksek gerçekleşmiştir; bu durum, iki aşamalı klasik bir mimarinin bile aşırı parametreli tek aşamalı varyantlardan daha sağlam olabileceğine işaret etmektedir. Bu bulgu, model seçim sürecinde mimari yeniliğin tek başına performans iyileşmesi anlamına gelmediği; veri kümesi büyüklüğü ile model kapasitesi arasındaki ilişkinin titiz biçimde değerlendirilmesi gerektiği yönünde önemli bir yöntemsel ders sunmaktadır.

Operasyonel kalibrasyon açısından, YOLOv8s modelinin tahmin güven eşiği 0,50 ile 0,85 aralığında deneysel olarak değerlendirilmiş; 0,60 güven eşiğinin üzerindeki tespitlerin anlamlı oranda gerçek pozitif ürettiği, bu eşiğin altındaki tespitlerin ise yanlış pozitif oranını belirgin biçimde artırdığı gözlemlenmiştir. Bu doğrultuda sistem, 0,60 ve üzeri güven değerlerine sahip nesne tespitlerini geçerli görüntü sinyali olarak değerlendirecek biçimde yapılandırılmıştır. Çalışmanın temel kısıtı, eğitim veri kümesinin ağırlıklı olarak açık alan gözetim kameralarından derlenmiş olması ve bu durumun açık alan ile araç kabini arasında bir alan kayması (domain shift) problemi oluşturmasıdır; bu kayma modelin kabin içi genellenebilirliğini sınırlandırmaktadır. Bu sınırlılık, kabine özgü veriyle ince ayar yapılmış modellerin geliştirilmesi gerekliliğini ortaya koymaktadır.

3. SONUÇ

Bu çalışmada, araç içi silah ve bıçak tespiti için tek aşamalı ve iki aşamalı nesne tanıma mimarileri özdeş koşullarda karşılaştırmalı olarak değerlendirilmiştir. YOLOv8 ailesinin beş varyantı, YOLO11 ailesinin beş varyantı ve bölge önerisi tabanlı Faster R-CNN olmak üzere on bir model; özdeş veri kümesi, özdeş hiperparametreler, 416×416 giriş çözünürlüğü ve NVIDIA A100 donanımıyla 50 epoch boyunca eğitilmiş; böylece başarım farklarının yalnızca model mimarisinden kaynaklanması güvence altına alınmıştır.

Bulgular, YOLOv8s modelinin hem mAP@50 (0,860) hem de mAP@50-95 (0,658) metriklerinde on bir aday arasında Pareto-optimal en yüksek başarımı sergilediğini ve bu üstünlüğü görece daha güç bir görev olan bıçak sınıfında da koruduğunu göstermektedir. 100 epoch'a uzatılan eğitimde YOLOv8s; mAP@50 = 0,8614, mAP@50-95 = 0,6713, precision = 0,9117 ve recall = 0,7662 değerlerine ulaşmıştır. YOLOv8s, Faster R-CNN'i mAP@50 metriğinde 2,04 puan ve daha katı mAP@50-95 metriğinde 7,43 puan geride bırakmış; aynı zamanda yaklaşık 340 kat daha hızlı çıkarım ve yaklaşık 3,7 kat daha düşük parametre yükü sağlamıştır. Faster R-CNN'in küçük nesne sınıfında 0,000 AP@50-95 değeri üretmesi, iki aşamalı mimarinin bu görevdeki yapısal sınırlılığını doğrudan ortaya koymuştur. YOLO11 ailesinin büyük varyantlarının görece düşük başarımı ise model kapasitesi ile veri büyüklüğü arasındaki dengesizliğin önemini vurgulamaktadır.

Gerçek zamanlılık, doğruluk ve uç cihaz konuşlandırma uygunluğu birlikte değerlendirildiğinde, YOLOv8s araç içi gerçek zamanlı tehdit tespiti için en uygun aday olarak öne çıkmaktadır. Gelecek çalışmalarda, açık alan ile araç kabini arasındaki alan kaymasını gidermek amacıyla kabine özgü ve dengeli sınıf dağılımına sahip bir veri kümesinin oluşturulması, geniş açılı kabin kameralarına yönelik veri artırma stratejilerinin geliştirilmesi ve görüntü modalitesinin konuşma transkripsiyonu ile akustik analiz gibi tamamlayıcı modalitelerle bütünleştirildiği çok modlu bir füzyon çerçevesinin tasarlanması öncelikli yönelimler olarak değerlendirilmektedir.

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DEMOGRAPHIC PREDICTORS OF INTERNET USAGE TIME AND SOCIAL COMPARISON: A QUANTITATIVE STUDY

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ABSTRACT
With the increasing use of the internet, interest in individuals' digital behaviors and the reasons behind these behaviors is growing. Accordingly, examining the factors influencing individuals' digital behavior has become an important research topic. While digital environments enable individuals to access information, they also offer the opportunity to constantly observe the lives, achievements, and opinions of other individuals. In this context, social comparison processes have become an important element of digital life. Although there are numerous studies in the literature on internet use and social comparison, studies that examine the effects of demographic variables on internet use duration and different dimensions of social comparison are still limited. Therefore, this study aims to examine the potential effects of demographic variables such as age, gender, education level, monthly income, and marital status on individuals' internet use duration and the ability and opinion dimensions of social comparison. Based on this, a quantitative research design was created, and data were obtained from adult individuals through a structured survey. Independent samples t-tests, analyses of variance, correlation analyses, and multiple regression analyses were used in the analysis of the research data consisting of 286 adults. The research findings reveal that age, a demographic variable, negatively predicts internet usage time. Furthermore, it was found that single individuals use the internet more than married individuals. However, the explanatory power of demographic variables on both the ability and opinion dimensions of social comparison was found to be quite limited. No significant relationships were observed between internet usage time and the dimensions of social comparison. In conclusion, the findings suggest that demographic factors play a certain role in explaining internet usage time, but that the tendency toward social comparison can be considered a more independent and stable trend than demographic characteristics.
Keywords: Internet usage time, social comparison, demographics.

INTRODUCTION
With the rise of digitalization, internet use has become an integral part of daily life. Used by a wide segment of society, from young people to adults, the internet has increasingly become central to life. Internet use is primarily for purposes such as communication, socialization, access to information, spending time, entertainment, shopping, and completing professional tasks (Uslu, 2022). Although different segments of society use the internet frequently, there are significant differences in usage times. For example, some professionals may only use LinkedIn for limited purposes (Baumann & Utz, 2021). On the other hand, some individuals may spend a large part of their day online. It is important to examine and understand the reasons for these differences in internet usage times among individuals, because internet usage time is associated with various psychological, social, and behavioral consequences (Keles et al., 2020). Personality and personality differences can, of course, be one of the determinants of differences in internet usage times. In addition, demographic characteristics such as age, gender, marital status, education level, and income are considered important factors in explaining internet usage behavior (Abdioğlu & Harman, 2022; Calderon Gomez et al., 2022). Accordingly, examining the demographic antecedents of internet usage time appears to contribute to understanding the distribution of digital behaviors within society and revealing different user profiles. However, as is known, the internet is not only used for accessing information and communication, but also provides a social environment where individuals can compare themselves to others (Verduyn et al., 2017). Social and professional media platforms such as Instagram, Facebook, and LinkedIn, in particular, enable individuals to constantly learn about other people's lifestyles, achievements, opinions, and experiences (Yang et al., 2018). Therefore, a more detailed understanding of interactions occurring in the online environment necessitates an examination of individuals' social comparison processes.

According to Social Comparison Theory, individuals have a need to evaluate themselves and gain information by comparing themselves to others (Festinger, 1954). These comparisons allow individuals to make assessments about their own competence, achievements, thoughts, and social status (Lim et al., 2021). Thus, individuals can adapt to their social environment and shape their self-perception. Social comparison includes two dimensions depending on the elements being compared. The first is ability comparison, which involves comparing an individual's achievement, performance, and competence. The other is opinion comparison, where individuals compare their ideas, views, attitudes, and thoughts (Gibbons & Buunk, 1999). Just as with internet usage time, findings regarding the relationship between social comparison and demographic characteristics show variability in different studies (Buunk et al., 2020; Noon et al., 2022). This situation reveals the need to examine the demographic determinants of social comparison. This study examines the effects of demographic characteristics on internet usage time and ability- and opinion-based social comparison. It also aims to reveal the relationships between internet usage time and the two dimensions of social comparison. To this end, the following research questions were addressed: Do demographic variables affect internet usage time? Do demographic variables affect ability- and opinion-based social comparison? Is there a significant relationship between internet usage time and ability-based and opinion-based social comparison?

This study aims to contribute to the understanding of digital behaviors and the relevant literature by identifying the potential effects of demographic factors on internet usage time and social comparison and its dimensions. The unique aspect of this study is the examination of different elements of internet usage time and social comparison within the same research model. These variables have mostly been studied independently in the literature, or social comparison has been treated as a single-dimensional construct (Aldrovandi et al., 2021; Lee, 2022). In this respect, the study is expected to contribute to a better understanding of the demographic foundations of digital behaviors and social comparison processes.

CONCEPTUAL FRAMEWORK AND RESEARCH QUESTIONS

Demographic Characteristics and Internet Usage Time

Internet use appears to be widespread across all segments of society today, but there can be differences in internet usage time among these groups.

These differences can be influenced by factors such as the individual's social context and personality. Another factor thought to influence this difference, and which is the subject of this study, is demographic characteristics (Abdioğlu & Harman, 2022; Calderon Gomez et al., 2022; Dalgic-Tetikol et al., 2022).

Age is a significant demographic factor associated with internet usage time (Abdioğlu & Harman, 2022; Noon, 2021). A large number of studies show that young people use the internet for longer periods than older people (Abdioğlu & Harman, 2022; Dalgic-Tetikol et al., 2022). The fact that the new generation is introduced to technology at an earlier age and adapts more easily to digital life, in parallel with the increase in digitalization, can be considered among the reasons for this situation. Although the vast majority of studies show that young people spend more time online, the magnitude of the relationship between age and internet usage time varies across different samples (Festic et al., 2021; Pacheco, 2023). In this context, it can be said that the findings regarding the effect of age on internet use are not entirely homogeneous.

The findings also present a complex picture when viewed from a gender perspective. While some studies show that women spend more time online than men (Bünning et al., 2023), other studies show that men spend more time browsing than women (Acilar, 2020). Some studies, however, found no statistically significant differences in terms of gender (Festic et al., 2021). In this context, it is understood that the effect of gender on internet use may vary depending on differences in usage purposes and sample sizes.

Other demographic factors where inconsistent findings were observed are education level, income, and marital status. While it might be thought that individuals with higher education levels would spend less time online due to their increased awareness, conversely, it could also be argued that they would use the internet for longer periods for purposes such as accessing information and professional development, as required by their education.

Regarding income, it might be thought that individuals with higher incomes would use the internet for longer periods due to their greater access to digital devices and the internet. Conversely, the fact that internet access has become much easier may have weakened or rendered insignificant the effect of

income on internet usage time. On the other hand, it can be argued that single people spend more time on the internet than married people because they dedicate more time to social interaction, communication, and entertainment activities. Findings from previous research show inconsistencies in the effects of education level, income level, and marital status on internet usage time (Abdioğlu & Harman, 2022; Dalgic-Tetikol et al., 2022; Festic et al., 2021).

Generally, while there are studies indicating that demographic characteristics such as age, gender, education level, income, and marital status may be related to internet usage time, it is also observed that the findings regarding the effects of these variables are inconsistent among different samples. Based on this, the first research question is formulated as follows:

RQ1. Do demographic variables predict internet usage time?

Demographic Characteristics and Social Comparison

Social comparison, which refers to a person's tendency to compare themselves to others in certain aspects, is considered in two dimensions as ability comparison and opinion comparison (Gibbons & Buunk, 1999). In ability comparison, the individual compares their abilities, achievements, and performance with others, while in opinion comparison, they compare the ideas, opinions, attitudes, and thoughts of others and themselves (Gibbons & Buunk, 1999). In the literature, just like with internet use, it is seen that the findings regarding the relationships between demographic characteristics and social comparison vary in different studies.

From an age perspective, it is seen that young people use social media more intensively and participate in online social interactions more frequently than older individuals. This suggests that young individuals may be more exposed to social comparison processes. Some studies have reported negative relationships between age and social comparison, showing results that support this view (Buunk et al., 2020; Noon et al., 2021). However, some other studies have shown this relationship to be weak or statistically insignificant.

When evaluated in a gender context, some studies indicate that women are more prone to social comparison. It seems reasonable that women would engage in such comparisons, particularly in terms of appearance, social relationships, and achievement. However, some other studies have shown no significant differences between women and men in the context of social comparison (Lee et al., 2022).

The literature shows a similar picture when considering education level, income, and marital status. As education level increases, awareness, information seeking, and more exchange of ideas are expected, and consequently, more comparisons of opinions can be expected. As income increases, comparisons of social status and achievement may increase, and it can be assumed that income may particularly affect comparisons of abilities. The situation is much more complex regarding marital status. Since the social environments, social networks, and lives of single and married individuals differ, both ability-based and opinion-based social comparisons may differ according to marital status. Literature findings show inconsistencies in the effects of age, income, and marital status on social comparison and its dimensions (Aldrovandi et al., 2021; Buunk et al., 2020).

In general, there are studies indicating that age, education level, gender, income, and marital status can influence social comparison. However, inconsistencies regarding the strength and direction of these effects are also evident. Furthermore, most research dealing with social comparison has examined this construct as a single dimension, failing to evaluate the dimensions of ability and opinion comparison separately. Based on this, the research question formulated is as follows:

RQ2. Do demographic variables predict ability-based and opinion-based social comparison?

Internet Usage Time and Social Comparison

Beyond the purpose of acquiring information, there are many underlying factors in internet use. At its core, these include purposes such as communication and entertainment (Uslu, 2022). Through internet use, individuals can easily access the social lives, achievements, ideas, opinions, and experiences of others (Verduyn et al., 2017).

The widespread use of social media platforms, in particular, significantly facilitates this. Increased social media traffic and sharing create an environment conducive to comparison between individuals.

It can be assumed that individuals who use the internet more frequently will have more opportunities to compare themselves to others. This is because increased internet usage time increases the possibility of

encountering more people. Furthermore, since increased usage time means access to more social information and exposure to more content, a connection between internet usage time and social comparison can be expected (Verduyn et al., 2017). In fact, this comparison can encompass both skill comparisons (including achievements and performance) and opinion comparisons (including ideas and thoughts), and can differentiate itself internally. Since the internet provides individuals with the opportunity to both observe the achievements and performance of others and access their thoughts and opinions, it can be expected that internet usage time is related to both ability-based and opinion-based social comparison. While current studies indicate that internet usage time can increase social comparison (Verduyn et al. 2017; Yang et al., 2018), there are also differences regarding the direction and strength of the relationship. Based on this, the final research question is formulated as follows:
RQ3. Is internet usage time associated with ability-based and opinion-based social comparison?
The conceptual framework of the study is shown in Figure 1.

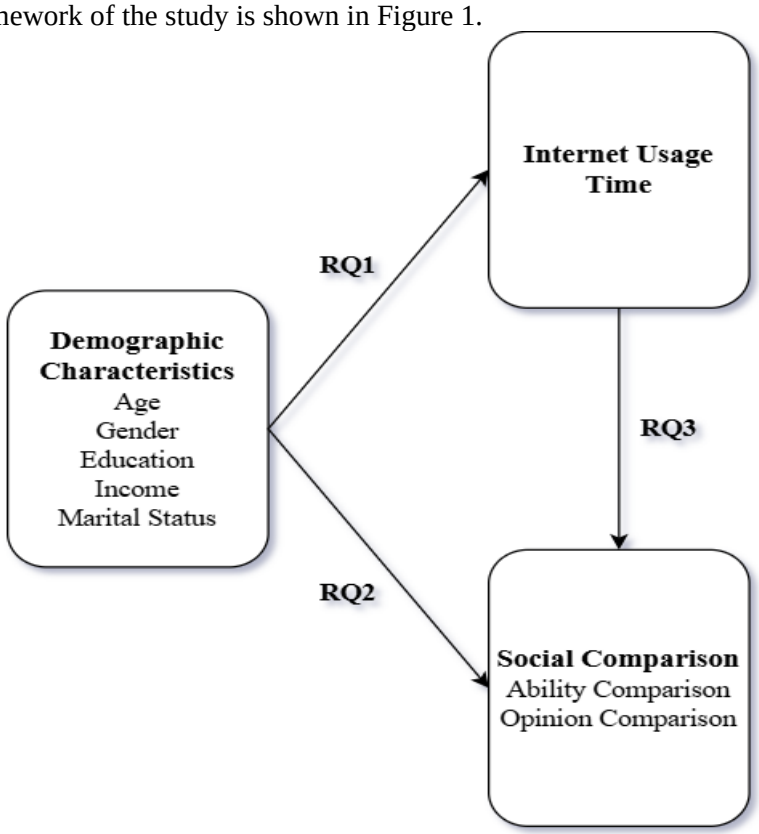

Figure 1. Conceptual Model of the Study

METHOD

Procedure and Participants

A quantitative research design was created to achieve the study's objective. Data for the research was collected using a face-to-face survey technique. The survey consisted of questions measuring internet usage time, social comparison, and demographic characteristics. Additionally, a control question was added by the researcher. Ethical committee approval was obtained before data collection. The survey was administered to approximately 300 people. Fourteen surveys were eliminated through reverse-coded statements in the social comparison scale and the control question. Therefore, the research sample consisted of 286 participants. Participants were adults and university students from Afyonkarahisar province. A convenience sampling technique was adopted to increase the sample size, and accordingly, all participants who use the internet were included in the research.

Measures

Internet Usage Time: A single, open-ended question was created to determine participants' internet usage time. The question was: "On average, how many hours a day do you use the internet?"

Social Comparison: Social comparison was measured using the Iowa-Netherlands Comparison Orientation Scale, developed by Gibbons & Buunk (1999). This 11-item instrument assesses two dimensions: skills and opinions. In the original version, two items are reverse-coded, and each item is rated on a 5-point Likert scale, ranging from (1) "strongly disagree" to (5) "strongly agree." The scale was translated into Turkish and validated by Teközel (2000). An example item is: "I always pay a lot of attention to how I do things compared with how others do things."
Demographic characteristics: The most commonly used demographic characteristics in scientific research have been preferred. In this context, gender, education level, age, income, and marital status variables have been measured.

Analytical Approach
Descriptive statistics, difference tests, and correlations were used to establish a general profile of the participants and scales. Furthermore, factor analysis was conducted to determine the quality of the measurement instruments, and reliability coefficients were calculated. Due to the complex findings in the literature, the study was conducted through research questions rather than hypotheses. Multiple regression analysis was used to answer the exploratory research questions.

FINDINGS
Demographic Findings, Descriptive Statistics, and Correlations
When the demographic profiles of the 286 participants were examined, the majority were female (57%), single (72%), and high school graduates (58%). The average age of the participants was 27, and their average monthly income was 23,656 TL. Their average daily internet usage time was 6 hours, and their general social comparison level was 3.27. This value indicates that it is slightly above the average. When examined in terms of dimensions, the average of the ability comparison was 2.88, while the average of the opinion comparison was 3.95. It is understood that the participants made more opinion comparisons. In terms of social comparison and its dimensions, no significant difference was found between gender, marital status, and education level groups. Similarly, internet usage time did not differ according to gender and education level. However, it was found that single participants (M=6.50) used the internet more than married participants (M=4.21) [$t(272) = 4.584$, $p < .001$.)].
The overall reliability of the social comparison scale was determined to be α: 79.8, the ability comparison dimension α: 81.4, and the opinion comparison dimension α: 70.0, indicating that the measurement instrument has acceptable reliability. The factor structure of the measurement instrument was also obtained as in the original adaptation study. The total explained variance of the two-dimensional structure was obtained as 50.42%.
Pearson correlation analysis was applied to determine the relationships between variables and is presented in Table 1.

Table 1. Correlations

	1	2	3
1. Internet Usage Time	1	-	-
2. Ability Social Comparison	-.03	1	-
3. Opinion Social Comparison	.01	.28**	1

Not. *N* = 286. **p < .01.
The findings indicate no significant relationship between participants' internet usage time and comparisons of social skills and opinions. However, a positive relationship was found between comparisons of skills and comparisons of opinions.

Multiple Regressions
Multiple regression analysis was conducted to test the power of age, gender, education, income, and marital status to influence internet usage time.
The model was found to be significant [$F(5.277) = 3.025$, $p = .011$]. The model explains 5.2% of the variance in internet usage time ($R^2 = .052$). When the independent variables were examined, only age was found to be a significant predictor ($\beta = -.204$, $p = .006$). Accordingly, internet usage time decreases as age increases.

In the regression analysis conducted to predict skill comparison, the model was not found to be significant [F(5.272) = 1.569, p = .169]. The model explained only 2.8% of the variance (R^2 = .028). Although only the marital status variable appeared significant (β = -.184, p = .013), the model was not found to be significant overall.

Similarly, the regression analysis conducted to explain the comparison of opinions did not reveal a significant profile [F(5.277) = 1.261, p = .281]. The model explained only 2.2% of the variance (R^2 = .022). Although the income variable appeared significant (β = .148, p = .036), the model was not found to be significant overall.

DISCUSSION & CONCLUSION

In this study, the effects of demographic characteristics such as age, gender, education level, income and marital status on the duration of internet use and the ability and opinion dimensions of social comparison were examined. Additionally, the relationships between internet usage time and dimensions of social comparison were investigated. According to the findings, demographic variables explain the duration of internet use to a limited extent, but are insufficient to explain the ability and opinion dimensions of social comparison.

Findings regarding the first question of the research show that age significantly and negatively affects the duration of internet use. This result seems to coincide with the findings of previous studies showing that young individuals use the internet more intensively (Abdioğlu & Harman, 2022; Açık et al., 2021; Dalgic-Tetikol et al., 2022). The fact that they are introduced to digital technologies at an earlier age and make the internet a more central part of their daily lives may explain why young individuals stay online longer. When examined in terms of marital status, it was determined that single individuals use the internet more than married individuals. The relevant finding reveals that the time spent on social interaction, entertainment and leisure activities may differ depending on marital status. However, the fact that marital status did not emerge as a significant predictor in the regression analysis indicates that the duration of internet use may be affected by different individual and environmental variables rather than demographic factors. In addition, the fact that gender, education level and income variables do not have significant effects on internet usage time is in line with the findings reported in previous studies (Festic et al., 2021).

Findings regarding the second question of the research show that demographic characteristics do not affect neither the ability nor the opinion dimension of social comparison. Although marital status seems to have significant effects on ability comparison and income opinion comparison, the fact that the developed regression models are not significant as a whole requires the results to be evaluated cautiously. The finding in question suggests that social comparison tendency may be linked to individual and psychological characteristics rather than demographic characteristics (Buunk et al., 2020; Gibbons & Buunk, 1999). It can be considered that variables such as self-esteem, personality traits, self-perception and social media usage patterns may be more decisive in social comparison processes.

Regarding the third question of the research, no significant relationships were found between internet usage time and the ability and opinion dimensions of social comparison. This result shows that internet usage duration alone does not increase the tendency for social comparison. Although the internet offers individuals the opportunity to observe the lives, successes and opinions of others (Verduyn et al., 2017), it can be thought that the purpose of use and the platforms used may be more effective on social comparison rather than the amount of time spent on the internet. For example, the social comparison experiences of individuals who use the internet for professional purposes and individuals who use social media extensively may differ (Baumann & Utz, 2021).

The research has some limitations. First of all, the data was collected by convenience sampling method and in a single province. This situation limits the generalizability of the results. Additionally, internet usage time was assessed through a single-item measurement and usage purposes were not taken into account. In future studies, it may be reasonable to examine the effects of variables such as social media use intensity, self-esteem, personality traits and psychological well-being on social comparison. In addition, studies on different age groups and cultural samples may contribute to a more comprehensive evaluation of existing findings.

When the findings are evaluated in general, it is seen that demographic characteristics have a certain role in explaining internet usage behaviors, but are quite limited in explaining social comparison

tendencies. This suggests that social comparison may be a more stable psychological orientation that is relatively independent of demographic characteristics.

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IS CYBERLOAFING ALWAYS HARMFUL? RECONSIDERING POSITIVE OUTCOMES IN DIGITAL WORKPLACES

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ABSTRACT
Cyberloafing, defined as employees' use of corporate and personal internet for non-work-related purposes during working hours, has generated contrasting views regarding its potentially harmful and beneficial consequences. In the current literature, cyberloafing is mostly described as a behavior that reduces productivity, wastes time, and lowers individual and organizational performance. Therefore, cyberloafing is generally examined from the perspectives of counterproductive work behavior, workplace deviance, and organizational norm violation, and is considered an undesirable behavior. However, recent research shows that cyberloafing does not only lead to negative consequences and, under certain conditions, can also provide some beneficial outcomes for employees and organizations. Both this ambivalent nature of cyberloafing and the different findings in the existing literature necessitate a detailed examination of the concept for a better understanding. Therefore, this study aims to re-evaluate the dominant negative approach to cyberloafing and discuss its potential positive outcomes at a conceptual level. Accordingly, the cyberloafing literature has been examined from the perspectives of psychological recovery, resilience, creativity, learning, innovative behaviors, and employee well-being. This study, drawing particularly on resource conservation theory and the recovery approach, details how employees can use cyberloafing as a coping, stress-reducing, and resource replenishment mechanism in the face of intense work demands and psychological burdens. The study fundamentally points out that evaluating the consequences of cyberloafing solely in a binary, positive or negative way is insufficient. Instead, it argues that the effects of the behavior can vary depending on a number of factors such as the purpose of use, duration, intensity, and organizational context. Specifically, it suggests that short-term and controlled cyberloafing can contribute to refreshing employees' cognitive resources, support creativity, and improve psychological well-being. Conversely, it emphasizes that excessive and uncontrolled internet use will continue to trigger undesirable negative behaviors. The study reveals that cyberloafing should not be considered solely as harmful behavior, and that it is important to address it in digital work environments from a more balanced, contextual, and multidimensional perspective.
Keywords: Cyberloafing, psychological recovery, creativity, employee well-being

INTRODUCTION
With the development of digital technologies, access to the internet and online platforms has become much easier in both professional and daily life. However, high integration with digital platforms also brings with it problematic internet use and psychological and behavioral issues such as addiction (Kuss & Griffiths, 2017). These problems, mostly stemming from unconscious and intensive use, can lead to long-term issues such as stress, depression, loneliness, and conflict (Açık et al., 2021; Andreassen, 2015). A similar situation exists in the workplace, and behaviors resulting from unconscious and intensive internet use are considered undesirable behaviors in organizations (Chavan et al., 2022).

One such behavior is cyberloafing, defined as engaging in non-work-related activities online during working hours (Lim, 2002). Non-work-related behaviors such as online shopping, online gambling, playing online games, or browsing social media platforms fall under the scope of cyberloafing (Blanchard & Henle, 2008).

In the literature, cyberloafing is mostly considered an undesirable behavior in organizations, harming them and reducing performance (Aghaz & Sheikh, 2016; Lim & Teo, 2024; Yang et al., 2023). However, recently there has been a significant increase in studies focusing on the positive aspects of this behavior, such as relieving employee stress, increasing performance, providing mental refreshment, and increasing innovation (Baş & Şirin, 2023; Narwal, 2023; Rahman et al., 2022).

These developments indicate that cyberloafing may not always be negative and that the behavior can actually change from positive to negative depending on its purpose, duration, and context. This raises the question of whether cyberloafing is always harmful or whether it can be beneficial for employees and organizations under certain conditions. Therefore, this study aims to evaluate cyberloafing from a more holistic perspective and to reveal both its positive and negative implications and their contexts. Thus, this study aims to move beyond the prevailing negative perception of cyberloafing and highlight the potential positive aspects of the behavior.

This study critically examines the traditional negative approach to cyberloafing and discusses the increasingly positive perspective in the literature. The main argument of the study is that cyberloafing is not inherently harmful behavior; rather, its effects vary depending on the purpose of use, duration, and organizational context (Andel et al., 2019; Kwala & Agoyi, 2024). Accordingly, the study aims to present the positive and negative effects of cyberloafing on employee and organizational outcomes within a holistic framework.

This conceptually designed study is expected to contribute to moving beyond the traditional perspective that considers cyberloafing only as an undesirable work behavior and to increase awareness of the potential positive consequences of this behavior. Furthermore, the study is expected to provide a conceptual foundation for future empirical research by opening new areas of discussion regarding the consequences of cyberloafing in different contexts.

CONCEPTUAL FRAMEWORK

Cyberloafing as an Undesirable Workplace Behavior

Recently, cyberloafing, a behavior frequently encountered, is largely considered a negative behavior in the literature (Lim & Teo, 2024; Yang et al., 2023). While early studies defined cyberloafing as employees using the organization's internet infrastructure for personal purposes (Lim, 2002), today it has gained a broader meaning encompassing not only corporate internet use but also all non-work-related online activities during working hours (Lim & Teo, 2024). Studies focusing on the negative effects of cyberloafing on individual and organizational performance treat this behavior as undesirable and harmful in organizations. From this perspective, cyberloafing is considered a behavior that reduces employee productivity, lowers organizational performance, distracts, and wastes employees' time (Askew et al., 2014; Lim, 2002). Especially with the recent increase in digitalization, the widespread use of social media platforms, online shopping, and internet use for entertainment, this has begun to be seen as a problem area.

One reason for viewing cyberloafing negatively is that it is considered a counterproductive behavior. Counterproductive work behaviors include conscious actions that can harm the proper functioning and goals of an organization (Spector & Fox, 2010). From this perspective, cyberloafing shares similar characteristics with counterproductive work behaviors. According to this view, cyberloafing is considered a negative behavior that harms the functioning of the organization, just like work slowdowns, misuse of resources, or behaviors that violate organizational rules (Lim, 2002). Another perspective that views cyberloafing negatively is that it is considered within the context of workplace deviance and workplace misconduct. In these perspectives, cyberloafing is considered a violation of organizational norms, a behavior that leads to deviation from organizational goals and does not contribute to these goals (Blanchard & Henle, 2008; Lim, 2002).

The relevant literature does not limit the harmful aspects of cyberloafing solely to employee performance. It also discusses various legal and technological risks. Internet use for personal purposes can lead to information security vulnerabilities, increase the risk of malware, and limit the efficient use of infrastructure due to intensive technology use (Blanchard & Henle, 2008; Lim, 2002). Furthermore, employees' use of illegal platforms and downloading copyrighted files can lead to legal repercussions for the organization. Accordingly, many organizations have recently developed internet use policies to prevent the harmful effects of cyberloafing (Lim & Teo, 2024).

As seen, the prevailing view in the literature is that cyberloafing is a harmful behavior that reduces workplace efficiency, decreases performance, and creates organizational costs (Lim & Teo, 2024; Yang et al., 2023). Accordingly, most studies have focused on the negative aspects of this behavior, examining its impact on organizational costs and revealing its connections to negative outcomes (Askew et al., 2014).

However, in recent years, some research has shown that cyberloafing is not as negative as it is often portrayed, and may even be beneficial both individually and organizationally (Baş & Şirin, 2023; Narwal, 2023; Rahman et al., 2022). In particular, it is argued that under certain conditions, this behavior can yield positive results due to its functions such as employee well-being, psychological refreshment, recovery, and relaxation.

Positive Outcomes of Cyberloafing

While much of the literature on cyberloafing focuses on its harms, there has been an increase in studies highlighting the potential benefits of this behavior in recent years. It is thought that, in the context of psychological well-being, coping, and psychological recovery, this behavior may not always be harmful in an organizational setting (Pindek et al., 2018).

Today, intense work demands, exposure to vast amounts of information due to the use of digital technologies, and switching between multiple tasks create cognitive load (Arnold et al., 2023; Hasan, 2024). Furthermore, all these factors make it necessary for employees to feel pressured by time, to constantly focus their attention on work, to exert intense cognitive effort, and to achieve high performance in today's work environment. This necessity eventually leads to the depletion of psychological resources and mental fatigue. In this context, some studies consider cyberloafing as a kind of micro-break that allows for a temporary escape from work and other intense demands (Andel et al., 2019). Accordingly, activities such as short browsing sessions on social media and reading news can contribute to mental refreshment. From a psychological recovery perspective, cyberloafing allows employees to disconnect from work for a certain period, refresh their mental energy, and reduce their stress levels (Andel et al., 2019; Henle & Blanchard, 2008). According to this viewpoint, cyberloafing contributes to the psychological well-being of employees by reducing mental burden.

In addition to psychological recovery, some studies suggest that cyberloafing can enhance innovation and creativity (Narwal, 2023; Rahman et al., 2022; Tsai, 2023).

Employees who are constantly engaged in routine activities at work, especially when they engage in a certain level of cyberloafing, can gain new information, observe new ways of working, and develop new ideas. Thus, employees who move away from the rigidity of work life can increase their creativity in terms of associations and learning new ideas (Tsai, 2023). In this respect, cyberloafing is not always harmful, sometimes it can be described as a medium that supports innovation and positively changes employee performance (Narwal, 2023; Rahman et al., 2022).

Another positive consequence of a certain level of cyberloafing is that it contributes to employees' information acquisition and learning processes (Liu et al., 2026). Online platforms enable employees to keep up with current developments, acquire new information in various fields, and improve their professional skills accordingly.

Examining cyberloafing solely from the perspective of productivity loss can be considered an incomplete approach in this context. As seen, positive outcomes such as psychological recovery, stress reduction, creativity, learning, and innovation demonstrate that cyberloafing can be beneficial under certain conditions (Andel et al., 2019; Henle & Blanchard, 2008; Narwal, 2023; Rahman et al., 2022; Tsai, 2023). Of course, this does not mean that cyberloafing is always harmful or always beneficial. The consequences of the behavior can vary depending on the context, the intensity, duration, purpose, and type of the behavior. Considering the contextual aspects of the behavior seems important for a more comprehensive understanding of the phenomenon.

A Contextual View of Cyberloafing

A review of the literature on cyberloafing reveals conflicting and differing findings regarding the consequences of this behavior (Uslu, 2025a). While some argue that cyberloafing reduces performance and productivity and creates various organizational costs, others suggest the opposite, claiming it increases performance and fosters innovation and creativity. These contradictory findings indicate that evaluating cyberloafing in a one-dimensional way is inappropriate and that it is related to the context of the conditions under which the behavior occurs (Andel et al., 2019; Lim & Teo, 2024).

One of the relevant conditions is the purpose for which the behavior is performed, because employees' reasons for using the internet can differ. Previous theoretical work suggests that online activities are driven by diverse motivations, including information seeking, entertainment, and social interaction

(Uslu, 2022). Accordingly, some employees engage with the internet for short breaks, mental relaxation, acquiring new information, and stress reduction, while others may visit online platforms to escape their responsibilities at work, simply for entertainment, or to pass the time. Therefore, the purpose for which the same behavior is performed can also affect its results. Cyberloafing for the purpose of passing time and entertainment appears to have negative consequences, but behavior aimed at learning, acquiring information, or mental recovery seems more likely to lead to positive results, especially in the long term (Liu et al., 2026).

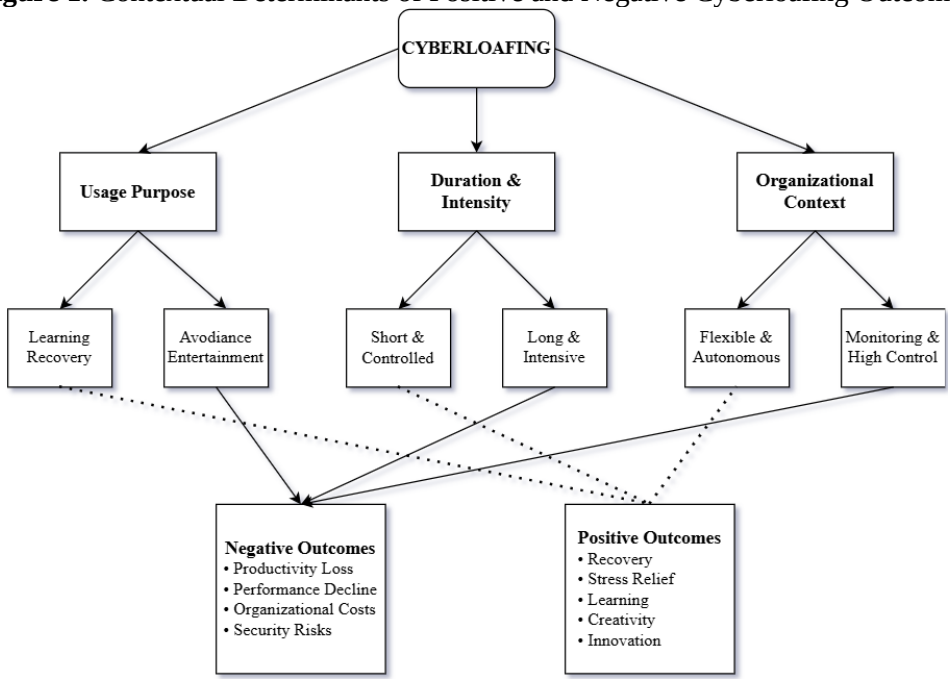
Besides the intended purpose of use, another important aspect to consider is the duration and intensity of the behavior. Short-term and controlled online activities can contribute to mental rest and the refreshment of cognitive resources, while long and intense online activities can lead to disengagement, inefficiency, distraction, and decreased performance (Andel et al., 2019; Askew et al., 2014; Lim & Teo, 2024). This situation is similar to problematic internet use. Digital detox practices that limit time usage provide purposeful and controlled internet use, benefiting individuals' health in the long run (Uslu, 2025b).

Problematic internet use, which can be described as intense and prolonged, results in many negative outcomes. A similar situation exists in cyberloafing, and short-term and controlled use can produce more positive outcomes. In this regard, the level of the behavior becomes important.

Organizational environment and context are influential in shaping the outcomes of cyberloafing. In organizational environments where high discipline, control, and authority prevail, and information security risks are high, cyberloafing may have negative consequences. On the other hand, in organizations with high employee autonomy, cyberloafing may have more positive outcomes (Blanchard & Henle, 2008; Andel et al., 2019; Lim & Teo, 2024).

As can be seen, cyberloafing is a type of behavior with a multi-dimensional structure and should not be evaluated purely as positive or negative (Blanchard & Henle, 2008; Lim & Teo, 2024). Whether it is considered harmful or beneficial depends on factors such as the organizational context in which the behavior occurs, the underlying purpose or reason for the behavior, and the duration and intensity of the behavior. Based on the main argument of this study, the effects of cyberloafing need to be evaluated from a contextual perspective. Figure 1 shows the conditions under which positive and negative consequences of cyberloafing occur.

Figure 1. Contextual Determinants of Positive and Negative Cyberloafing Outcomes



Note: Created by the author. Solid arrows indicate conditions associated with negative outcomes, whereas dotted arrows indicate conditions associated with positive outcomes.

CONCLUSION

This study aims to comprehensively examine both the positive and negative consequences of cyberloafing in organizational life, starting from the question of whether cyberloafing is always and under all circumstances a negative behavior. In the literature, cyberloafing is mostly evaluated negatively in the context of decreased performance, inefficiency, security risks, and organizational costs (Askew et al., 2014; Lim & Teo, 2024; Lim, 2002). Accordingly, it is observed that counterproductive work behaviors and deviant behaviors are dominant perspectives regarding the behavior. In this respect, it stands out as an undesirable and negative behavior. However, recent studies show that, on the contrary, there is a growing literature suggesting that cyberloafing has positive aspects such as increasing innovation, reducing stress, and enhancing learning and creativity (Andel et al., 2019; Henle & Blanchard, 2008; Narwal, 2023; Rahman et al., 2022; Tsai, 2023). This situation reveals that virtual procrastination is too complex a behavior to be categorized simply as either a positive or negative behavioral pattern.

When evaluated within the context of the reviewed literature, it can be stated that the consequences of cyberloafing behavior are not amenable to universal conclusions such as negative or positive. Contrary to universal conclusions, the consequences of this behavior are clearly contextual (Uslu, 2025a). The prominent contexts here are the organizational context, the purpose of internet use, and the duration and intensity of use. Accordingly, the nature of the organizational context, the purposes of use by employees, and the duration and intensity of use shape the consequences of cyberloafing. Therefore, rather than focusing on whether cyberloafing is harmful or beneficial, it seems more meaningful to focus on what kinds of consequences it produces under what conditions.

This study is expected to contribute to the literature by offering a more balanced and contextual perspective, contrary to the prevailing negative view of cyberloafing. Furthermore, it is thought that the conceptual model developed within the context of this study can serve as a starting point for future empirical research. Future studies are recommended to empirically examine the effects of variables such as purpose of use, duration, and organizational context on the consequences of cyberloafing across different sectors and work styles.

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FARKLI TASARIM GEOMETRİLERİNE SAHİP LOWBED TREYLER RAMPALARININ İKİ MALZEME KULLANILARAK SONLU ELEMANLAR ANALİZİ

FINITE ELEMENT ANALYSIS OF LOWBED TRAILER RAMPS WITH DIFFERENT DESIGN GEOMETRIES USING TWO DIFFERENT MATERIALS

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ÖZET

Ağır ticari taşımacılık sektöründe kullanılan lowbed treyler rampaları, iş makineleri ve ağır yüklerin güvenli bir şekilde yüklenip boşaltılmasında rol oynamaktadır. Bu yapıların tasarımında, yüksek taşıma kapasitesi ve yapısal dayanımın yanı sıra toplam ağırlığın azaltılması, yakıt tasarrufu ve lojistik verimlilik açısından öncelikli parametreler arasında yer almaktadır. Bu çalışmada, bir lowbed treyler rampasının mukavemet değerlerinden ödün verilmeden hafifletilmesi hedeflenmiş ve bu amaçla üç farklı rampa geometrisi tasarlanmıştır. Tasarımların yapısal performansını ve malzeme alternatiflerini incelemek amacıyla, yüksek mukavemetli yapı çeliği S700 ile aşınmaya dayanıklı ileri yüksek mukavemetli çelik Hardox 400 olmak üzere iki farklı malzeme grubu tercih edilmiştir. Modellenen geometrilerin mekanik davranışları, rampanın uç noktasına ve orta noktasına uygulanan iki farklı yükleme konumu altında incelenmiştir. Böylece 3 farklı tasarım, 2 farklı malzeme ve 2 farklı yükleme konumu kombinasyonu ile toplamda 12 farklı statik analiz senaryosu oluşturulmuş ve sonlu elemanlar yöntemi yazılımıyla çözdürülmüştür. Analizler sonucunda elde edilen toplam deformasyon, eşdeğer gerilme ve güvenlik faktörü verileri birbiriyle karşılaştırılmıştır. Çalışma sonuçları, geometrik değişiklikler ile rampa ağırlığında maksimum %11,81 oranında bir hafifleme sağlandığını göstermiştir. Analiz senaryoları arasında kritik gerilmelerin rampa orta noktasına yükleme yapıldığında yoğunlaştığı görülmüş, optimize edilen Tasarım 3'ün her iki malzeme grubunda da emniyet sınırları içinde kalarak en optimum performansı sergilediği tespit edilmiştir. Bu çalışma, lojistik sektöründe parça hafifletme ve malzeme optimizasyonu süreçlerine sistematik bir yaklaşım sunmaktadır.

Anahtar Kelimeler: Lowbed Rampası, S700, Hardox 400, Sonlu Elemanlar Analizi (FEA), Optimizasyon, Statik Analiz.

ABSTRACT

Lowbed trailer ramps used in the heavy commercial transport sector play a role in the safe loading and unloading of construction machinery and heavy loads. In the design of these structures, high load-bearing capacity and structural strength, as well as reducing total weight, are among the priority parameters in terms of fuel savings and logistical efficiency. In this study, the aim was to reduce the weight of a lowbed trailer ramp without compromising its strength values, and for this purpose, three different ramp geometries were designed. To examine the structural performance and material alternatives of the designs, two different material groups were preferred: high-strength structural steel S700 and wear-resistant advanced high-strength steel Hardox 400. The mechanical behavior of the modeled geometries was investigated under two different loading positions applied to the end and midpoint of the ramp.

Thus, a total of 12 different static analysis scenarios were created with 3 different designs, 2 different materials, and 2 different loading position combinations, and solved using finite element method software. The total deformation, equivalent stress, and safety factor data obtained from the analyses were compared with each other. The study results showed that a maximum weight reduction of 11.81% was achieved in the ramp through geometric changes. Among the analysis scenarios, it was observed that critical stresses were concentrated when loading was applied to the midpoint of the ramp.

It was determined that the optimized Design 3 exhibited the optimal performance while remaining within safety limits in both material groups. This study provides a systematic approach to part weight reduction and material optimization processes in the logistics sector.
Keywords: Lowbed Ramp, S700, Hardox 400, Finite Element Analysis (FEA), Optimization, Static Analysis.

INTRODUCTION

Lowbed trailers are specialized transport vehicles widely utilized for the safe transportation of heavy and oversized cargo. Commonly preferred for moving construction machinery, industrial equipment, and high-tonnage loads, these vehicles generally perform loading and unloading operations via ramps located at the rear section. Ramps constitute one of the most critical structural components of the trailer, as they are directly subjected to wheel loads during loading phases. Insufficient strength or excessive deformation in these components can lead to permanent structural modifications, failures in welded regions, and significant safety risks.

In contemporary engineering design, the Finite Element Method (FEM) is extensively employed to predict the behavior of structural components beforehand. Through this method, stress distributions, deformation magnitudes, and safety factors in systems with complex geometries can be calculated with high precision. Particularly, computer-aided engineering (CAE) software such as ANSYS provides effective and reliable solutions for the structural analysis of heavy transport vehicles.

A study conducted by Kütük (2019) focuses on the design and structural analysis of ramps used in lowbed trailers. The ramp model was developed in a 3D environment using CATIA and subsequently converted into a finite element model using HyperWorks/HyperMesh software. The model was partitioned into 413029 elements in total welded zones were defined using PENTA elements and boundary conditions along with loading scenarios representing actual operating conditions 20-ton (196.13 kN) vertical load were applied. The loads acting on the ramp were evaluated at 6 positions, and the resulting stress and deformation values were calculated for each scenario, reaching a maximum stress of 672.712 MPa at the sixth position and a maximum displacement of 10.525 mm in the second position. As a result of optimization studies, a lighter and more functional ramp design compared to the existing configuration was achieved. In the new design, material thicknesses and reinforcing elements were reorganized, thereby reducing the total weight by 14.4% and total manufacturing costs by 10% while maintaining structural durability. This reduction lowers the curb weight of the trailer, contributing to increased payload capacity and reduced fuel consumption.

The study by Koszaka et al. (2013) provides comprehensive data on the utilization of numerical methods within the design process. The forces and accelerations to which the trailer is exposed under various loading and operating conditions were calculated, aiming for a maximum payload capacity from 28 to 65 tons and a gross vehicle mass spanning from 48 to 84 tons, and baseline load values for strength calculations were determined in light of these data. Analyses were performed using Abaqus Standard software to optimize the modules, which include an extendable bed adjustable in by length up to 2 m and width up to 0.6 m, along with 2- 3-, or 5-axle configurations. Stress analyses conducted on the prepared models revealed the impact of structural details on the stress distribution across the components. Consequently, the support structure of the semi-trailer was revised to maximize strength while minimizing weight, allowing the overall length to be adjusted between 13.2 and 20.1 m depending on transport requirements.

In the study by Gedik et al. (2021), the structural effects and advantages of transforming conventional welded trailer chassis into a modular configuration were examined through an analytical approach. The authors developed a detachable chassis design to mitigate the disadvantages of welded structures, such as high production costs, prolonged assembly times, transportation difficulties, and high repair costs. Nonlinear static analyses were performed during the analytical process using ANSYS Workbench. To optimize solution time and enhance computational efficiency, taking advantage of the symmetrical nature of the chassis geometry and loading conditions, the analysis model, which utilized 688266 nodes and 667636 elements, was constructed symmetrically and simplified in SpaceClaim Direct Modeler. Under an applied load of 15000 N, the analytical results showed that the detachable chassis design reduced assembly time by 10%, lowered production costs, and provided substantial logistics advantages owing to the ability to disassemble the chassis into three separate parts.

When compared to the welded I-profile the assembled structure achieved a 10 mm deformation and 420 MPa stress, representing a 52% reduction in deformation and verifying safety despite an 18% increase in stress.

Rahmah (2024) analyzed the fatigue life of welded zones in the main beam of lowbed trailer chassis, which are widely utilized in logistics and heavy cargo transportation. Within the scope of the study, 3D modeling of the main beam was performed using Rhinoceros software, while structural analyses were executed via ANSYS software. The research specifically focused on fatigue cracks and stress concentrations that dynamic loads could induce in welded joints, evaluating the structure under 60-ton and 70-ton loading conditions. The analysis results confirmed the critical impact of operational cycle frequency and load magnitude on fatigue life, revealing maximum Von Mises stresses of 237.79 MPa and 277.42 MPa along with total deformations of 7.33 mm and 8.55 mm, respectively. Consequently, these findings indicated that under an annual frequency of 2920 cycles, the structure offers a maximum service life of 102.73 years, whereas an increase to 4380 cycles reduces the minimum fatigue life to 41.09 years.

In the study out by Alamsyah et al. (2025), the structural strength of bow ramp doors with dimensions of 8500 mm in length, 4400 mm in width, and a plate thickness of 12 mm was analyzed. The research concentrated on the ramp door of the Ro-Ro vessel named KMP Bahtera Nusantara (1500 GT), which plays a significant role in inter-island transportation in Indonesia. The primary objective of the study was to investigate the material's fatigue behavior and the effects of dynamic pressure loads generated by vehicles passing over the ramp during loading and unloading. This study demonstrates the necessity of compliance with BKI (Indonesian Classification Bureau) standards using BKI KI-A36 steel to avoid excessive elastic deformation in ramp door design, as well as the efficacy of numerical analysis methods in verifying structural integrity, which determined maximum working stresses of 81.53 MPa, 302.48 MPa, and 178.07 MPa, respectively and verified that the construction remains safe with safety factors ranging from 1.32 to 4.90.

Mapangandro et al. (2021) utilized a finite element approach to analyze the structural strength and fatigue life of a GT 1500 class Ro-Ro ferry bow ramp door, focusing on repetitive dynamic loads that trigger fatigue damage, a phenomenon responsible for 50% to 90% of all mechanical failures. To replicate true operating conditions, fixed and roller supports were applied to the 3D model, and two main load cases were formulated based on vehicle positioning: load acting directly on the girder and load acting between the girders. Simulating various vehicle masses, the minimum stress was observed under the sedan car load placed directly on the girder, with a value of 43.93 MPa. Conversely, the most critical scenario occurred when a large truck load was applied between the girders, resulting in a maximum stress of 397.02 MPa; the safety factor dropped to the marginal boundary of 1.007, reducing the estimated fatigue life to a minimum of 1.17 years over 5.35×10^4 load cycles.

Sengul and Caliskan (2024) carried out a static finite element analysis of a four-slice marine and railway capping ramp using the ANSYS 14.0 platform. Modeled with standard AH36 structural steel the structure was evaluated under maximum operational boundaries: train wagons with a total wheel mass of 100000 kg per slice and loaded trucks weighing 33500 kg per slice. Under the worst-case edge-loading conditions, the maximum recorded Von Mises stress was 192.4 MPa with a safety coefficient of 1.87. Structural deflection evaluations revealed a maximum deflection of 33 mm under extreme edge-loading, while wagon-induced loading caused a deflection of 29 mm. Additionally, the dead weight of the ramp and beam induced a midpoint displacement of 41.5 mm with a beam safety coefficient of 1.64, confirming that the structural integrity safely met all engineering expectations.

In this study, static structural analyses of the loading ramps of a lowbed trailer with a 10-ton load capacity were performed. Distinct from the existing literature, three 3D models were generated by reducing the weights of the ramp, two different appropriate material properties were defined, and loads representing actual operating conditions were applied two positions. Consequently, the structural adequacy of the ramp design was evaluated by determining the equivalent stress values, total deformation magnitudes, and safety factors. In line with the obtained results, the safe operating limits of the ramps were examined, and the suitability of the design for transport conditions was demonstrated.

MATERIALS and METHODS

In this study, material substitution and weight-reduction-oriented design modifications were investigated to enhance the structural performance of a lowbed ramp used in heavy-duty transportation. The methodology pursued within the scope of the study comprises the stages of defining material properties, geometric modeling, finite element analysis (FEA), and the applying loading scenarios.

Two different steel groups were selected to meet the high strength and wear resistance criteria in the ramp design. The mechanical behaviors were compared by utilizing S700 (High-Strength Structural Steel) and Hardox 400 (Wear-Resistant Steel) materials in the designs. The mechanical properties of the selected materials are presented in Table 1.

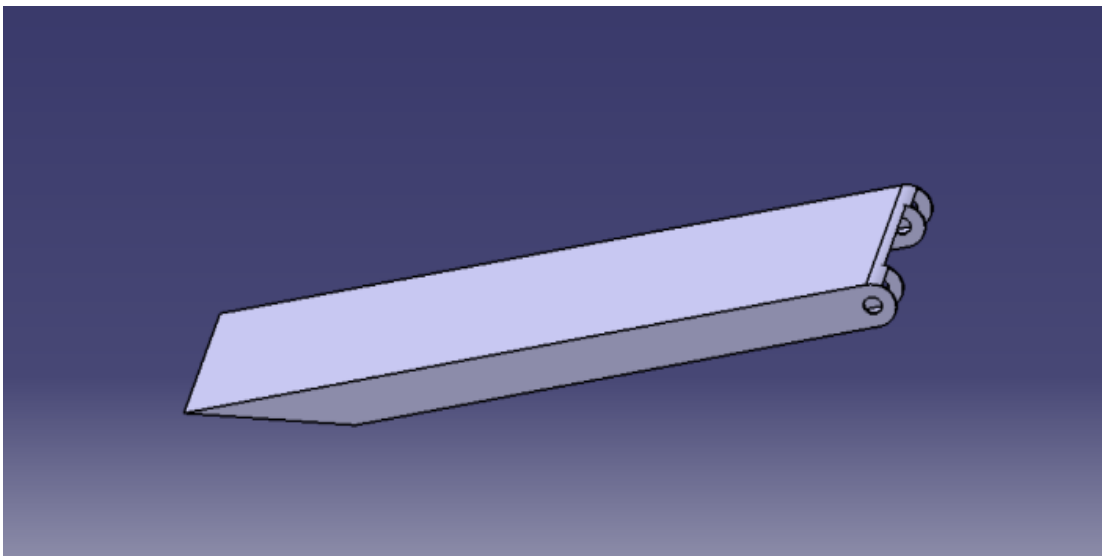
Table 1. Mechanical properties of the materials used in the analysis (SSAB, 2025)

Material	**Density (kg/m³)**	**Young's Modulus (GPa)**	**Poisson's Ratio**	**Tensile Yield Strength (MPa)**	**Tensile Ultimate Strength (MPa)**
S700	7850	210	0.3	700	850
Hardox 400	8000	190	0.29	1020	1250

Following the creation of the baseline geometry of the lowbed ramp, three different design versions (Geometry-I, Geometry-II, and Geometry-III) were developed to incrementally reduce its weight. The primary difference between these designs lies in the modifications made to the geometric forms of the load-bearing elements. At each design stage, a minimum weight target was pursued without compromising structural integrity. Geometric design of the geometry-I lowbed ramp is displayed in Figures 1a and 1b.

Table 2. Weights of the ramp designs according to the material used

Ramp Geometry	**Weight for S700**	**Weight for Hardox 400**
Geometry-I	450.22 kg	458.82 kg
Geometry-II	422.24 kg	430.31 kg
Geometry-III	397.04 kg	404.63 kg



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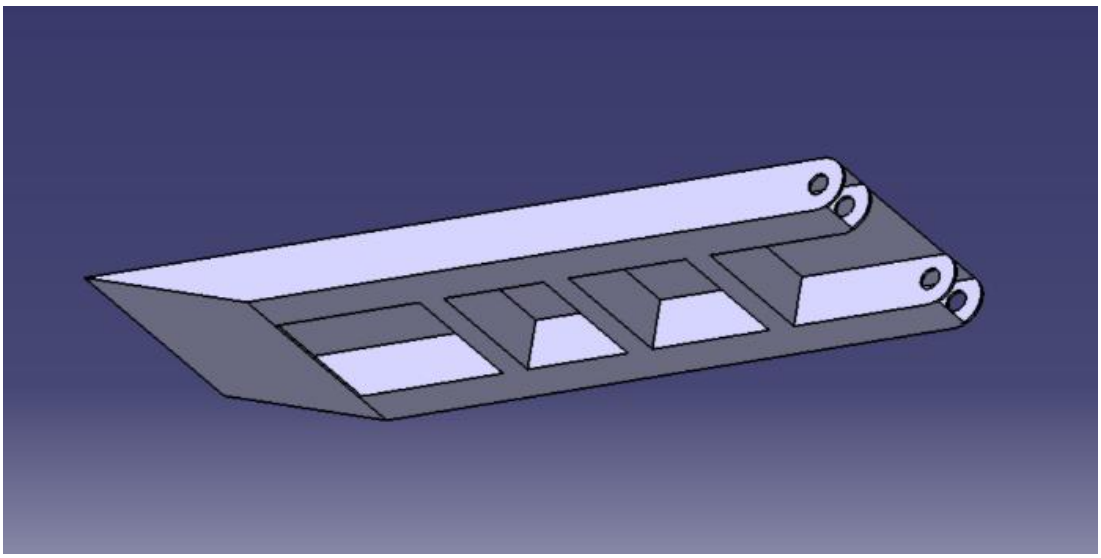

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Figure 1. (a) Upper and (b) lower views of Geometry–I

As shown in Figures 2 and 3, the sheet metal thicknesses for the design were selected as 10 mm for the main ramp plate and 8 mm for the wall thickness of the supporting U-profiles positioned at the lower part of the structure to enhance strength.

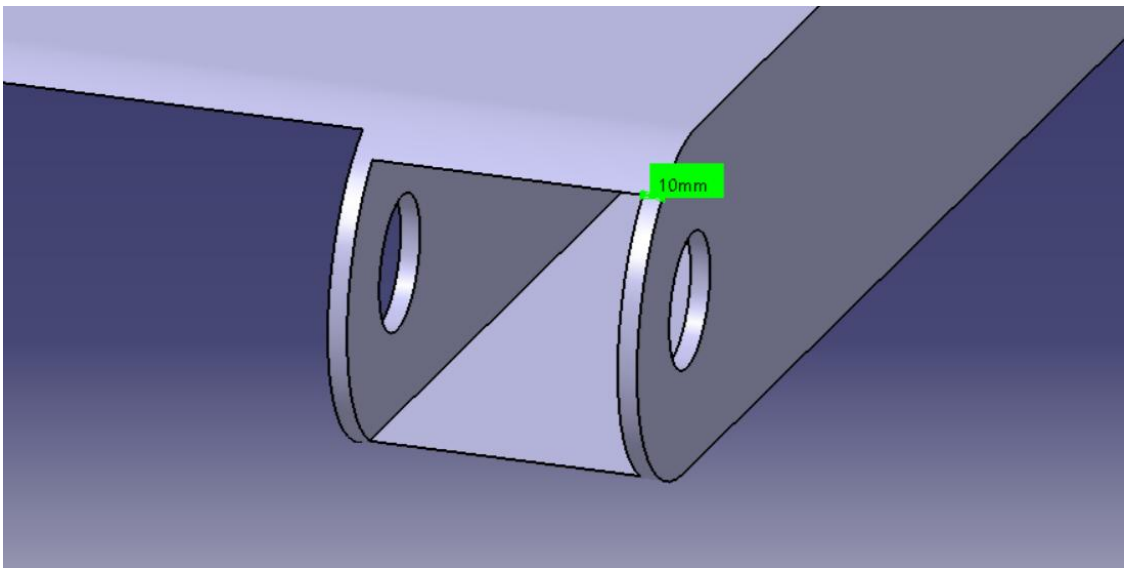


Figure 2. Main ramp plate thickness

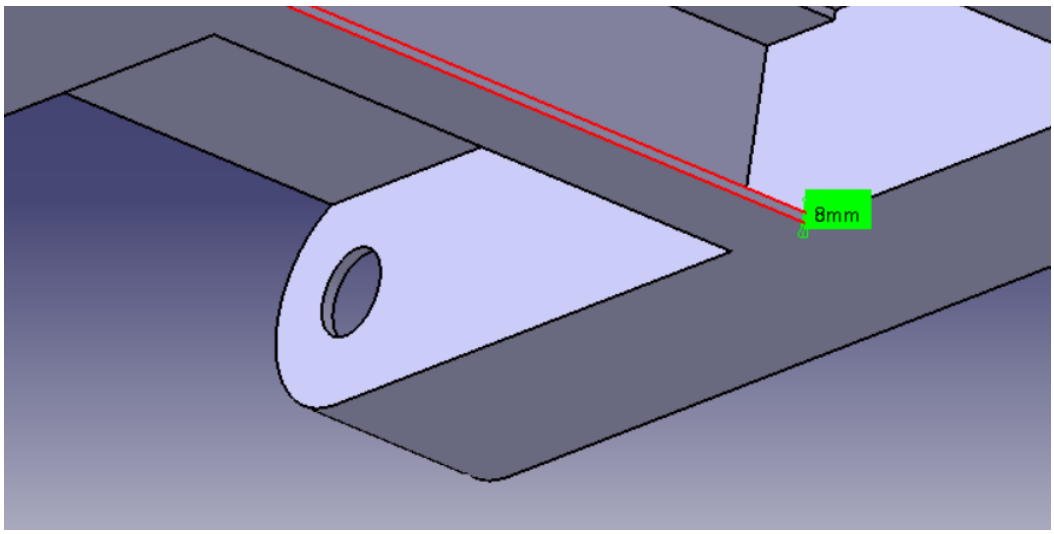
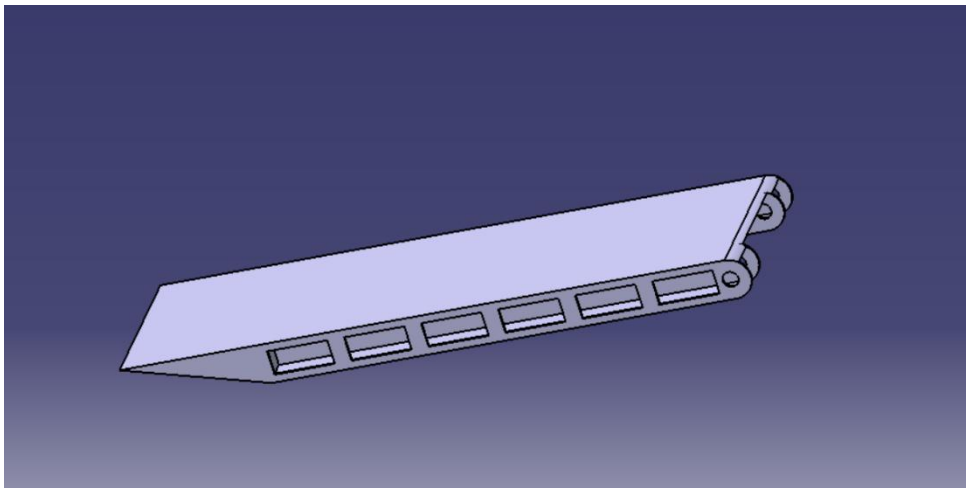


Figure 3. U-profile thickness

Geometric design of the geometry-II lowbed ramp is displayed in Figures 4a and 4b. As seen in Figure 5, the sheet metal thicknesses utilized in geometry–II are identical to those used in geometry–I. Geometric design of the geometry-III lowbed ramp is displayed in Figures 6a and 6b.



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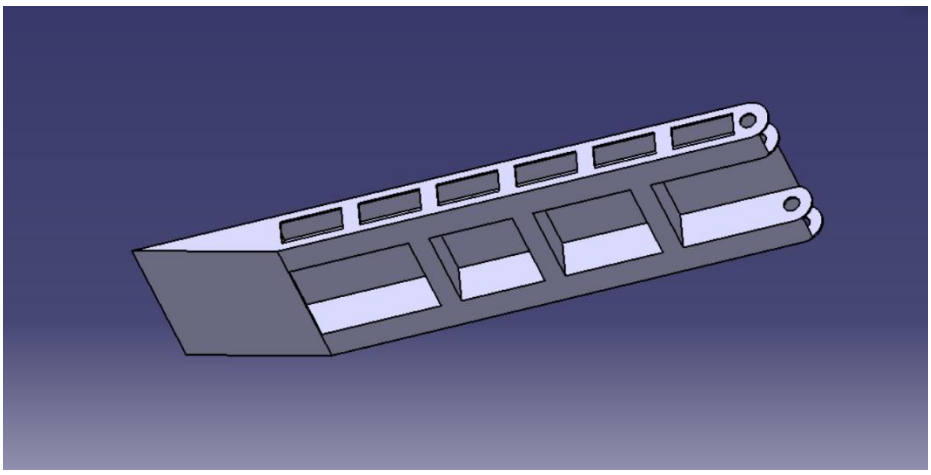

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Figure 4. (a) Upper and (b) lower views of geometry–II

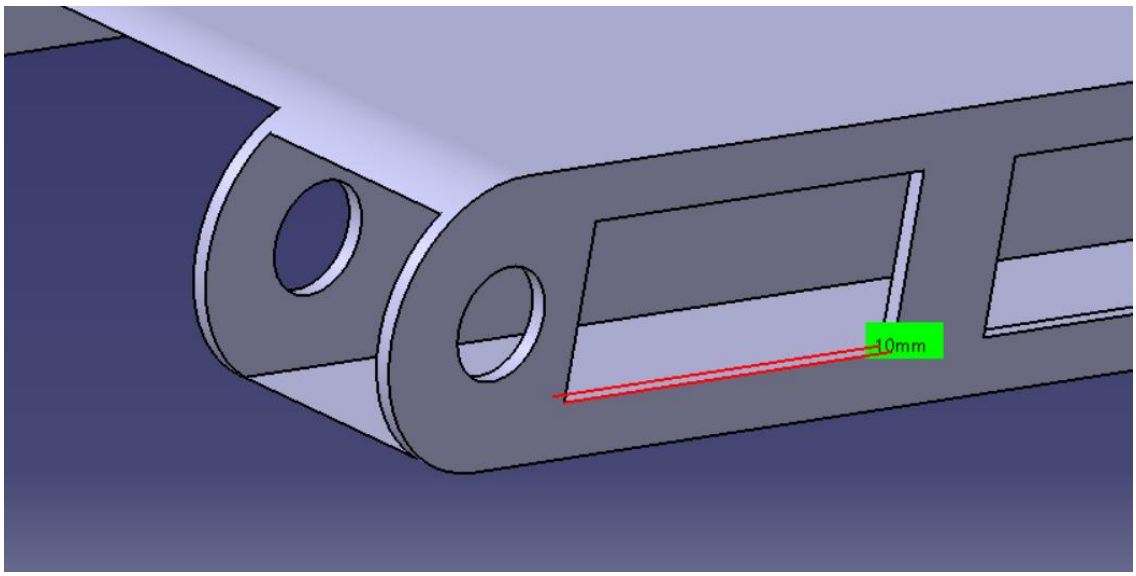
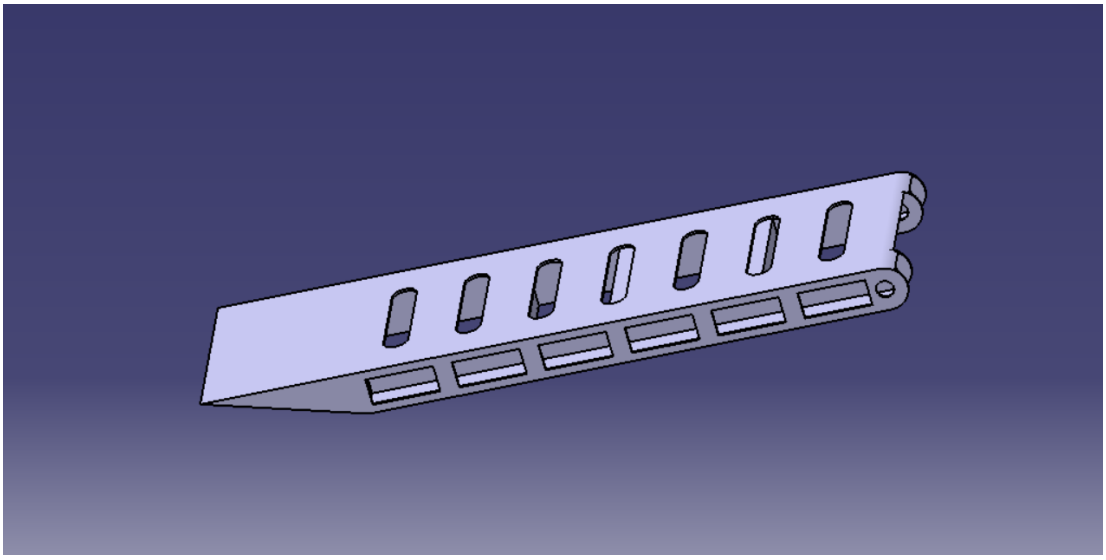


Figure 5. Main ramp plate thickness of geometry–II



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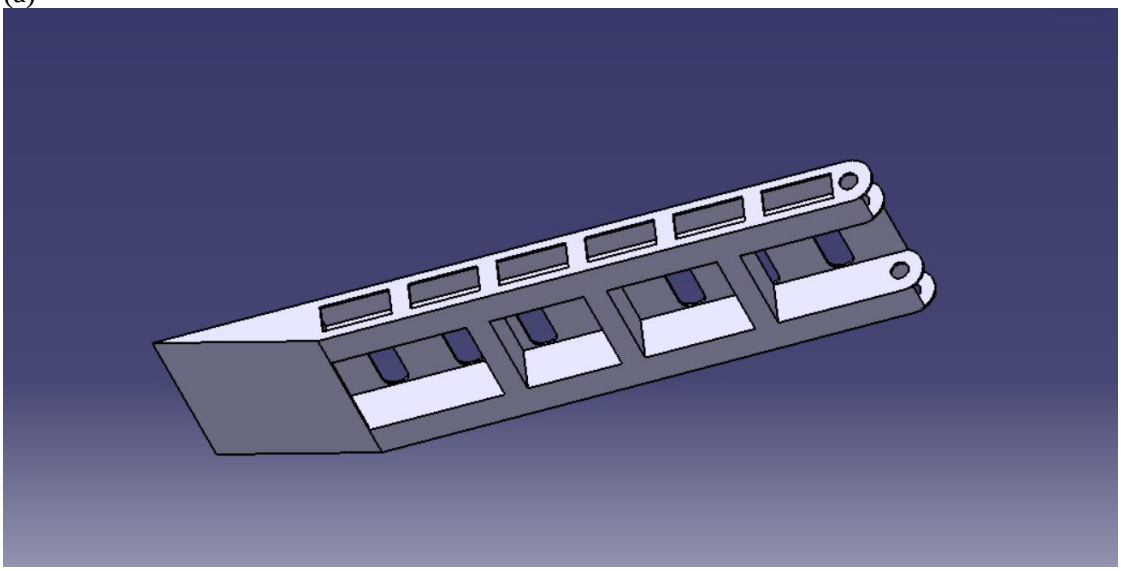


(b)

Figure 6. (a) Upper and (b) lower views of geometry–III

As indicated in Figure 7, the sheet metal thicknesses used in Geometry-III are identical to the sheet metal thicknesses used in Geometry-I and Geometry-II.

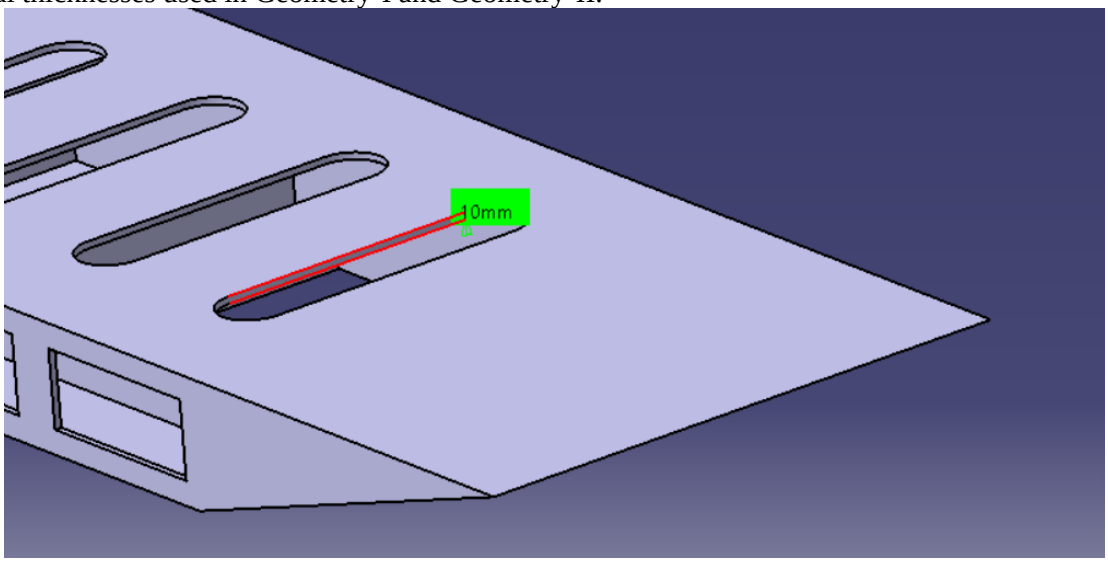


Figure 7. Main ramp plate thickness of geometry–III

Realistic loading points were determined to detect the stress and deformation values that would occur on the ramp. Considering a lowbed trailer with a payload capacity of 10 tons (Council of the European Union, 1996), the load exerted on each ramp was determined to be 5 tons. In this context, two different cases were examined:

Case 1 (Tip Region Loading): A vertical force with a magnitude of 50000 N was applied to the tip section of the ramp.

Case 2 (Middle Region Loading): A vertical force with a magnitude of 50000 N was applied to the middle section of the ramp.

Localized loading areas were defined on the upper surface of the ramp to accurately transmit the static loads exerted by that wheel surfaces actual under operating conditions. Accordingly, as shown in Figure 8, specific boundary lines were generated on the ramp geometry using the Face Split method in the ANSYS environment. In positioning the load to be applied to the midpoint of the ramp, the exact geometric center of the structure was taken as a reference, and the load was applied normally and homogeneously to the split surface, symmetrically divided around this center. The same surface-splitting technique was repeated for the tip of the ramp, ensuring that the load was safely transferred to the specific contact areas determined near the ramp's outer boundary. Consequently, load concentrations were prevented from causing artificial singularities, allowing stress distributions to be obtained in a manner closest to reality. This procedure was implemented identically for all designs.

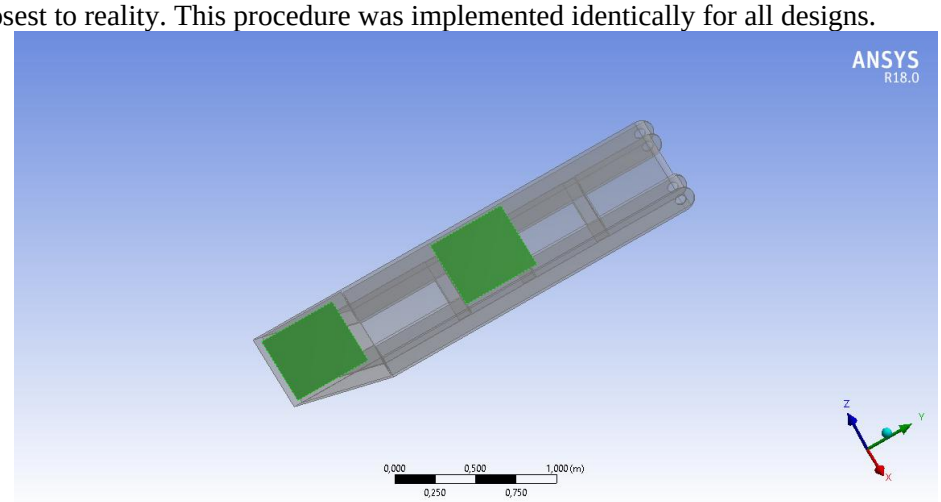


Figure 8. The ramp surface after the application of face split

Computer-Aided Design (CAD) and Finite Element Method (FEM) were utilized in an integrated manner for numerical analyses. The steps followed during the analysis process are as follows:
Generation of the Mesh Structure: A refined mesh structure was utilized in critical regions to enhance analysis accuracy.
Determination of Boundary Conditions: The points where the ramp connects to the lowbed chassis and the regions in contact with the ground were constrained using appropriate support conditions.
Loading Scenarios: Vertical loading was applied to two critical regions to simulate the operational processes of the ramp.
The mesh nodes, element quality, and skewness values obtained in the ramp models as a result of these implemented mesh strategies are provided in Tables 3 and 4.

Table 3. Mesh metrics of the ramp designs for S700 material

S700			
Ramp Geometry	**Mesh Nodes**	**Element Quality**	**Skewness**
Geometry-I	522368	0.81026	0.26885
Geometry-II	500570	0.80815	0.27225
Geometry-III	480702	0.80561	0.27584

Table 4. Mesh metrics of the ramp designs for Hardox 400 material

Hardox 400			
Ramp Geometry	**Mesh Nodes**	**Element Quality**	**Skewness**
Geometry-I	522404	0.81039	0.26871
Geometry-II	500421	0.80852	0.27184
Geometry-III	481161	0.80535	0.27626

To ensure the accuracy and reliability of the finite element analysis results, a mesh independence study was conducted on the ramp geometry. The model was evaluated across different mesh densities, ranging from coarse to fine, by monitoring the maximum Von Mises stress and total deformation values as key performance indicators. It was observed that further refinement of the mesh below a critical element size did not significantly alter the structural response. Consequently, an optimum mesh structure was selected to achieve a balance between computational accuracy and efficiency. The generated finite element mesh structures and element distributions for three developed ramp designs are illustrated in Figures 9, 10, and 11, respectively. As shown in the figures, the mesh was refined in a controlled manner to ensure continuity the component joints and at the cross-sectional transitions of the support profiles.

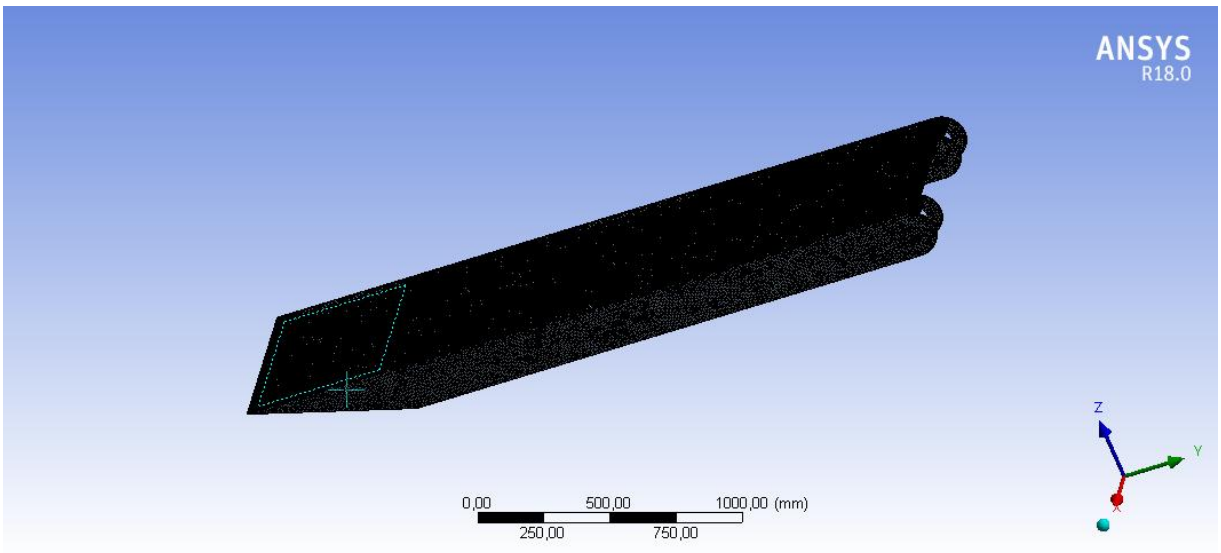


Figure 9. Finite element mesh structure of the geometry-I ramp model

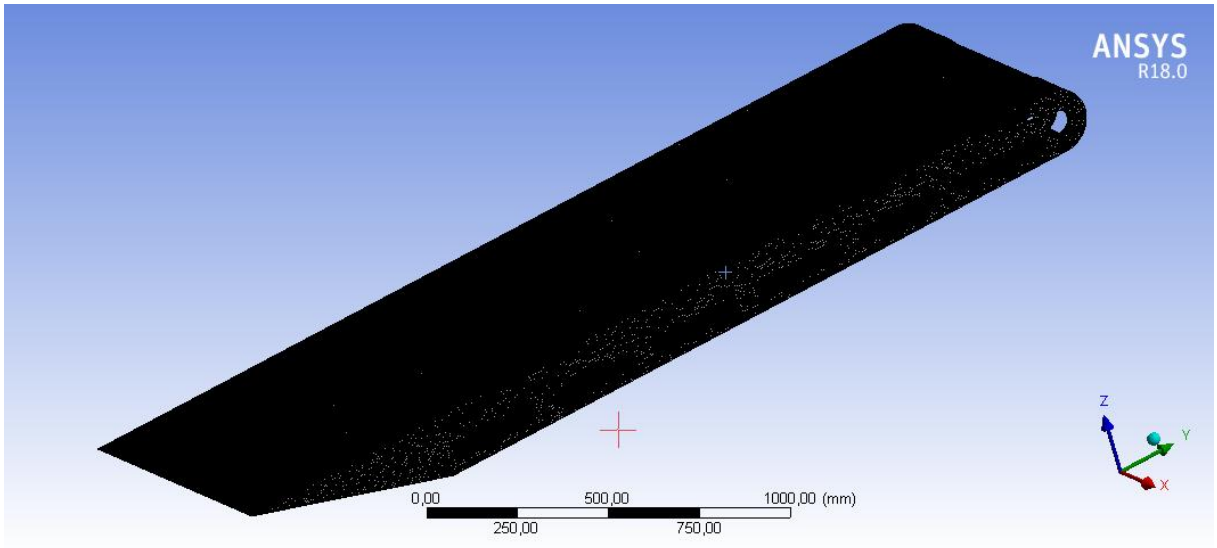


Figure 10. Finite element mesh structure of the geometry-II ramp model

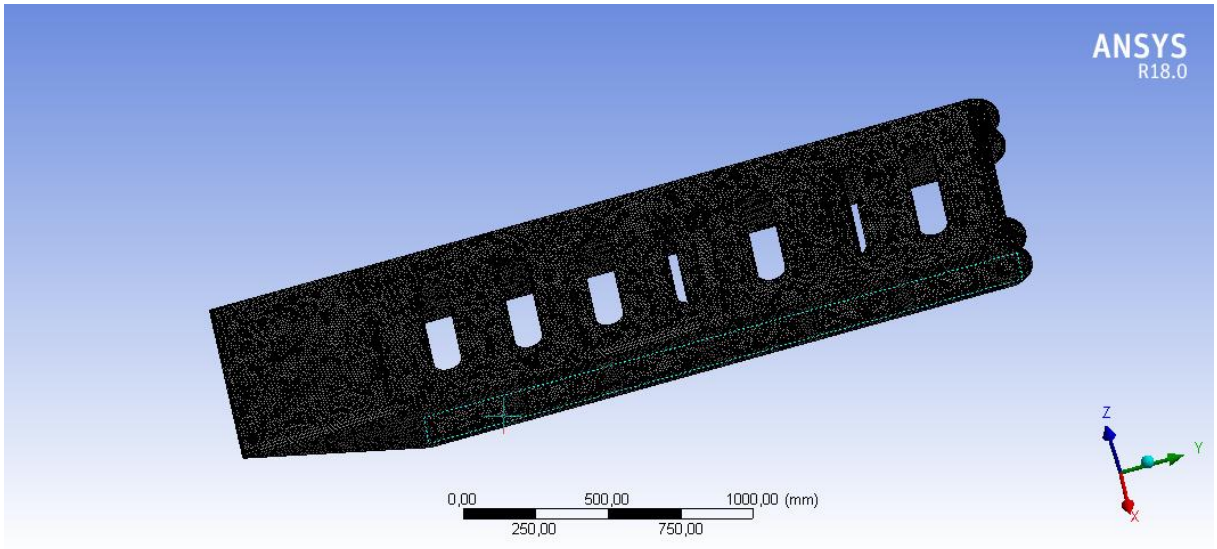
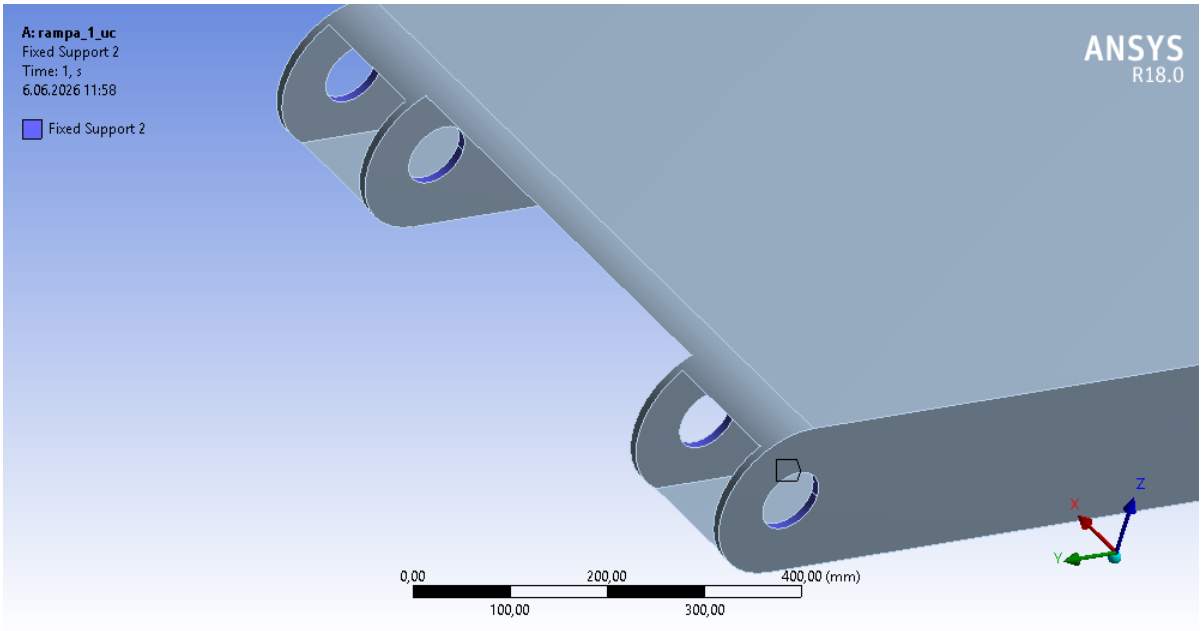
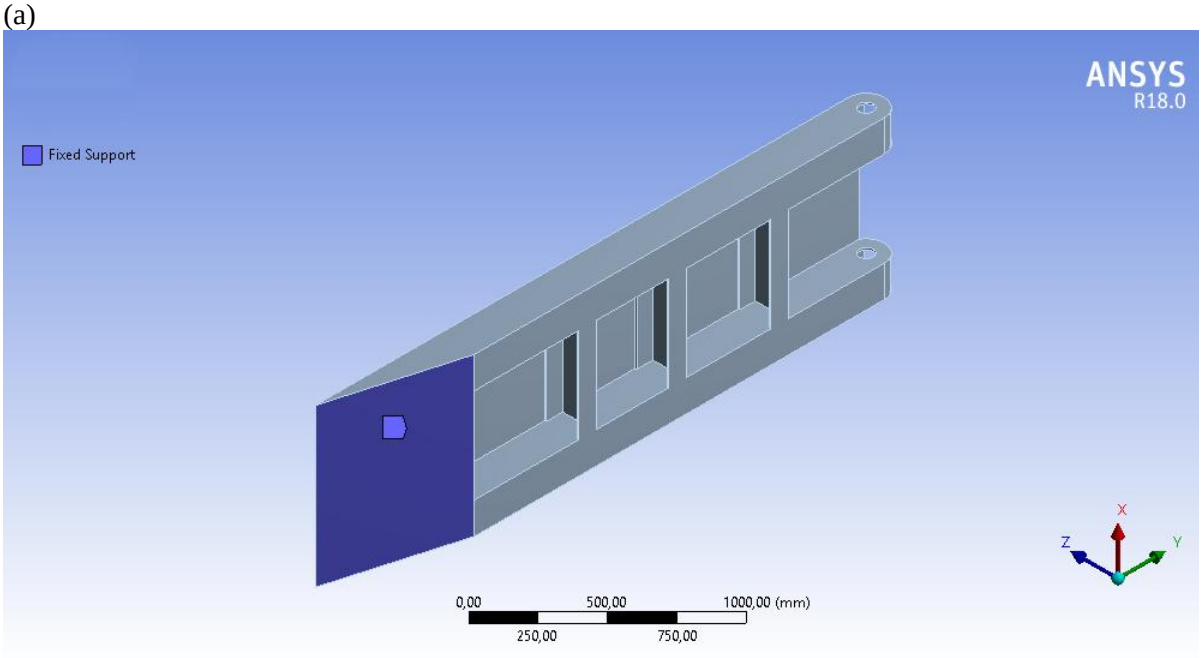


Figure 11. Finite element mesh structure of the geometry-III ramp model

To simulate the mechanical behaviors of the ramps during actual operation and loading as closely as possible to reality, the attachment points on the structure were defined with the necessary boundary conditions. Accordingly, a fixed support boundary condition was applied to the main pivot holes where the ramp is mounted to the trailer chassis, as well as to the surface where the ramp contacts the ground. This constraint procedure represents the structural relationship of the ramp mechanism with the trailer chassis under load, ensuring that the bending stresses and structural deformations induced by the applied vertical loads are concentrated in the correct regions. The fixed support locations and geometric constraint details for the developed designs are shown in Figures 12, 13, and 14.

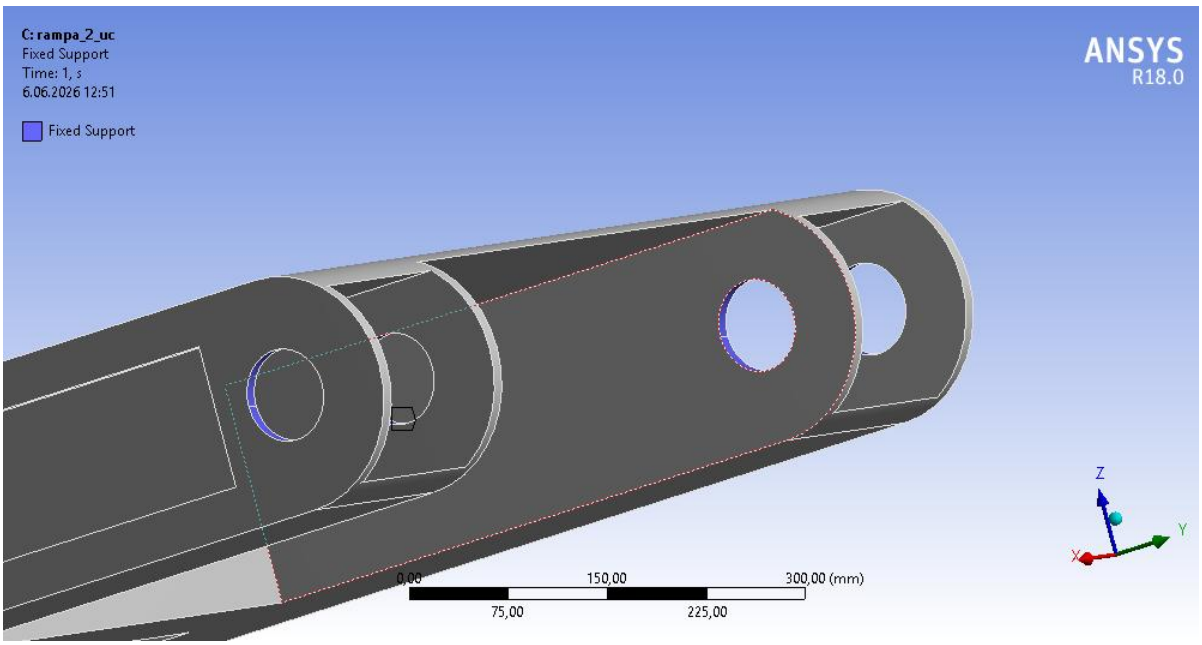


(a)

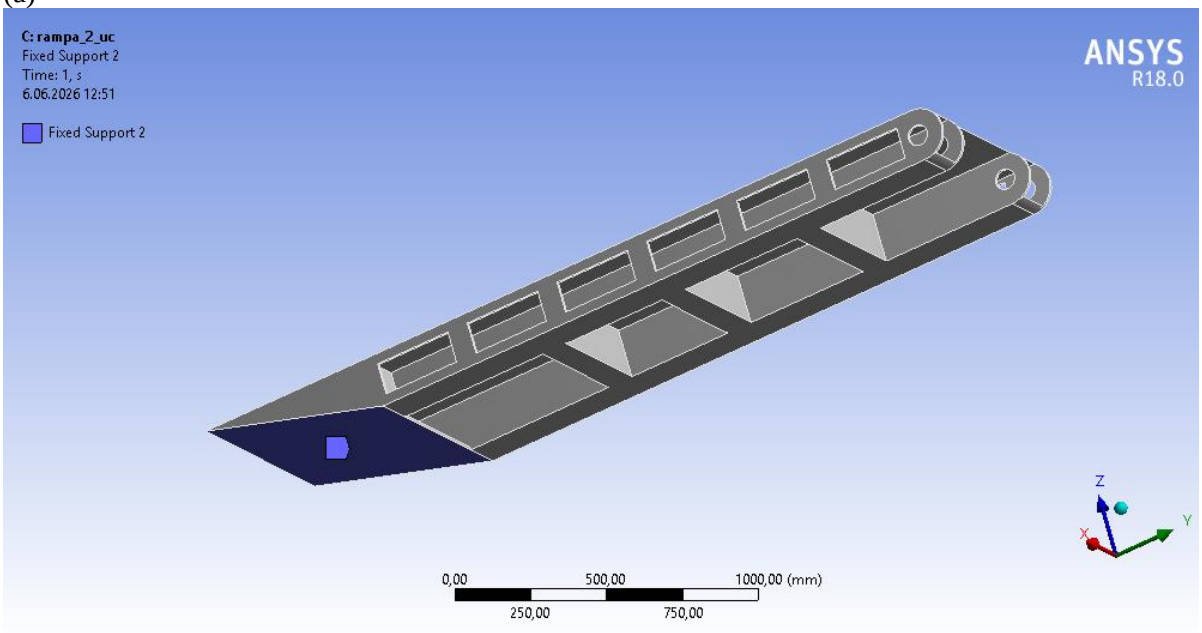


(b)

Figure 12. Fixed support illustration (a) close-up view of connection points, (b) overview of the surface for the geometry-I ramp model

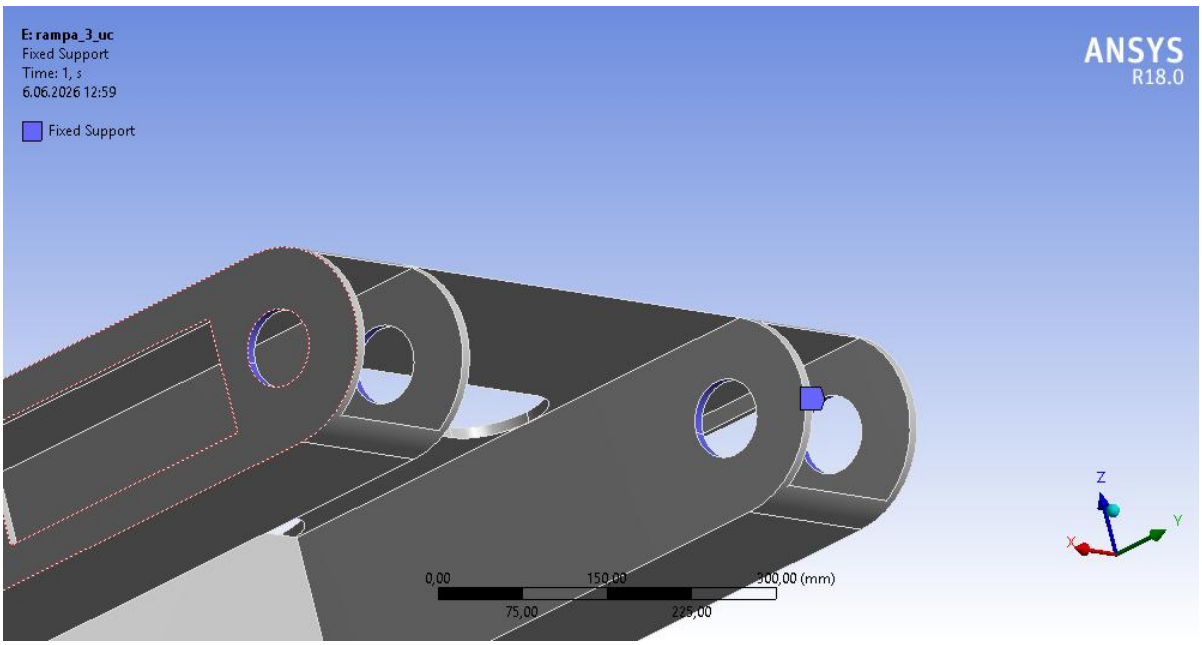


(a)

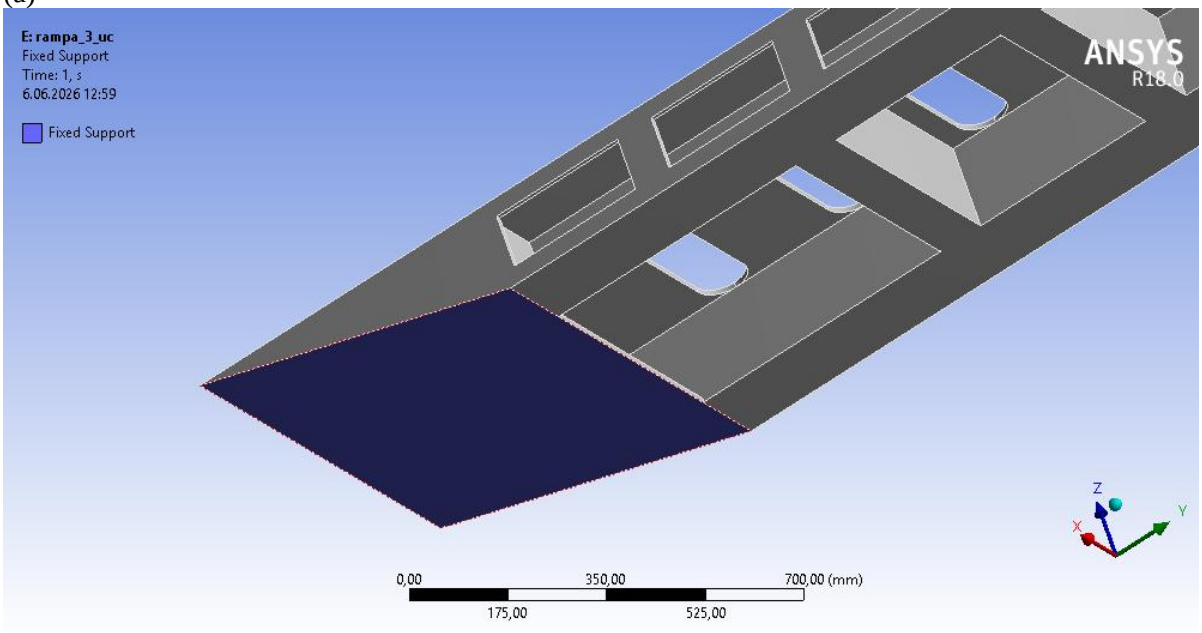


(b)

Figure 13. Fixed support illustration (a) close-up view of connection points, (b) overview of surface for the geometry–II ramp model



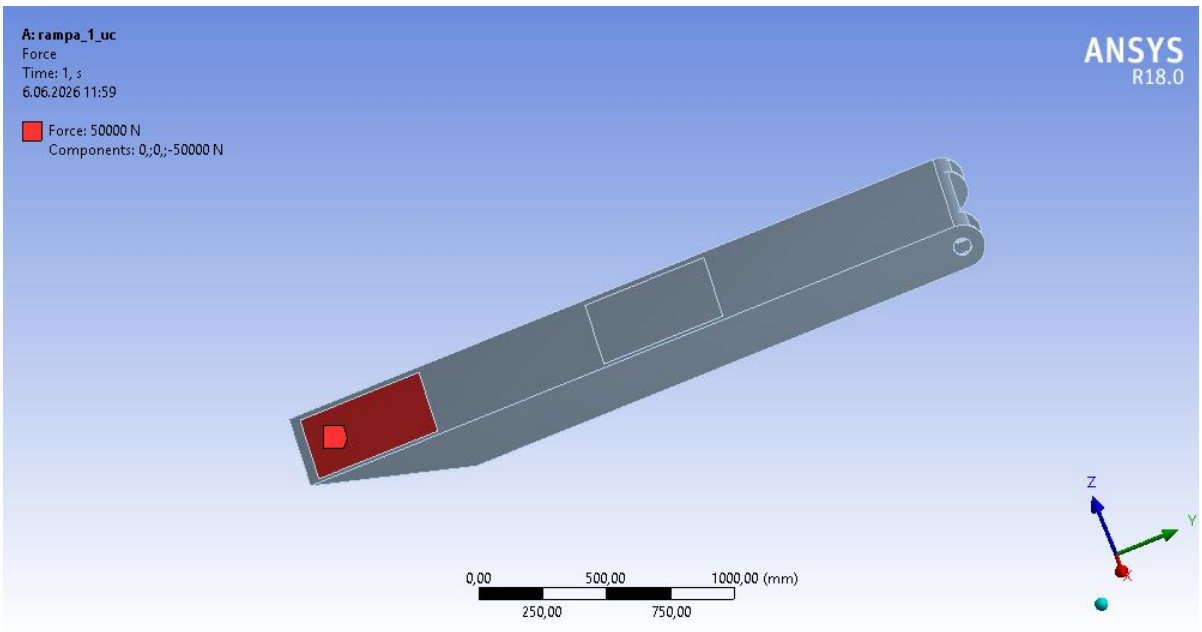
(a)



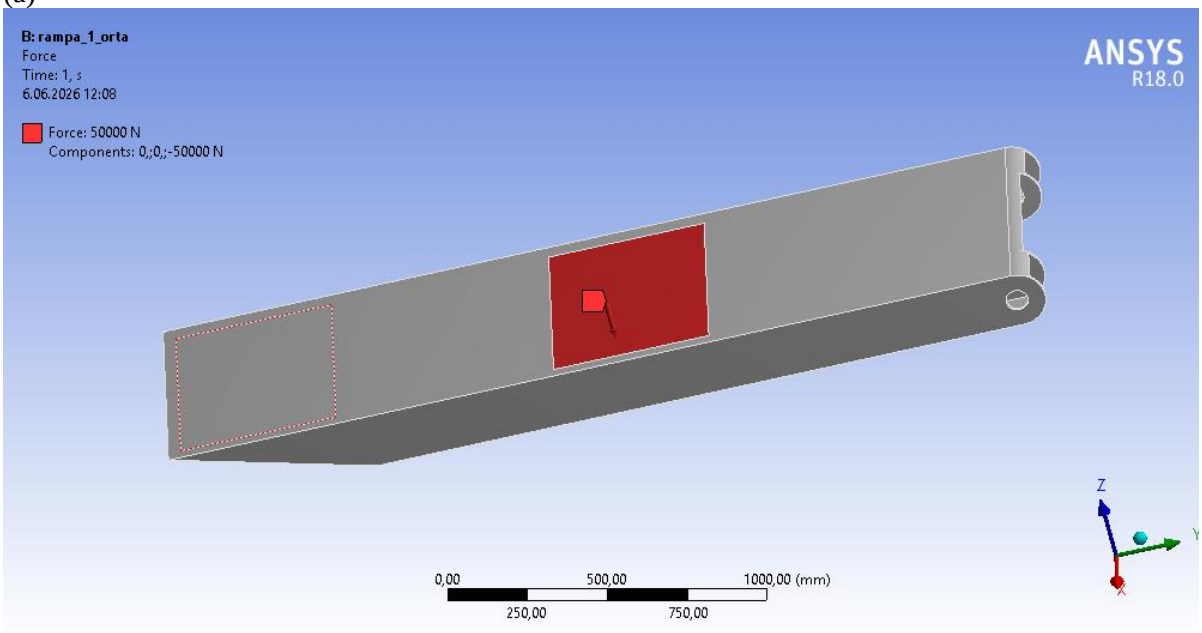
(b)

Figure 14. Fixed support illustration (a) close-up view of connection points, (b) overview of the surface for the geometry–III ramp model

The loading scenarios applied to the developed ramp designs are given in Figures 15, 16, and 17, respectively. The figures demonstrate the static force application areas and directions for Case 1 and Case 2, determined via the surface-splitting method. As a result of the analyses, the total deformation, equivalent stress, and safety factor values for all three designs and two different materials were obtained and presented comparatively.

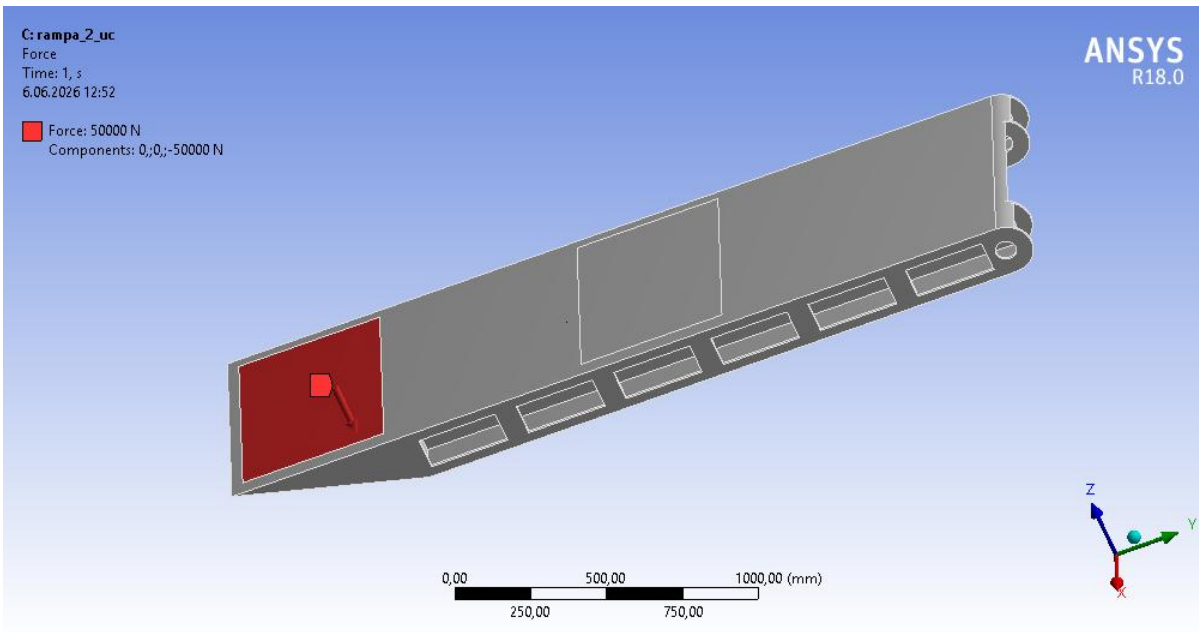


(a)

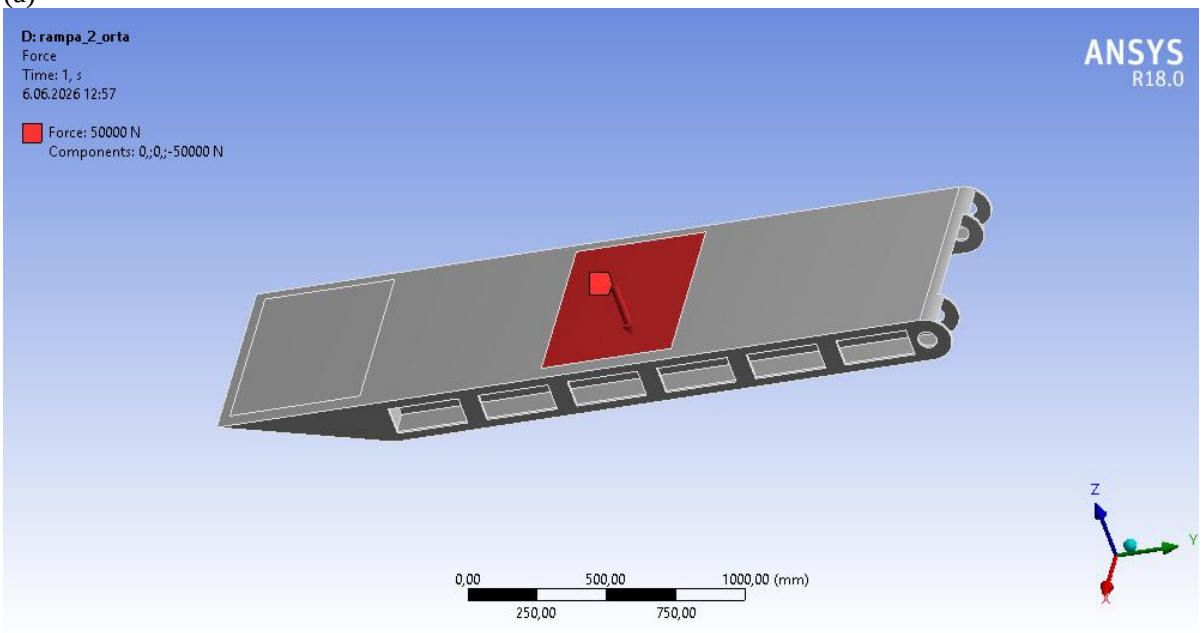


(b)

Figure 15. Loading boundary conditions for the geometry-I ramp model: (a) Case 1 and (b) Case 2

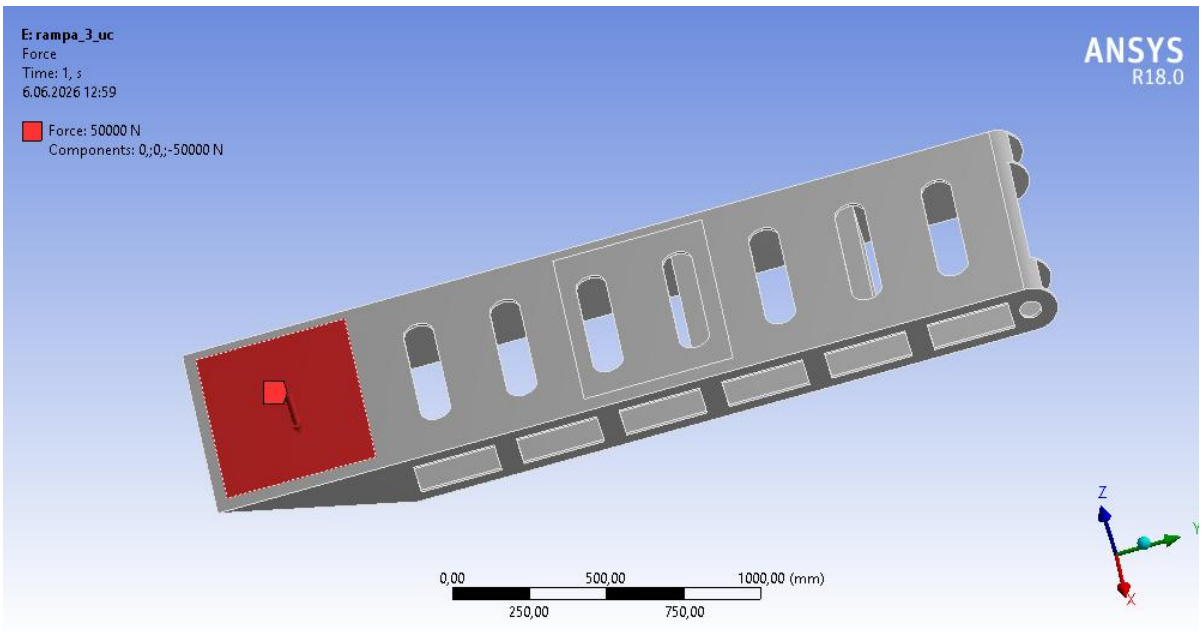


(a)

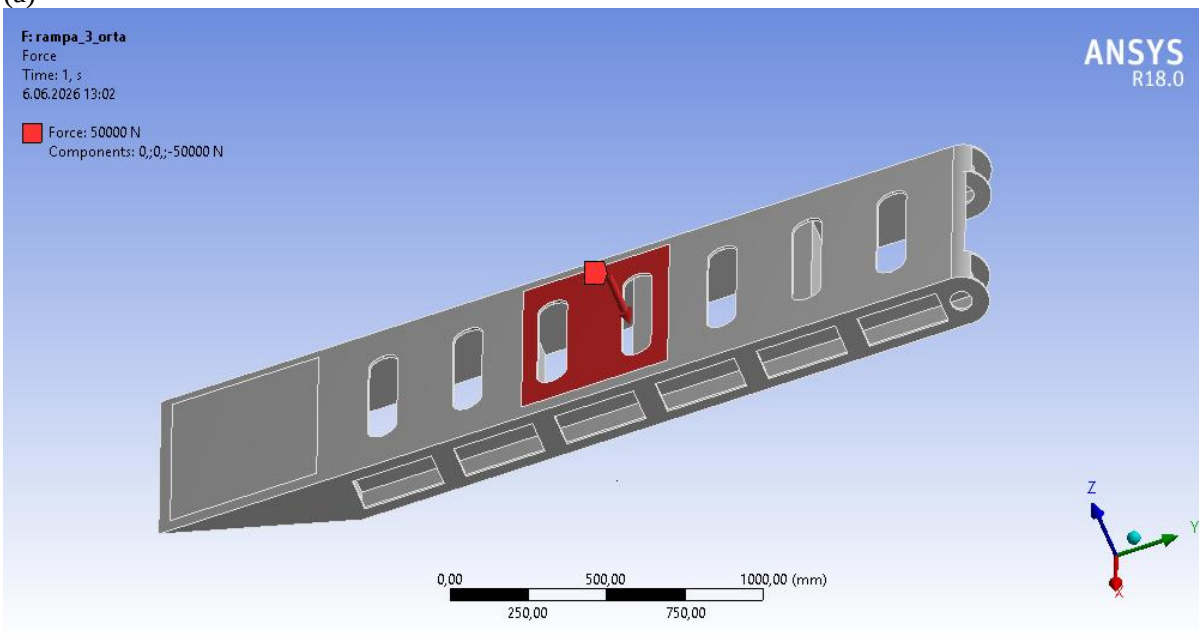


(b)

Figure 16. Loading boundary conditions for the geometry-II ramp model: (a) Case 1 and (b) Case 2



(a)



(b)

Figure 17. Loading boundary conditions for the geometry-III ramp model: (a) Case 1 and (b) Case 2

RESULTS

The analysis results of the Case 1 loading condition on geometry-I for the S700 material are provided in Figures 18 to 20.

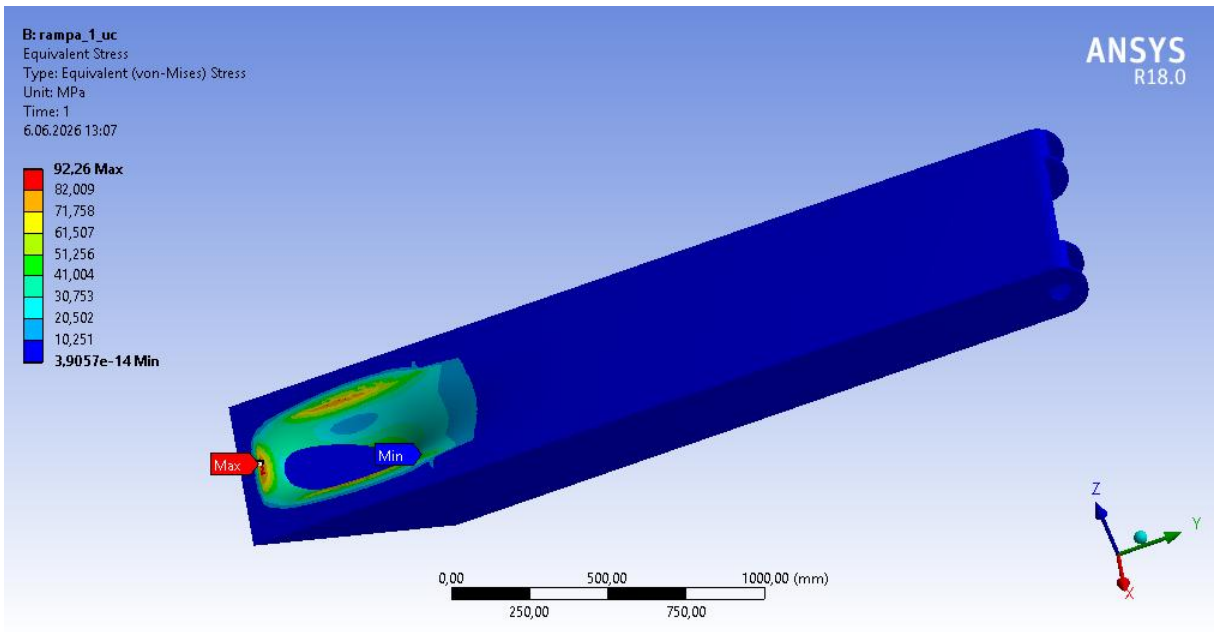


Figure 18. Stress value induced in geometry-I with S700 material for Case 1

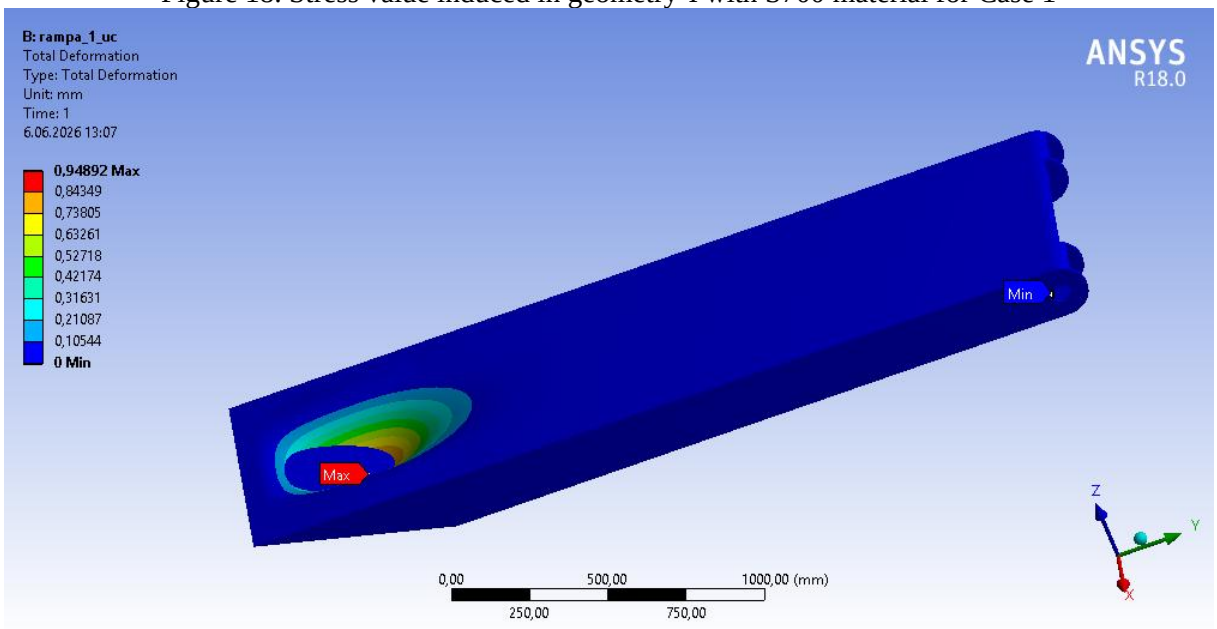


Figure 19. Total deformation induced in geometry-I with S700 material for Case 1

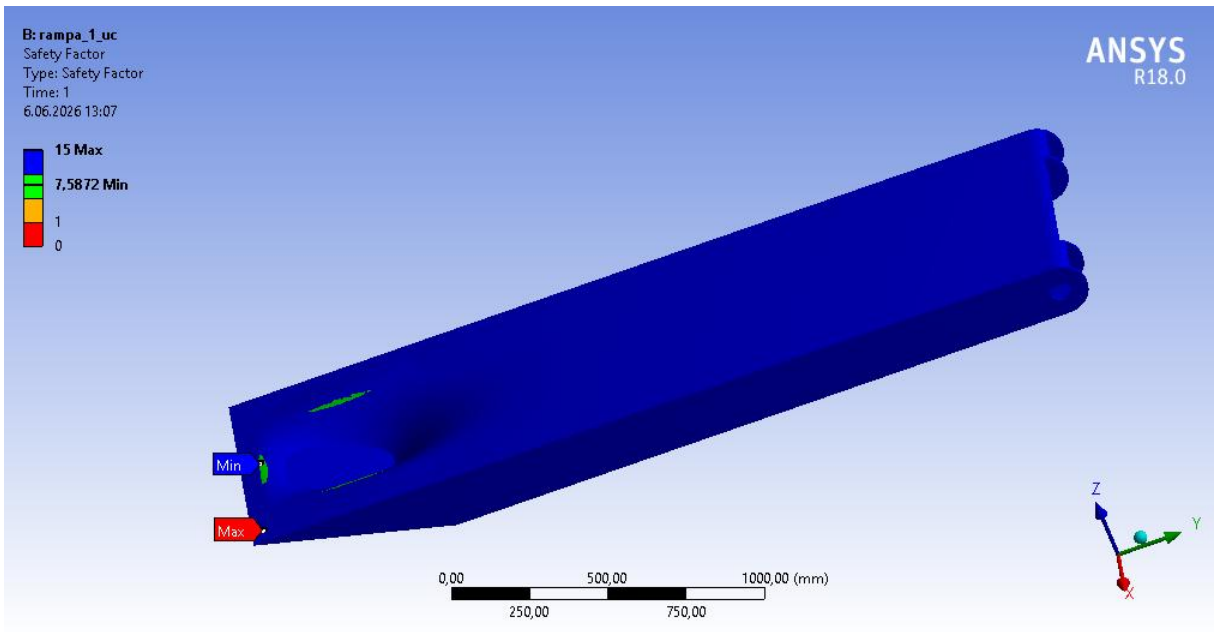


Figure 20. Safety factor induced in geometry-I with S700 material for Case 1

The analysis results of the Case 1 loading condition on geometry-II for the S700 material are shown in Figures 21 to 23.

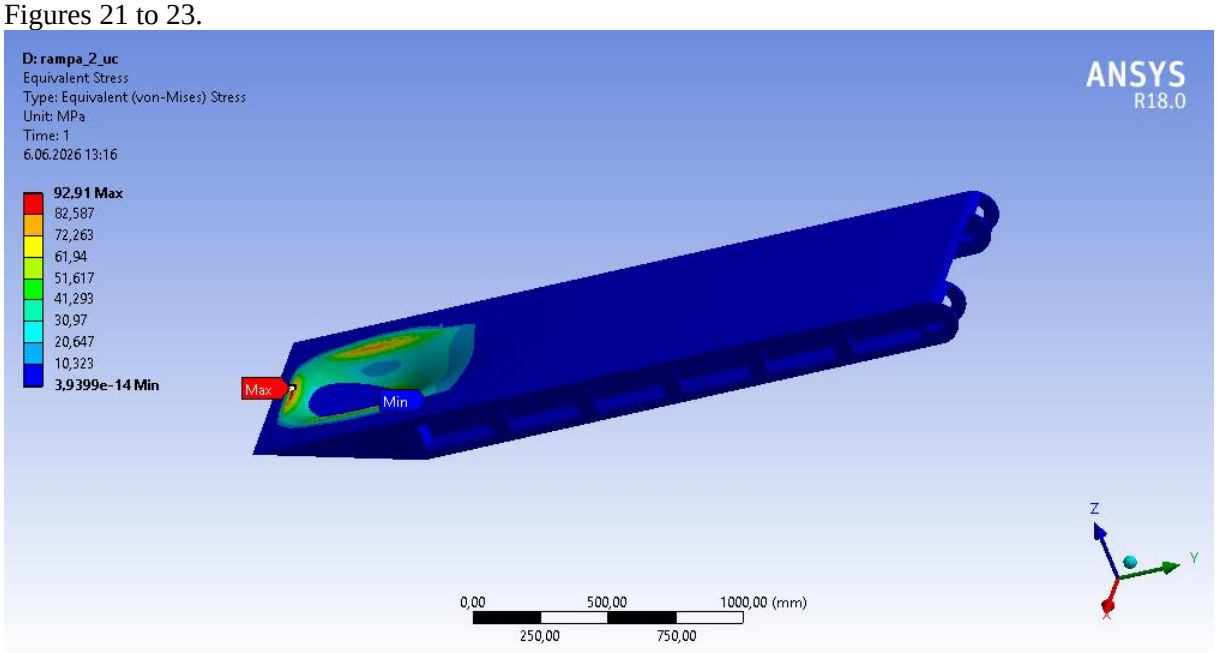


Figure 21. Stress value induced in geometry-II with S700 material for Case 1

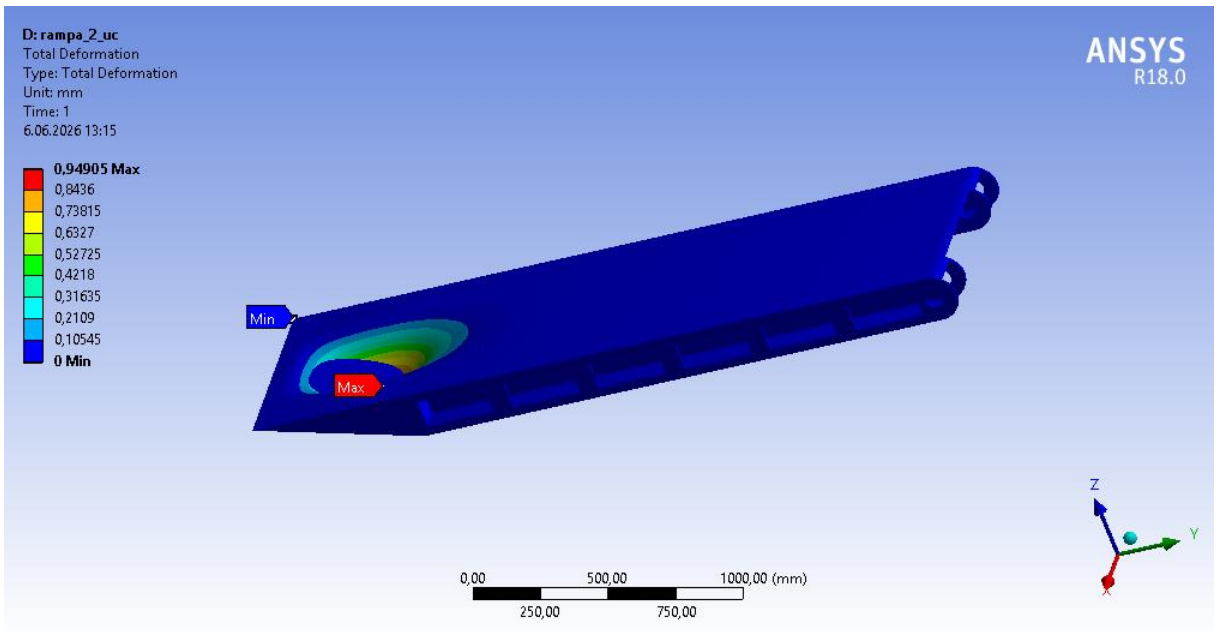


Figure 22. Total deformation induced under load in geometry-II with S700 material for Case 1

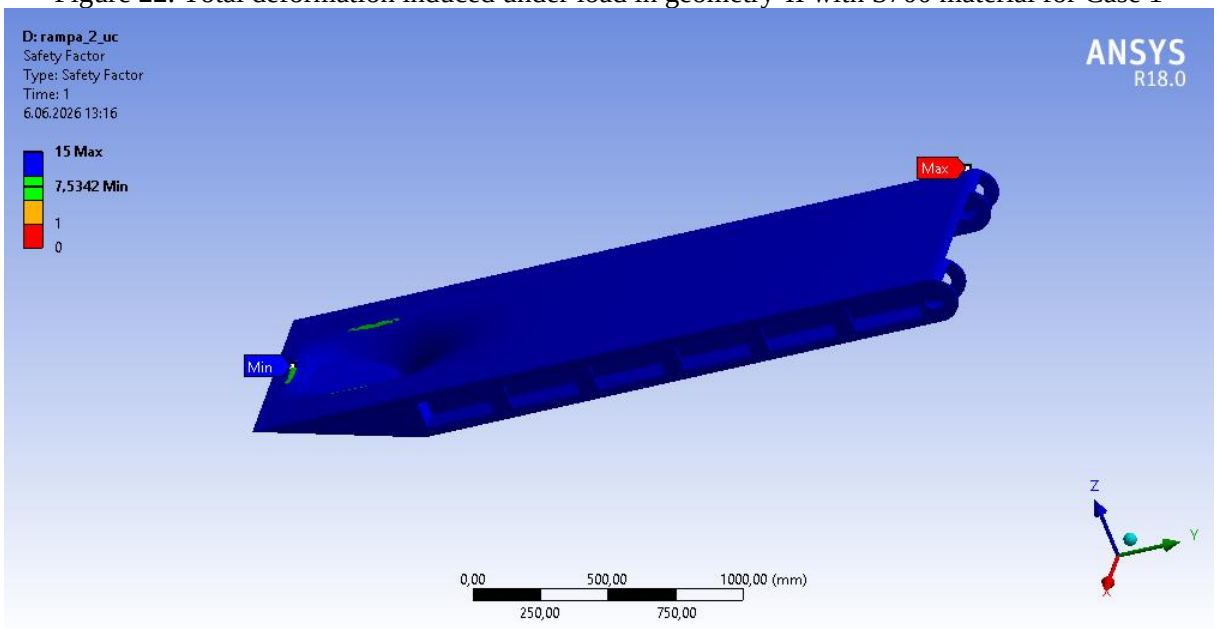


Figure 23. Safety factor induced in geometry-II with S700 material for Case 1

The analysis results of the Case 1 loading condition on geometry-III for the S700 material are presented in Figures 24 to 26.

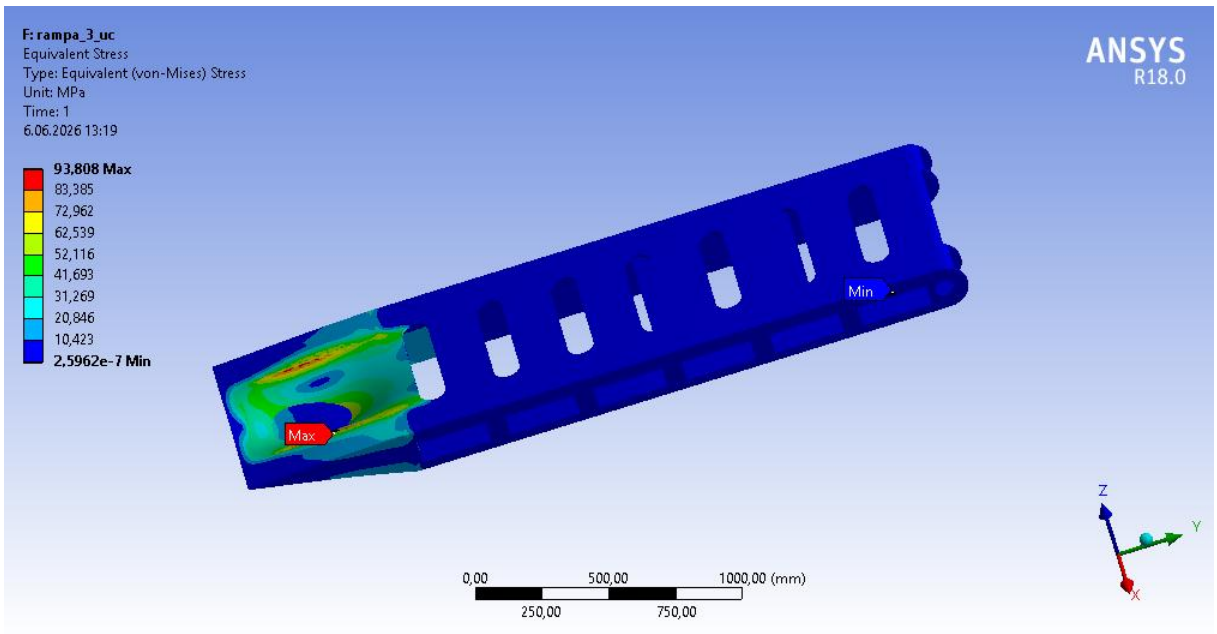


Figure 24. Stress value induced in geometry-III with S700 material for Case 1

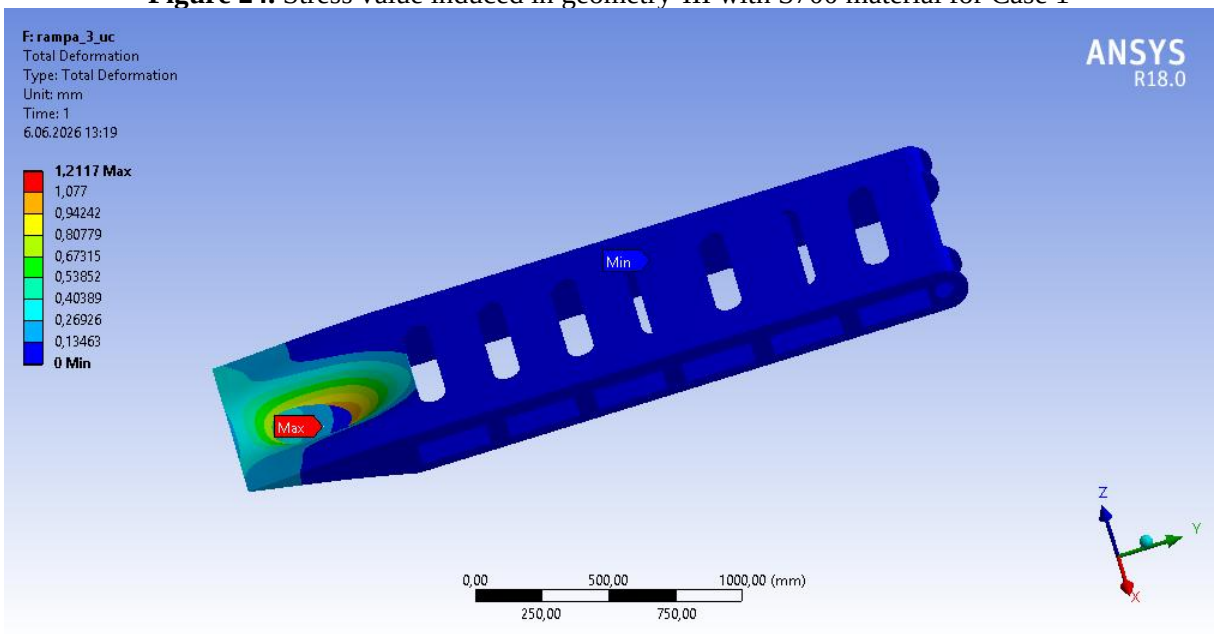


Figure 25. Total deformation induced in geometry-III with S700 material for Case 1

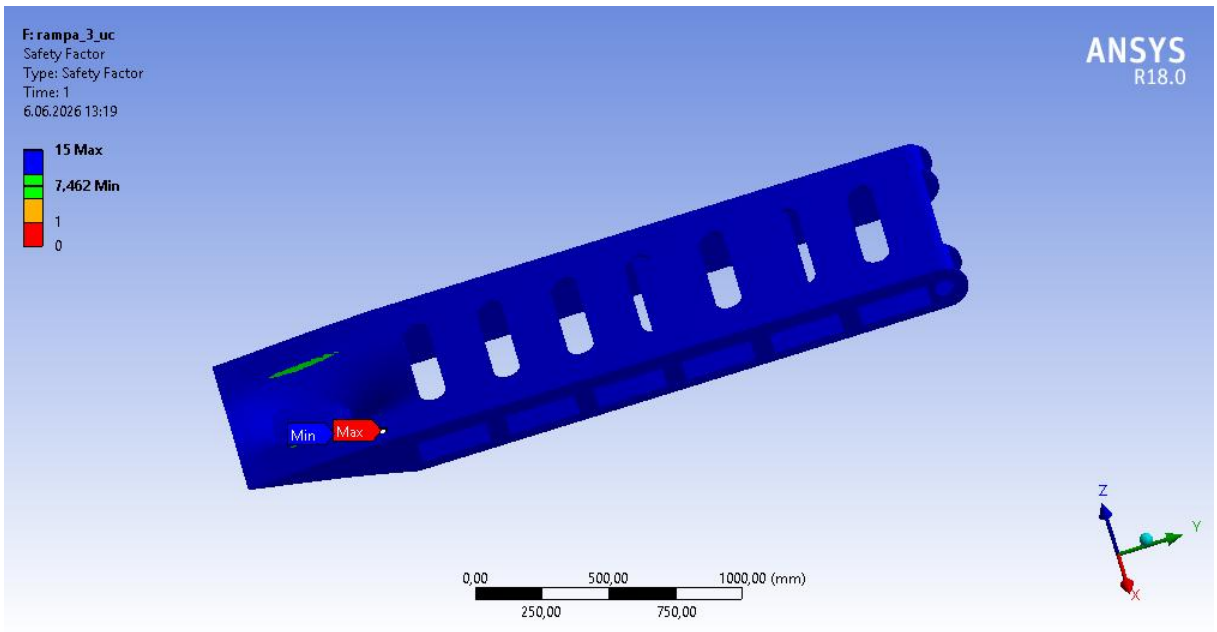


Figure 26. Safety factor induced in geometry-III with S700 material for Case 1

The analysis results of the Case 2 loading condition geometry-I for the S700 material are shown in Figures 27 to 29.

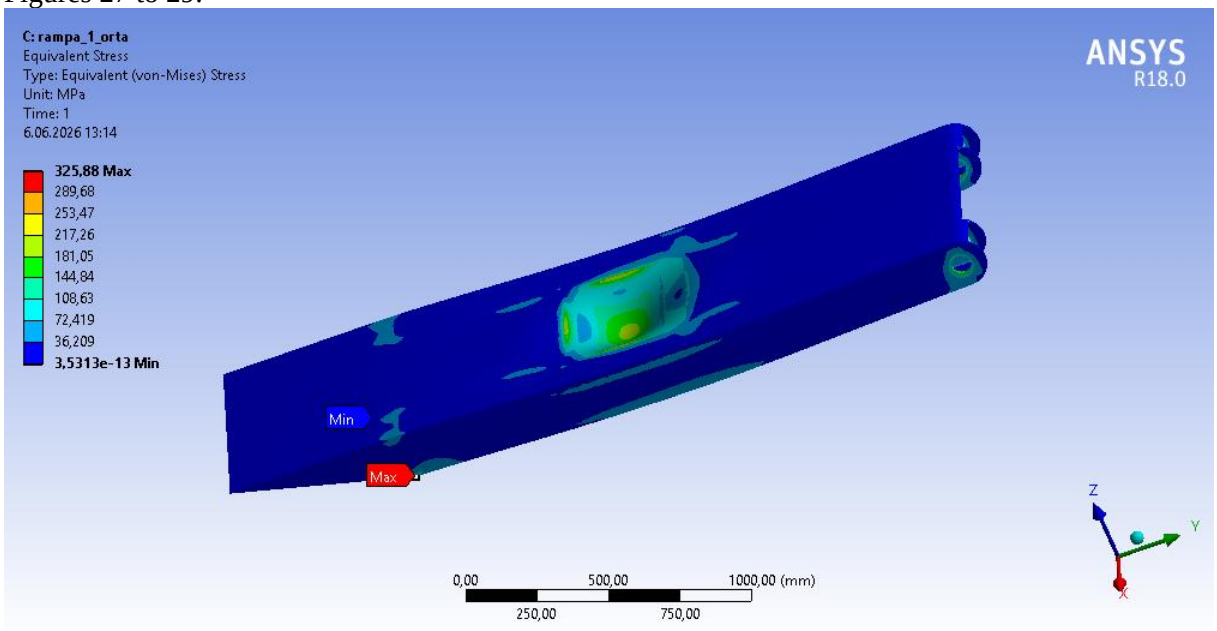


Figure 27. Stress value induced in geometry-I with S700 material for Case 2

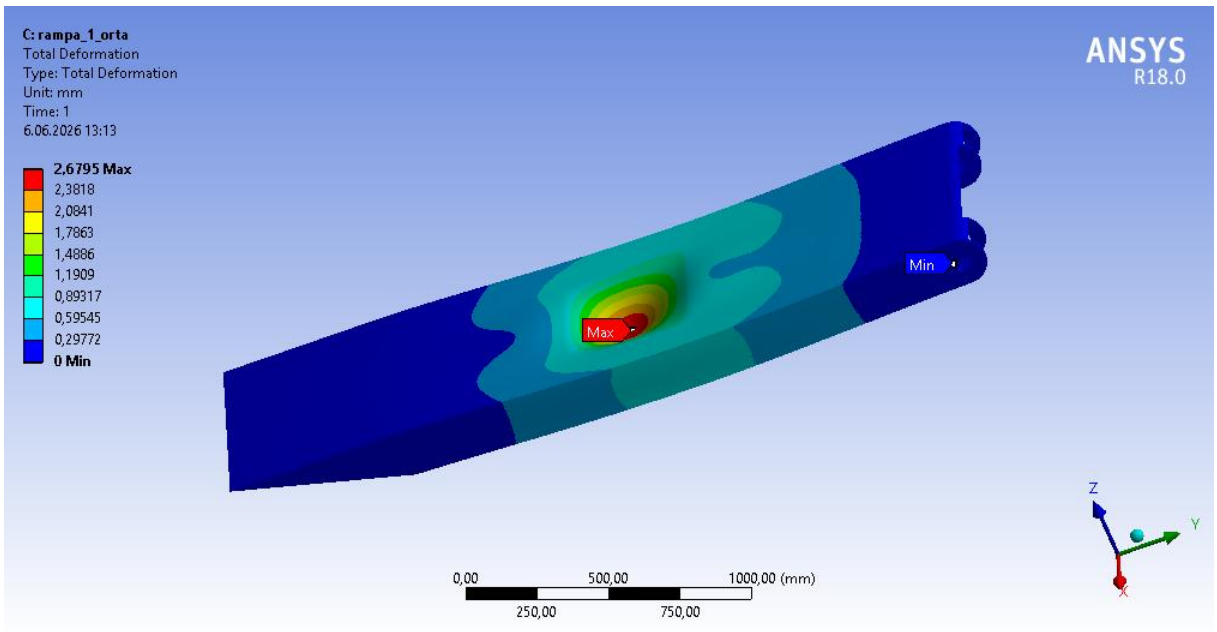


Figure 28. Total deformation induced in geometry-I with S700 material for Case 2

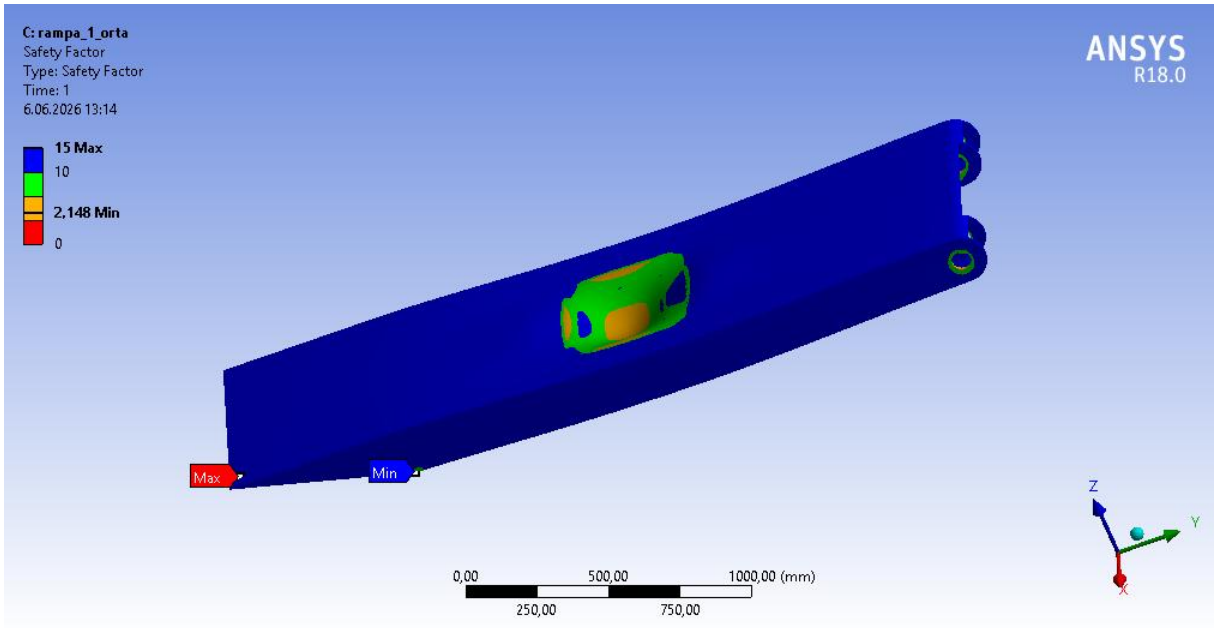


Figure 29. Safety factor induced in geometry-I with S700 material for Case 2

The analysis results of the Case 2 loading condition on geometry-II for the S700 material are displayed in Figures 30 to 32.

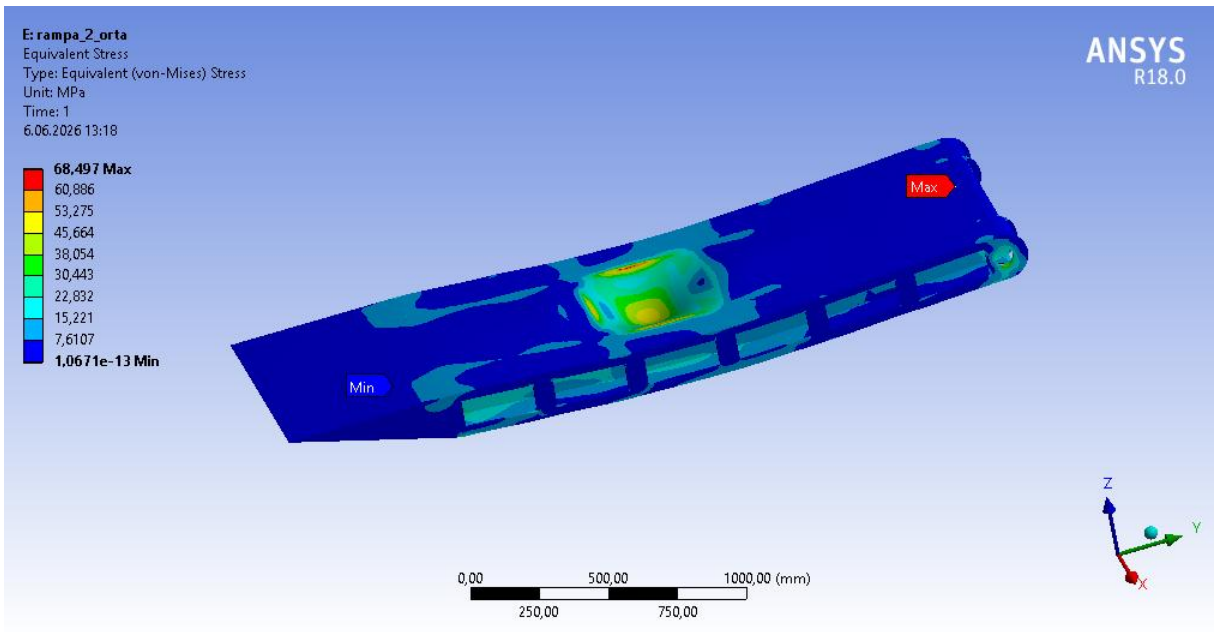


Figure 30. Stress value induced in geometry-II with S700 material for Case 2

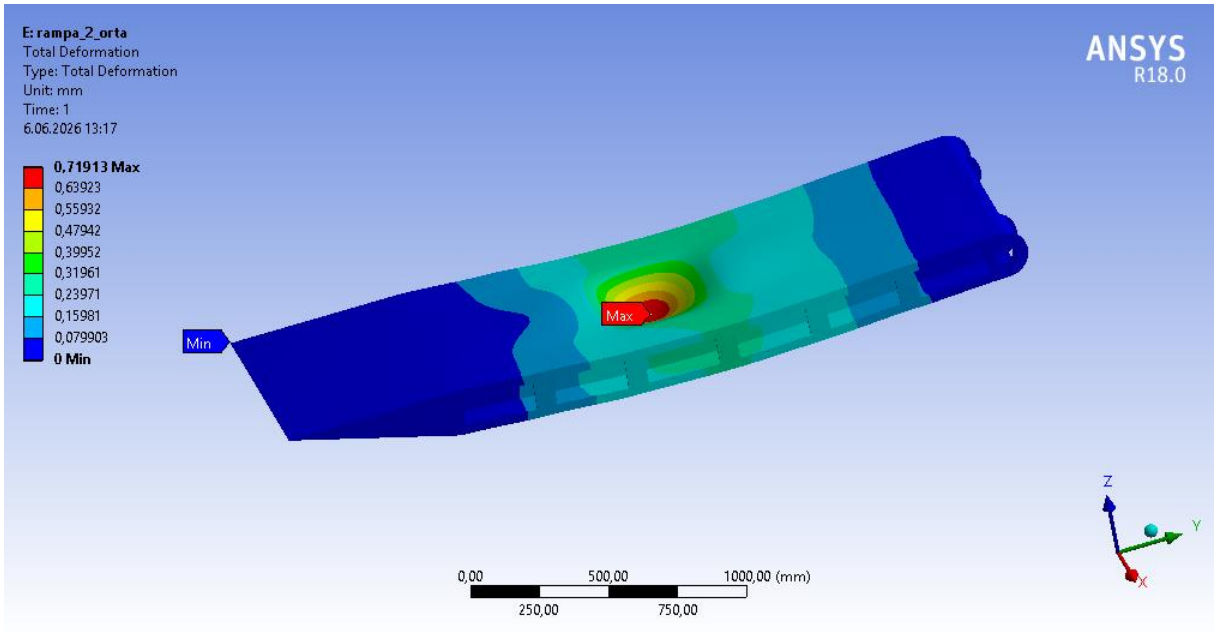


Figure 31. Total deformation induced in geometry-II with S700 material for Case 2

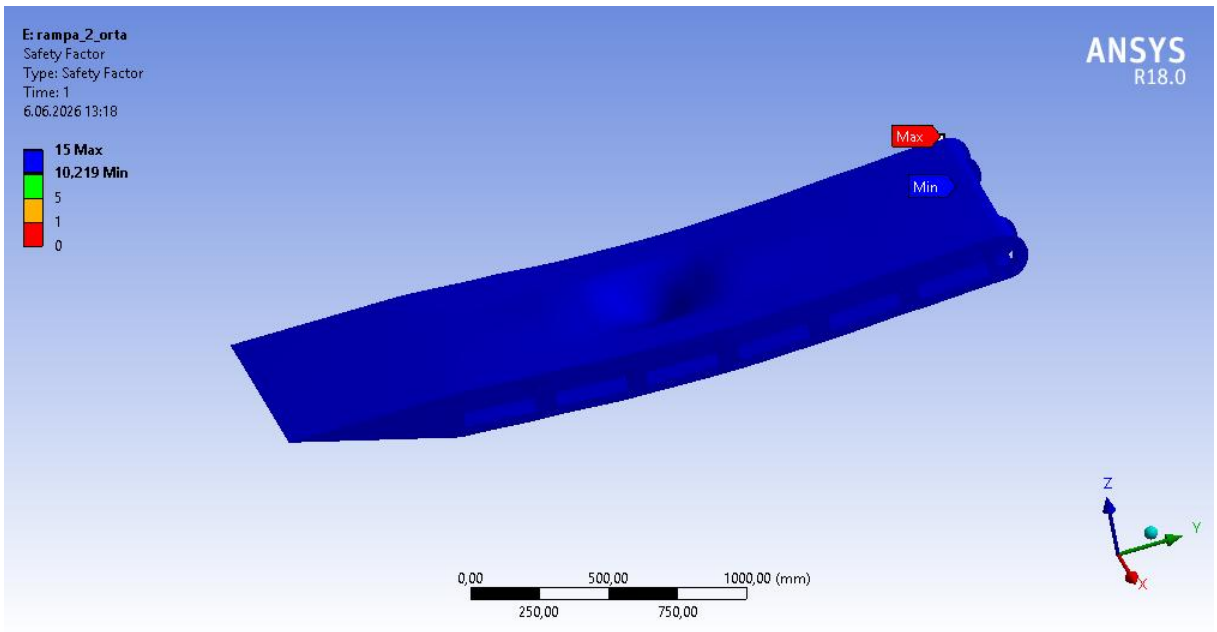


Figure 32. Safety factor induced under load in geometry-II with S700 material for Case 2

The analysis results of the Case 2 loading condition on geometry-III for the S700 material are indicated in Figures 33 to 35.

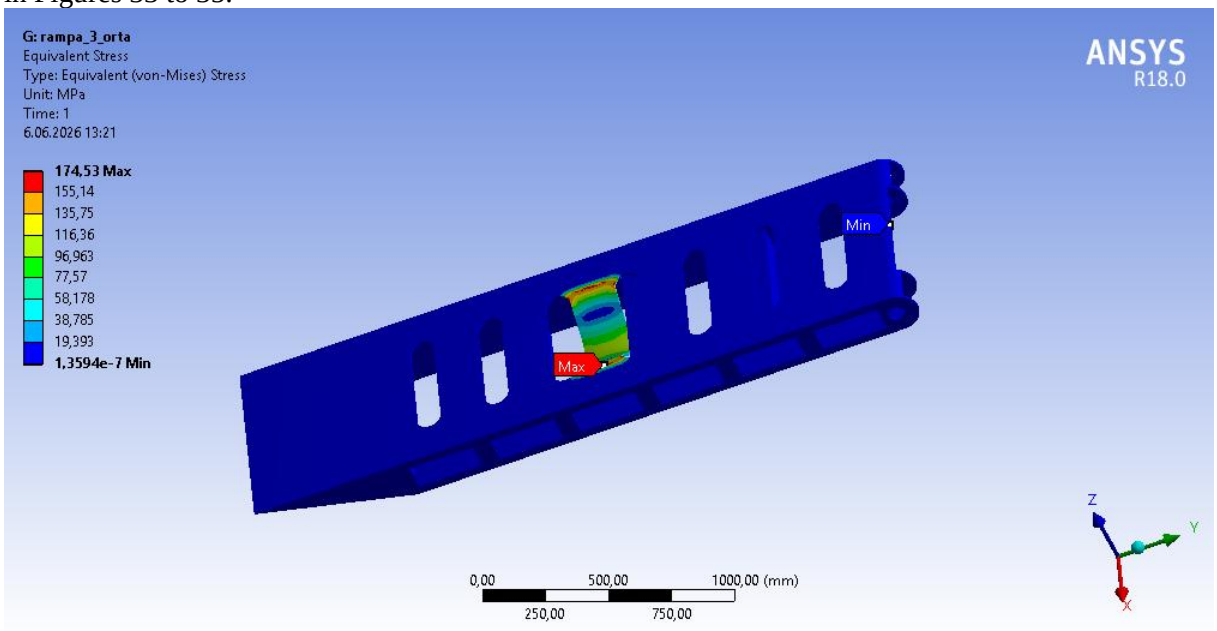


Figure 33. Stress value induced in geometry-III with S700 material for Case 2

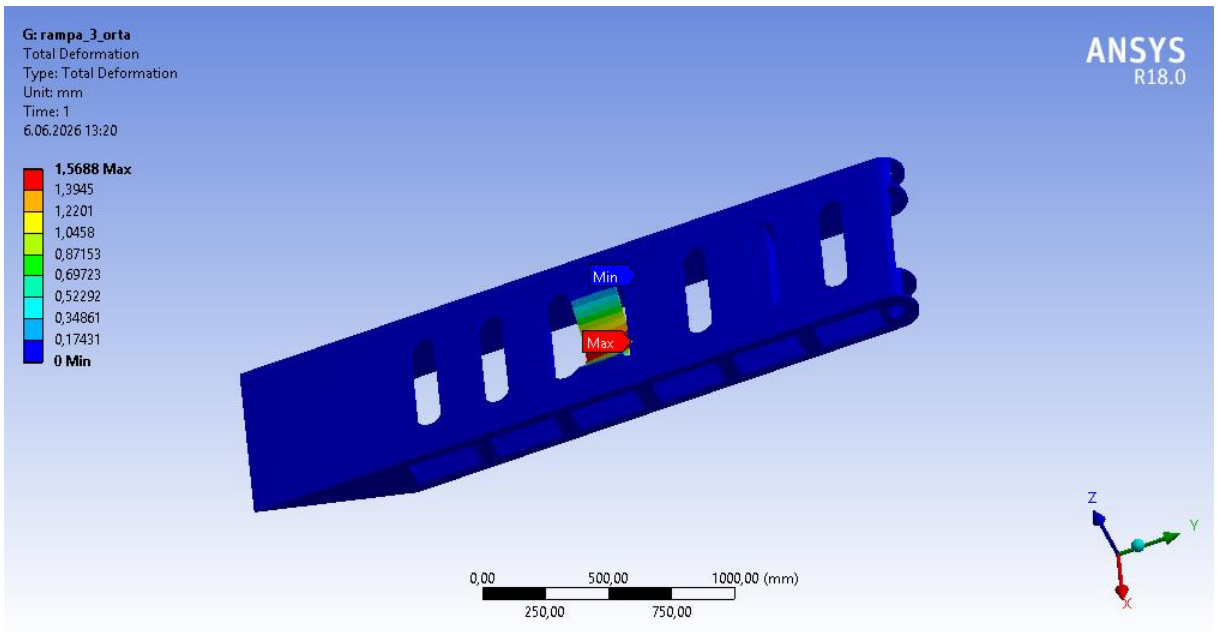


Figure 34. Total deformation induced in geometry-III with S700 material for Case 2

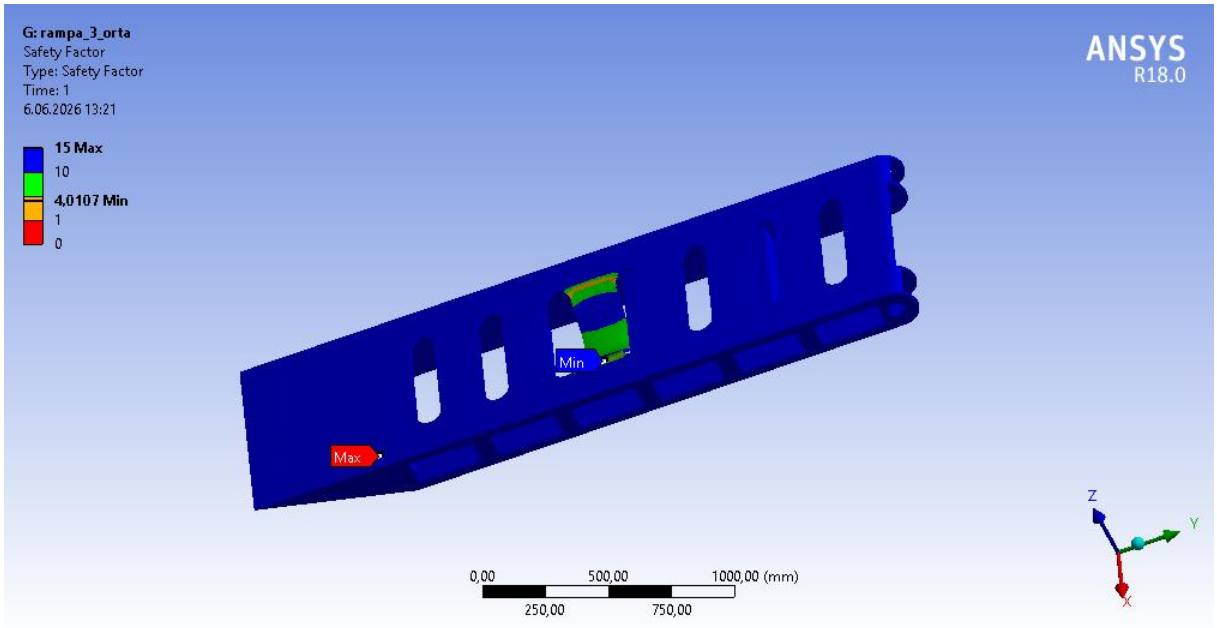


Figure 35. Safety factor induced in geometry-III with S700 material for Case 2

Table 5 presents the analysis results achieved for different geometries and loading conditions of the S700 material. Compared with the baseline model (geometry-I), the modifications geometry-II result in 0.70% increase in the maximum equivalent stress and a 0.01% change in the total deformation. Correspondingly, the safety factor decreased by 0.7%. In the geometry-III variation, where the weight optimization was highest, the maximum stress increased by 1.67% and the total deformation amount increased by 27.69% compared to the baseline model. Although this increase in flexibility occurred as a natural consequence of mass reduction in the structure, the total decrease in the safety factor for the geometry-III variation remained of 1.65% compared to the baseline model, and the structure preserved its high safety margins.

Table 5. Case 1 and Case 2 results for S700 material

Ramp Geometry	Load Case	Equivalent Stress (MPa)	Total Deformation(mm)	Safety Factor
Geometry-I	Case 1	92.26	0.94892	7.5872
	Case 2	325.88	2.6795	2.148
Geometry-II	Case 1	92.91	0.94905	7.5342
	Case 2	68.497	0.71913	10.219
Geometry-III	Case 1	93.808	1.2117	7.462
	Case 2	174.53	1.5688	4.0107

The Case 2 loading scenario, in which the load was applied directly to the geometric center, revealed far more pronounced changes due to the increased bending moment. When examining the geometry-I baseline model as a reference under Case 2; the geometry-II structure exhibited an extraordinary increase in localized strength. In Geometry-II, the maximum equivalent stress was reduced by 78.98% compared to the baseline model, while the total deformation amount was minimized by 73.16%.

Owing to this robust improvement, the safety factor of geometry-II increased by 375.74% relative to the baseline model, reaching its peak point. In the mass-optimized geometry-III model, a 46.44% decrease in maximum stress and a 41.45% improvement in total deformation were achieved under Case 2 loading compared to the baseline model. As a result, geometry-III succeeded in increasing the safety factor by 86.71% compared to the baseline model, offering a much safer structure despite the mass reduction.

The analysis results of the Case 1 loading condition on geometry-I for the Hardox 400 material are provided from Figures 36 to 38.

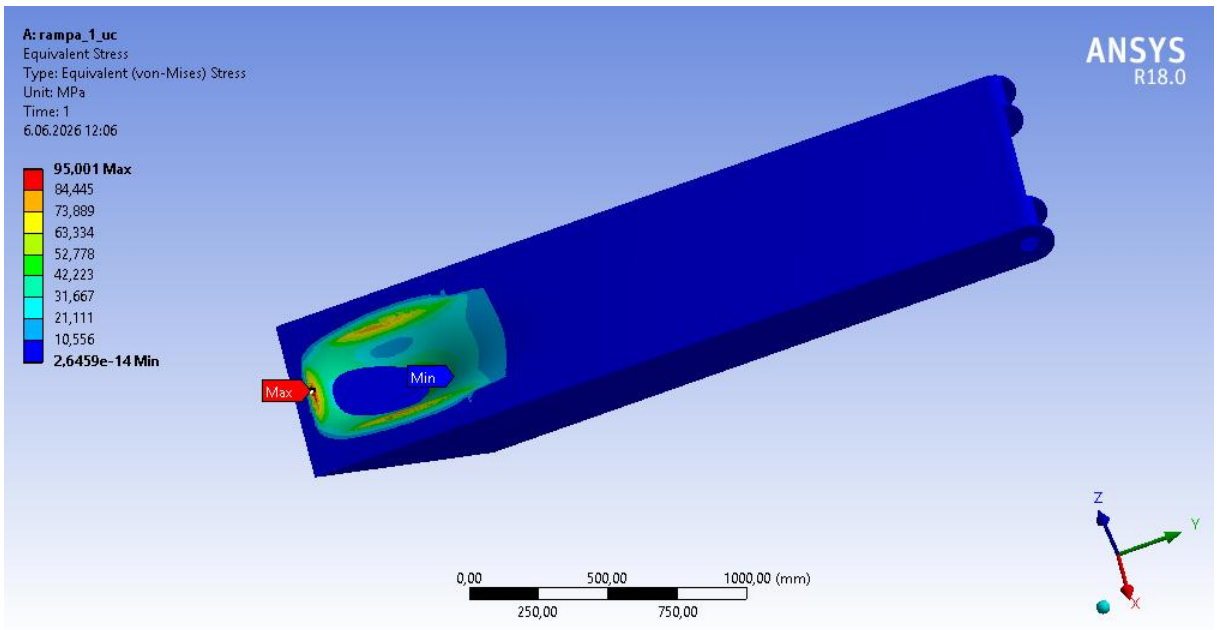


Figure 36. Stress value induced in geometry-I with Hardox 400 material for Case 1

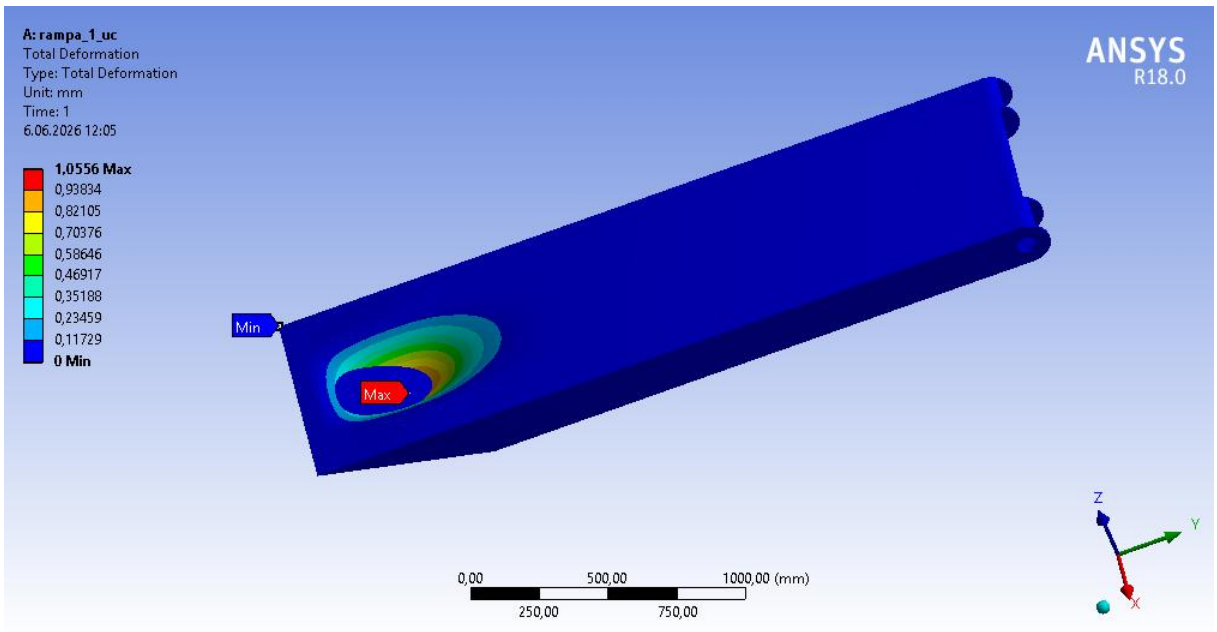


Figure 37. Total deformation value induced in geometry-I with Hardox 400 material for Case 1

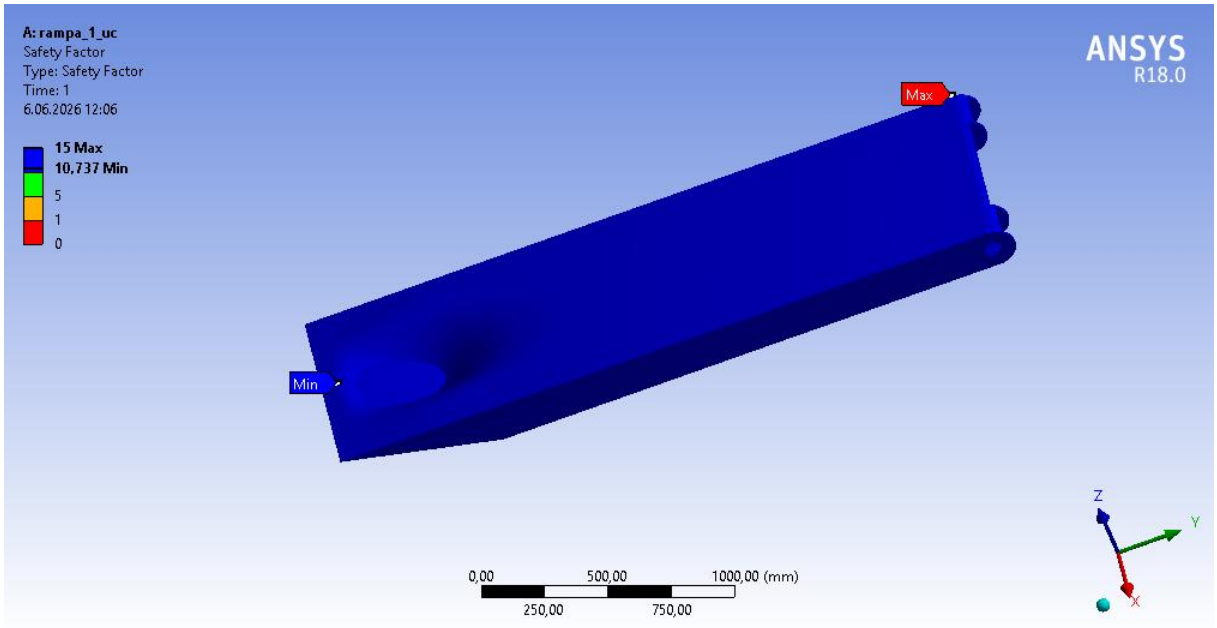


Figure 38. Safety factor value induced in geometry-I with Hardox 400 material for Case 1

The analysis results of the Case 1 loading condition on geometry-II for the Hardox 400 material are presented in Figures 39 to 41.

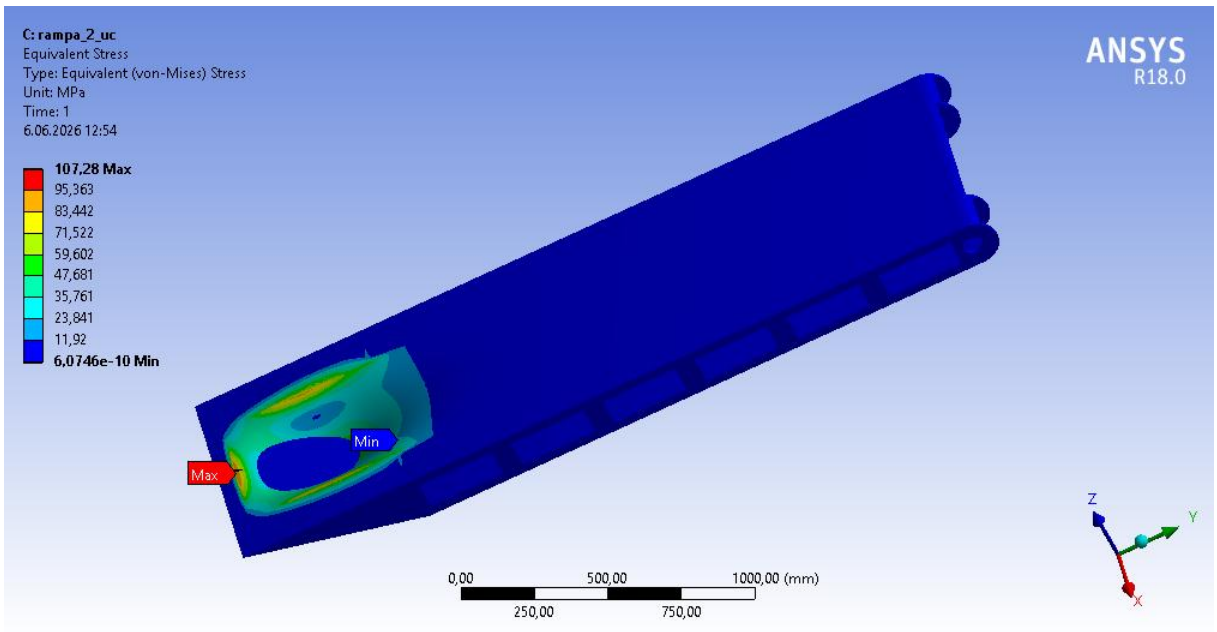


Figure 39. Stress value induced in geometry-II with Hardox 400 material for Case 1

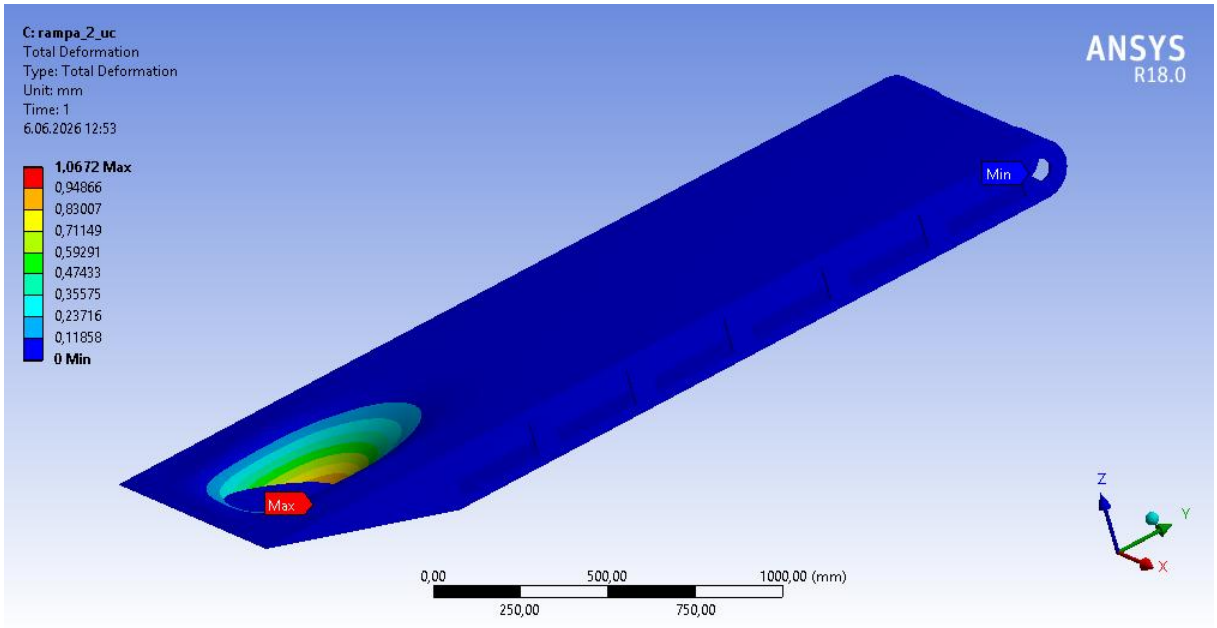


Figure 40. Total deformation value induced in geometry-II with Hardox 400 material for Case 1

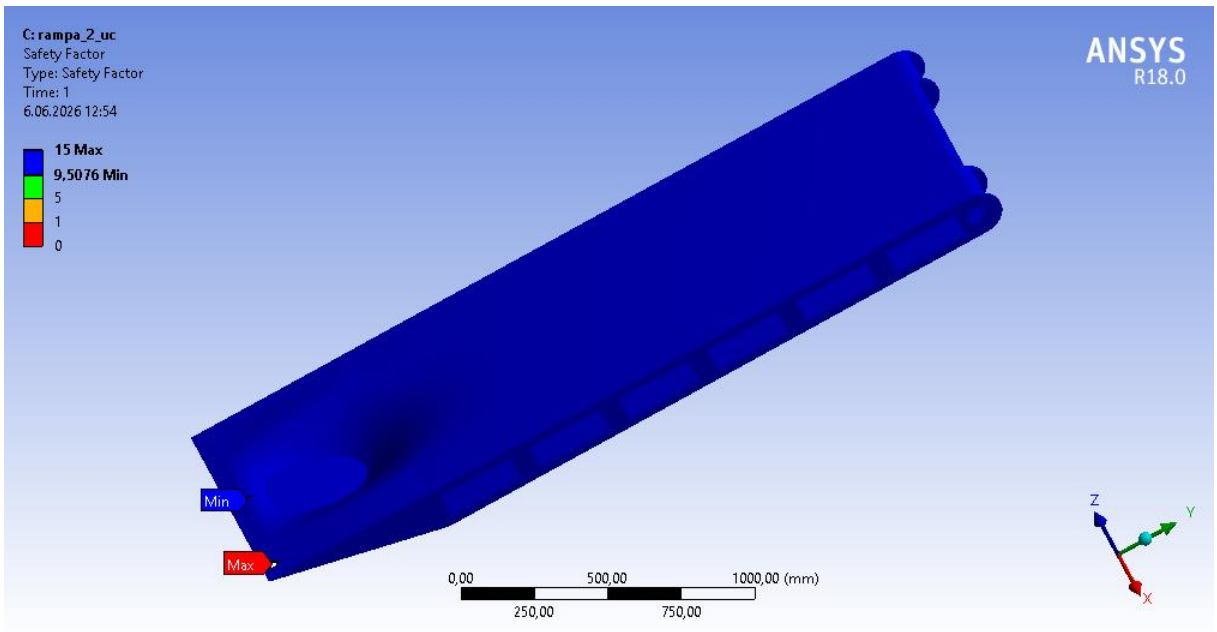


Figure 41. Safety factor value induced in geometry-II with Hardox 400 material for Case 1

The analysis results of the Case 1 loading condition on geometry-III for the Hardox 400 material are shown in Figure 42 to Figure 44.

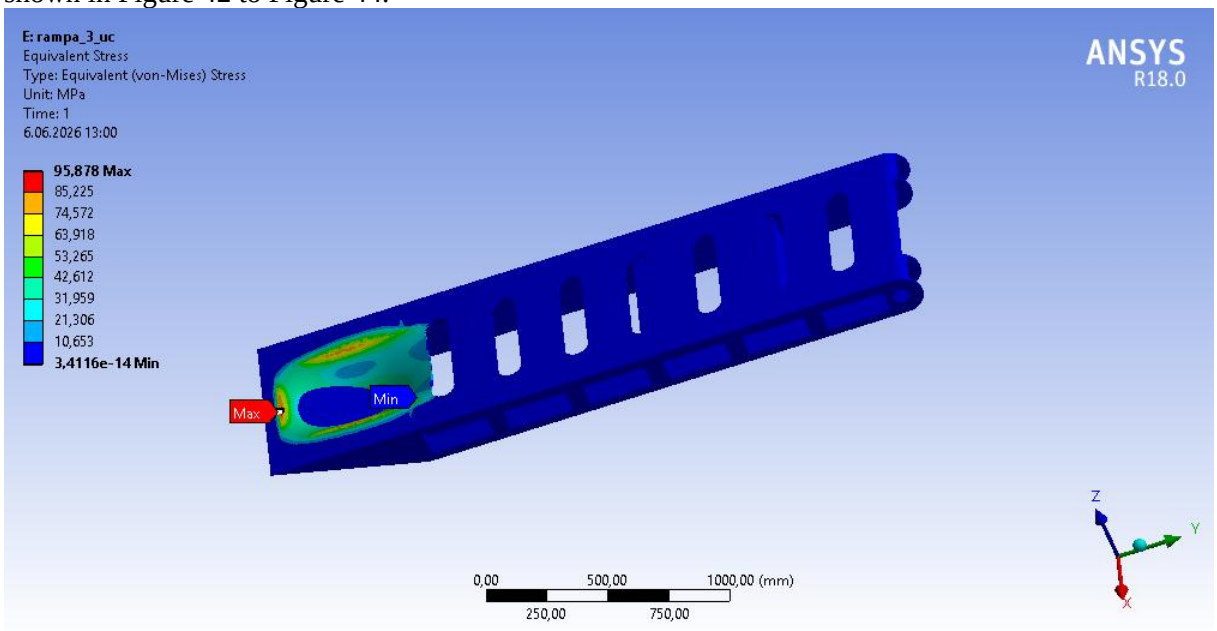


Figure 42. Stress value induced in geometry-III with Hardox 400 material for Case 1

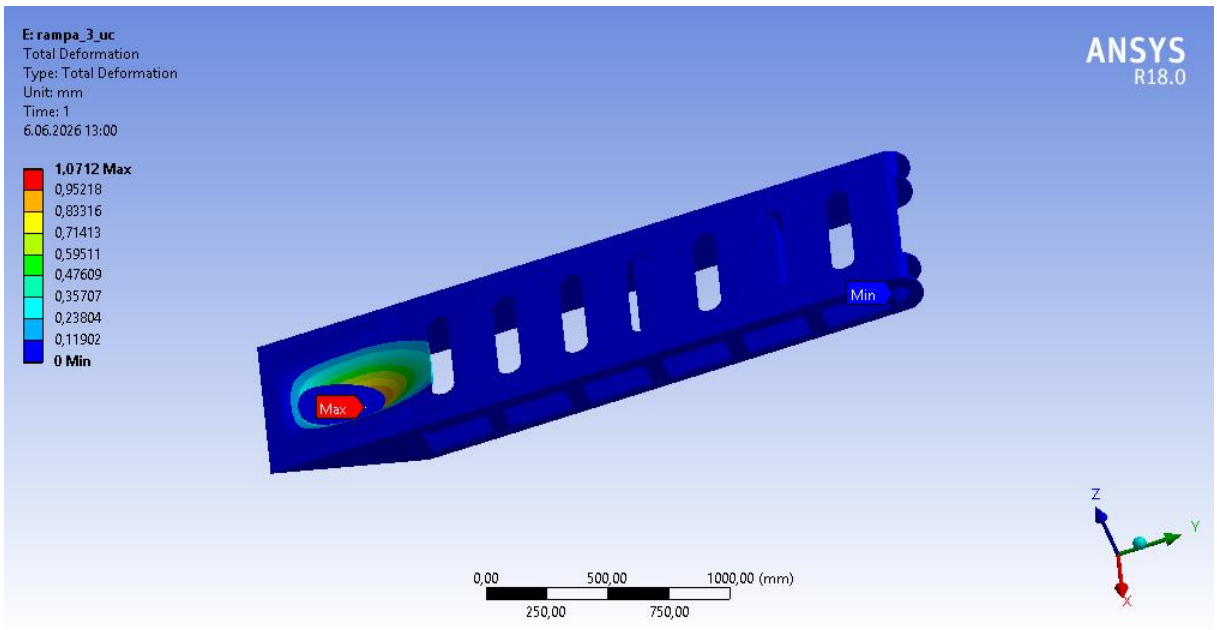


Figure 43. Total deformation value induced in geometry-III with Hardox 400 material for Case 1

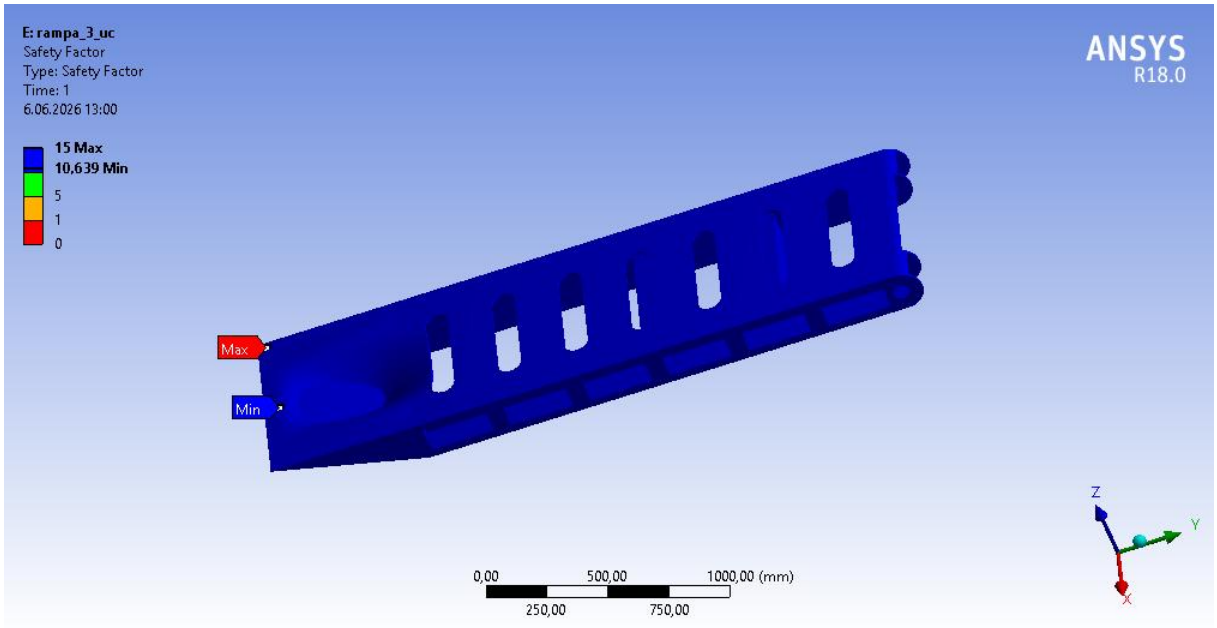


Figure 44. Safety factor value induced in geometry-III with Hardox 400 material for Case 1

The analysis results of the Case 2 loading condition on geometry-I for the Hardox 400 material are displayed in Figure 45 to Figure 47.

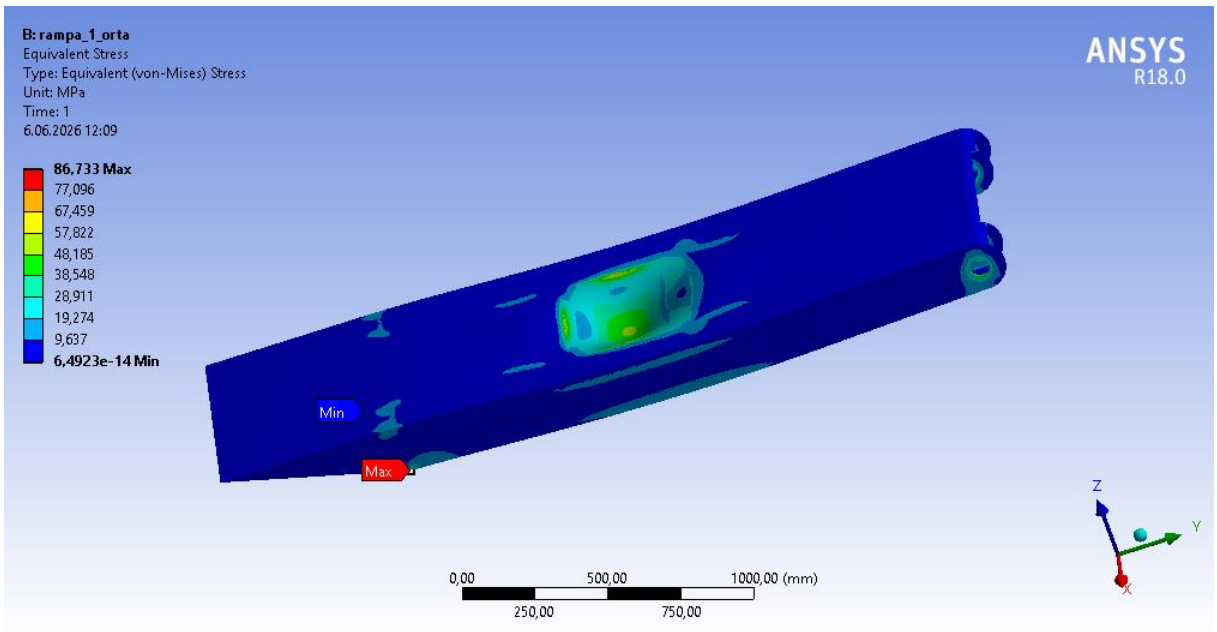


Figure 45. Stress value induced in geometry-I with Hardox 400 material for Case 2

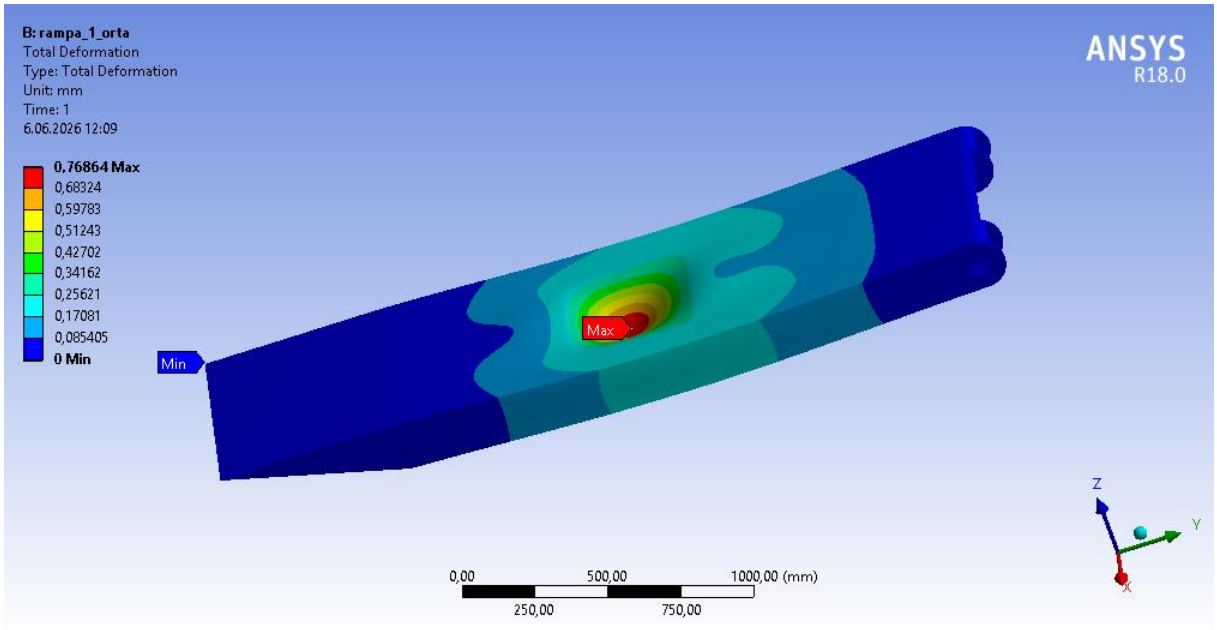


Figure 46. Total deformation value induced in geometry-I with Hardox 400 material for Case 2

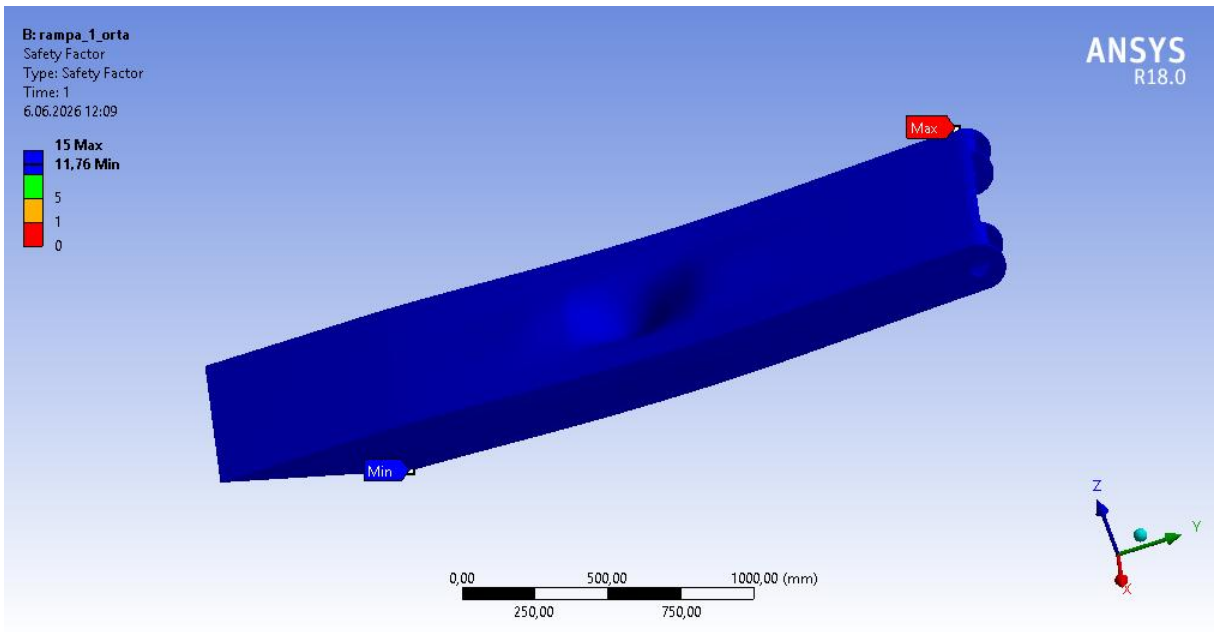


Figure 47. Safety factor value induced in geometry-I with Hardox 400 material for Case 2

The analysis results of the Case 2 loading condition on geometry-II for the Hardox 400 material are represented in Figure 48 to Figure 50.

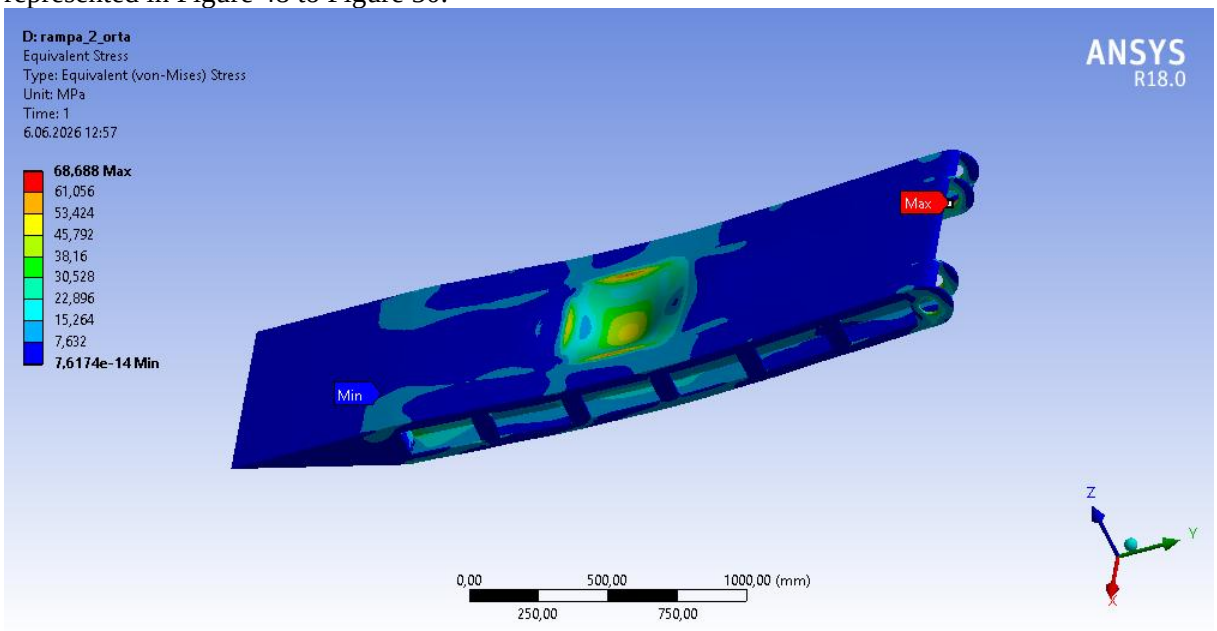


Figure 48. Stress value induced in geometry-II with Hardox 400 material for Case 2

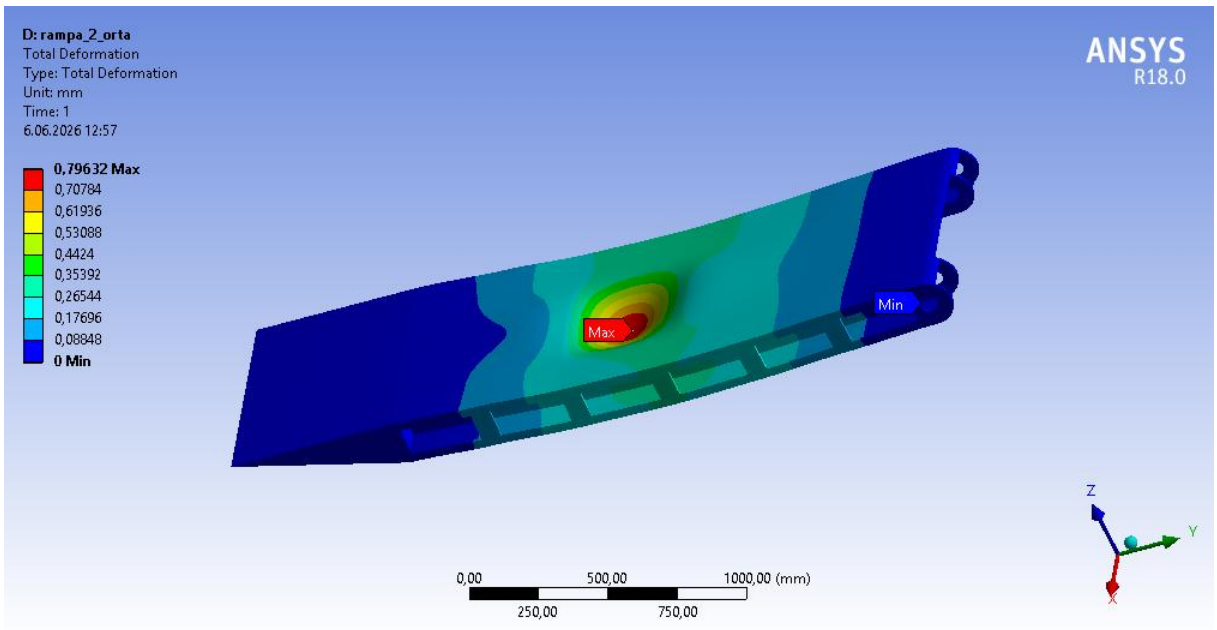


Figure 49. Total deformation value induced in geometry-II with Hardox 400 material for Case 2

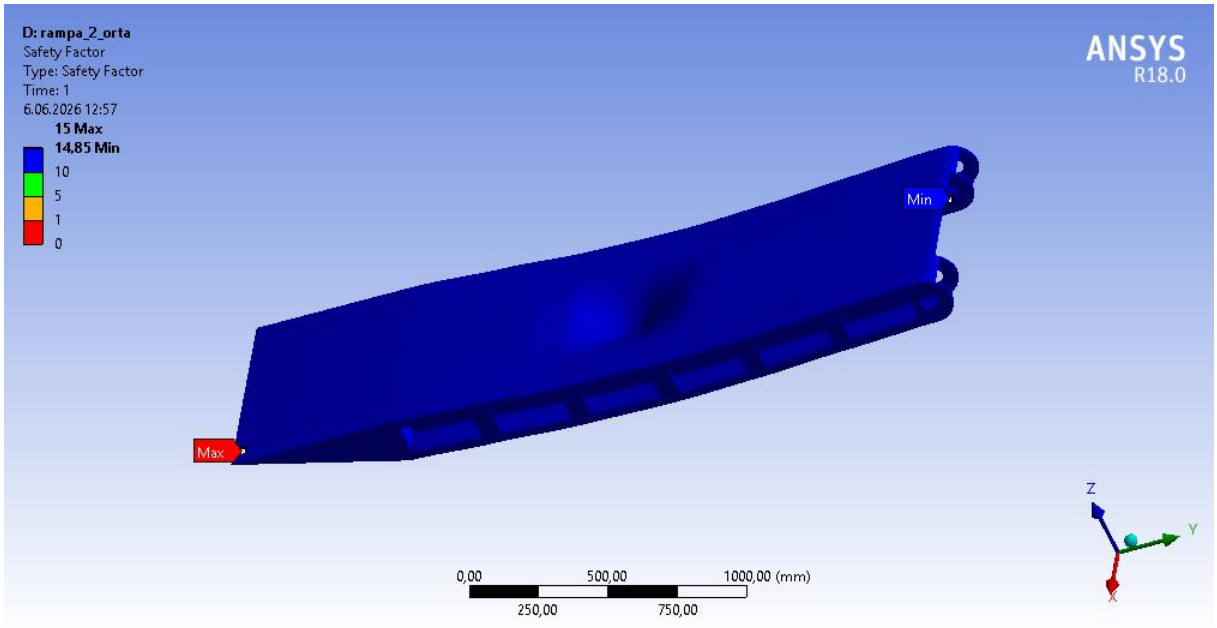


Figure 50. Safety factor value induced in geometry-II with Hardox 400 material for Case 2

The analysis results of the Case 2 loading condition on geometry-III for the Hardox 400 material are demonstrated in Figure 51 to Figure 53.

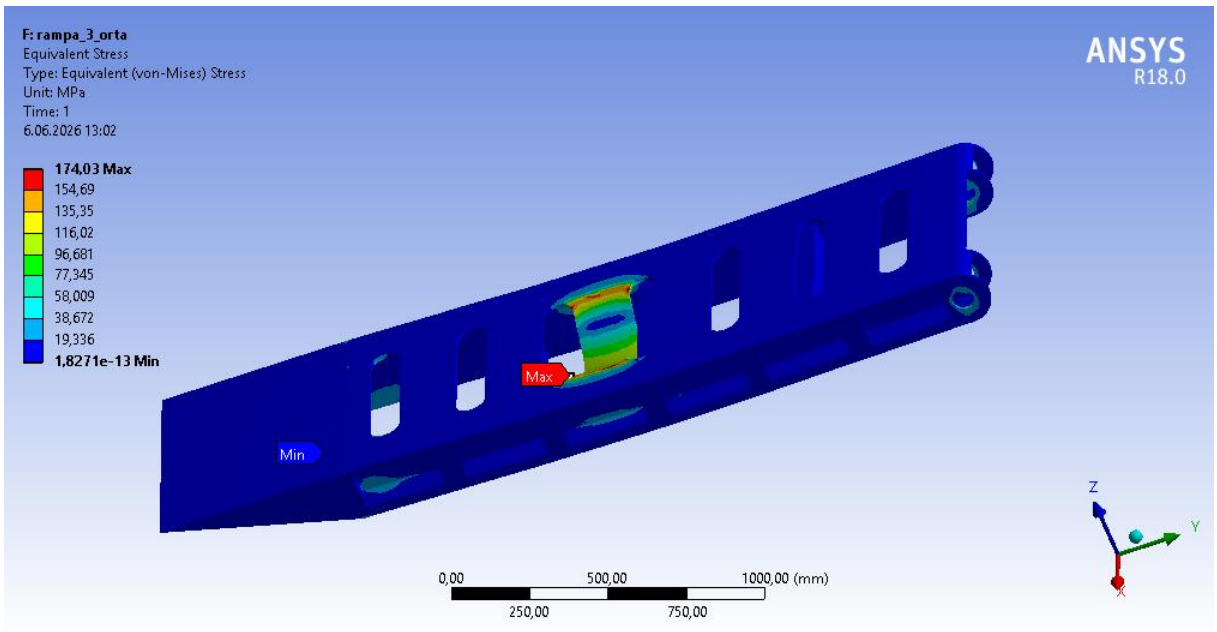


Figure 51. Stress value induced in geometry-III with Hardox 400 material for Case 2

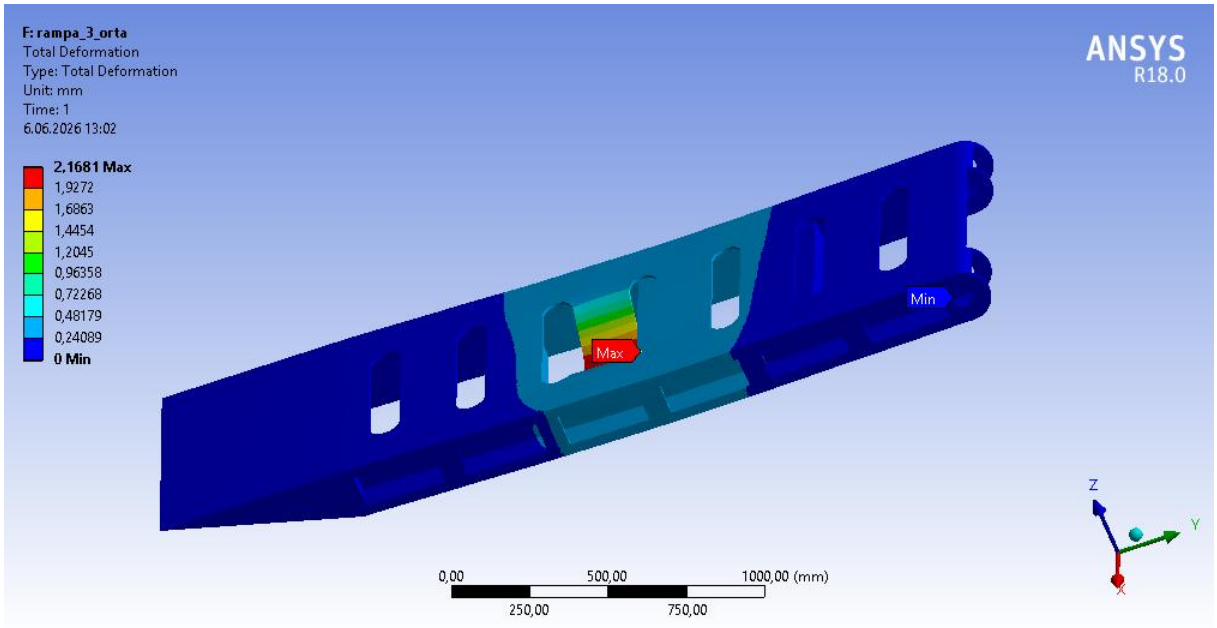


Figure 52. Total deformation value induced in geometry-III with Hardox 400 material for Case 2

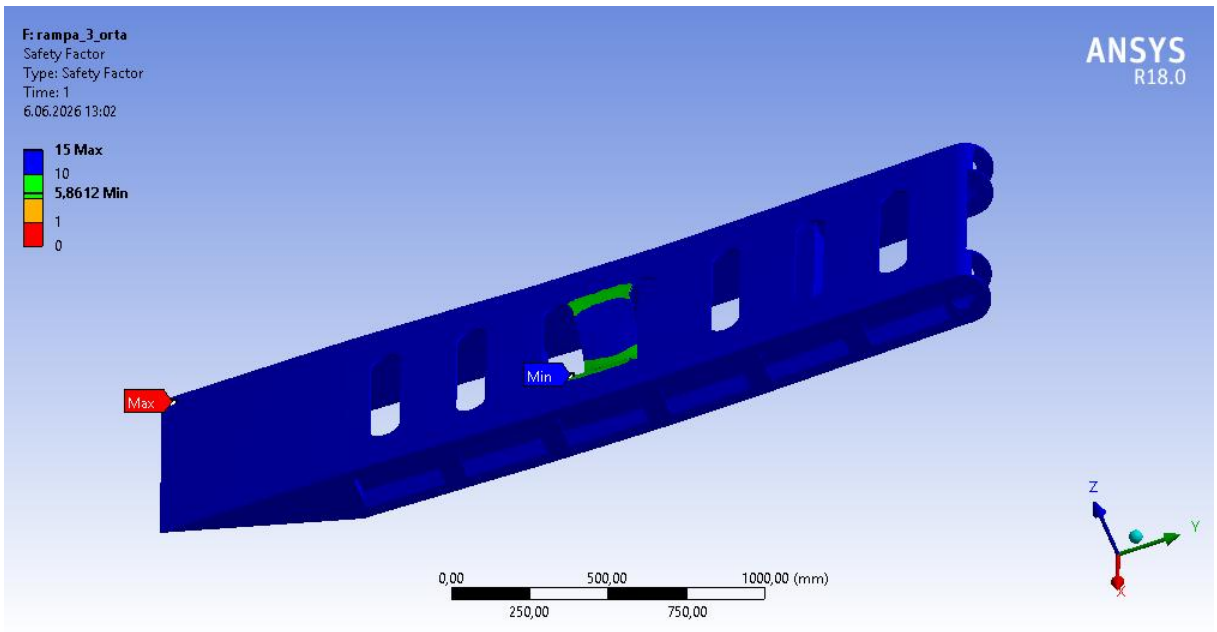


Figure 53. Safety factor value induced in geometry-III with Hardox 400 material for Case 2

Table 6 presents the analysis results attained for different geometries and loading conditions for the Hardox 400 material. When the effect of geometric modifications on stress was examined under the Case 1 tip region loading condition, it was observed that the maximum equivalent stress increased by 12.93% and the total deformation rose to a level of 1.10% in the geometry-II variation compared to the geometry-I baseline model. Correspondingly, an 11.45% reduction occurred in the safety factor. In the geometry-III model, while the maximum stress increase compared to the baseline model was calculated as merely 0.92%, the deformation increase remained at the level of 1.47%. Thereby, the safety factor of the geometry-III variation under tip loading decreased by only 0.91% compared to the baseline model, indicating that structural stability was almost completely preserved.

Table 6. Case 1 and Case 2 results for Hardox 400 material

Ramp Geometry	**Load Case**	**Equivalent Stress (MPa)**	**Total Deformation (mm)**	**Safety Factor**
Geometry-I	Case 1	95.001	1.0556	10.737
	Case 2	86.733	0.76864	11,76
Geometry-II	Case 1	107.28	1.0672	9.5076
	Case 2	68.688	0.79632	14.85
Geometry-III	Case 1	95.878	1.0712	10.639
	Case 2	174.03	2.1681	5.8612

When the Case 2 midpoint loading scenario for the Hardox 400 variations was analyzed, proportional changes were identified, indicating parallelism with the mechanical trends in the S700 group. Compared with the baseline model, Geometry-II provided a 20.8% improvement in the maximum stress value and a 3.6% improvement in the total deformation. As a result of these reductions, the safety factor increased by 26.27% relative to the baseline model. In the Geometry-III model, which underwent intensive mass reduction, the force acting on the midpoint increased the maximum equivalent stress by 100.65% relative to the baseline model and led to a 182.07% rise in the total deformation amount of the structure. However, owing to the high strength margin provided by the Hardox material compared to the baseline model, the reduction in the safety factor remained within acceptable limits despite these distinct increases in stress and deflection, thereby maintaining structural stability.

DISCUSSION and CONCLUSION

In this study, a comprehensive structural optimization and multi-scenario static analysis were conducted on heavy-duty lowbed trailer ramps by assessing three distinct geometric models using two advanced steel grades. Based on the integrated CAD/FEM numerical simulations, the following primary conclusions can be drawn:

Mass Reduction Performance: The geometric modifications implemented through sequential optimization successfully minimized structural mass. Compared to the baseline model (Geometry-I), Geometry-II achieved a mass reduction of 6.21% for S700 and 6.22% for Hardox 400. The maximum optimization was achieved with Geometry-III, yielding an impressive weight reduction of 11.81% for S700 and 11.81% for Hardox 400.

Structural Behavior under Tip Loading (Case 1): Under tip region loading, geometric modifications exerted only minor effects on structural stability. For the S700 group, the total safety factor reduction in Geometry-III was restricted to a minor 1.65%. For the Hardox 400 group, Geometry-III demonstrated remarkable structural stability, with the safety factor decreasing by only 0.91% while preserving a high safety margin of 10.639.

Structural Behavior under Midpoint Loading (Case 2): Due to the increased bending moment at the geometric center, Case 2 exposed major variations. Under the S700 application, Geometry-II displayed a substantial localized strength improvement, reducing the maximum equivalent stress by 78.98% and arising the safety factor by 375.74%. For the mass-optimized Geometry-III, the safety factor under Case 2 increased by 86.71% for S700 compared to the baseline, proving that mass reduction does not necessarily compromise safety when proper support forms are maintained.

Material Comparison: Hardox 400 consistently outperformed S700 across all geometric models in terms of safety margins and structural rigidity due to its superior mechanical characteristics. Even under intense mass optimization, Hardox 400 maintained a safe safety factor of 5.8612.

Based on the quantitative findings derived from the finite element analyses, Geometry-III is highly recommended for applications where fuel efficiency and vehicle payload capacity are prioritized, as it delivers an 11.81% weight reduction while maintaining safety factors well above standard engineering limits. However, when the trailer is expected to consistently undergo severe center loading conditions, Geometry-II can be utilized as a heavy-duty alternative to maximize localized bending resistance. Although Hardox 400 offers unparalleled structural safety and superior wear resistance against heavy vehicle tracks, its implementation increases the overall ramp weight slightly compared to S700 and involves higher material and machining costs. Therefore, a hybrid manufacturing strategy that uses Hardox 400 for the main contact plates, which are vulnerable to severe wear and S700 for the structural supporting U-profiles can be adopted to balance weight, cost, and longevity. Since this study focuses solely on linear static analysis under an assumed payload capacity, future research should integrate dynamic impact factors encountered during vehicle loading and unloading operations. Furthermore, transient dynamic simulations and high-cycle fatigue life analyses should be performed to evaluate the long-term durability of the optimized joint transitions and support profile welds under cyclic loading conditions.

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ARAÇ TAVAN BAGAJI BAĞLANTI AYAKLARININ YAPISAL VE AĞIRLIK OPTİMİZASYONUNUN SONLU ELEMANLAR ANALİZİ İLE İNCELENMESİ

INVESTIGATION OF THE STRUCTURAL AND WEIGHT OPTIMIZATION OF VEHICLE ROOF RACK MOUNTING BRACKETS USING FINITE ELEMENT ANALYSIS

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ÖZET

Araç tavanına entegre edilen bagaj taşıyıcı sistemleri, üzerlerine yerleştirilen yüklerin ağırlığı altında yapısal kararlılıklarını korumak zorunda olan ve doğrudan statik zorlanmalara maruz kalan elemanlardır. Bu çalışmada, tavan bagajı bağlantı ayaklarının yapısal bütünlüğünü ve statik davranışlarını incelemek amacıyla farklı geometrik boyutlarda tasarlanan bağlantı ayaklarının statik analizi yapılmıştır. Çalışma kapsamında; 3 cm yüksekliğinde içi dolu (3FD), 3 cm yüksekliğinde içi boş (3ED), 2 cm yüksekliğinde içi dolu (2FD), 2 cm yüksekliğinde içi boş (2ED) 2'şerli bağlantı ayakları ile 2 cm yüksekliğindeki içi dolu-boş 4 bağlantı ayağı olan 2FD4 ve 2ED4 olmak üzere 6 farklı model konfigürasyonu geliştirilmiştir. İçi boş olan tasarımların içinde 1 mm kalınlığında destek bağlantısı bulunmaktadır. Malzeme olarak otomotiv endüstrisinde yaygın olarak tercih edilen alüminyum alaşımı seçilmiştir. Modellerin tasarımları bilgisayar destekli teknik tasarım programı kullanılarak oluşturulmuş ve yapısal statik analizleri sonlu elemanlar analizi programı kullanılarak gerçekleştirilmiştir. Tasarımlara otomotiv standartları ve taşıma kapasitesi sınırları göz önüne alınarak düşey doğrultuda 100 kg (981 N) sabit yük uygulanmış; analizler sonucunda toplam deformasyon, maksimum Von Mises gerilmesi ve emniyet faktörü elde edilmiştir. Analiz bulgularına göre, içi boş tasarımların içi dolu tasarımlara kıyasla ortalama 6,4 kat daha hafif olduğu, ancak içi dolu modellerin deformasyonu minimumda tutarak daha yüksek güvenlik sunduğu görülmüştür. 2 cm yüksekliğindeki içi boş modeller incelendiğinde; ayak sayısının 2'den 4'e çıkarıldığı 2ED4 tasarımının, 2ED tasarımına göre deformasyon miktarını 2 kat azalttığı ve emniyet faktörünü 1,93 kat artırarak 4,47 seviyesine yükselttiği tespit edilmiştir. Sonuçlar; hafiflik, maliyet ve yapısal güvenilirlik kriterleri bir arada değerlendirildiğinde, 2ED modelinin tavan bagajı uygulamalarında ağırlık optimizasyonu ve yapısal yeterlilik açısından en ideal çözümü sunduğunu göstermektedir.

Anahtar Kelimeler: Araç tavan bagajı, Bağlantı ayağı tasarımı, Sonlu elemanlar analizi, Yapısal analiz, Alüminyum alaşım.

ABSTRACT

Roof-mounted luggage carrier systems are elements that must maintain their structural stability under the weight of the loads placed on them and are directly subjected to static stresses. In this study, static analysis of mounting brackets designed in different geometric dimensions was performed to examine the structural integrity and static behavior of roof luggage carrier mounting brackets. Within the scope of the study, 6 different model configurations were developed: 2 pairs of 3 cm high solid (3FD), 3 cm high hollow (3ED), 2 cm high solid (2FD), 2 cm high hollow (2ED) mounting brackets, and 2FD4 and 2ED4, which are 2 cm high solid-hollow mounting brackets with 4 mounting brackets. The hollow designs contain a 1 mm thick support connection. Aluminum alloy, commonly preferred in the automotive industry, was chosen as the material. The designs of the models were created using a computer-aided technical design program, and their structural static analyses were performed using a finite element analysis program. A constant load of 100 kg (981 N) was applied to the designs in the vertical direction, considering automotive standards and load capacity limits; the total deformation, maximum Von Mises stress, and safety factor were obtained as a result of the analyses.

According to the analysis findings, hollow designs are on average 6.4 times lighter than solid designs, but solid models offer higher safety by minimizing deformation. When the 2 cm high hollow models were examined, it was determined that the 2ED4 design, in which the number of legs was increased from 2 to 4, reduced the amount of deformation by 2 times and increased the safety factor by 1.93 times to 4.47 compared to the 2ED design. The results show that when lightness, cost, and structural reliability criteria are evaluated together, the 2ED model offers the most ideal solution in terms of weight optimization and structural adequacy in roof rack applications.
Keywords: Vehicle roof rack, Mounting bracket design, Finite element analysis, Structural analysis, Aluminum alloy.

INTRODUCTION

With the increasing user expectations in the automotive sector, the carrying capacity and functional features of vehicles have also advanced. Especially in areas such as camping, bicycle transportation, sports activities, and long-distance driving, the insufficiency of vehicle interior volume has increased the need for additional carrying systems. Vehicle roof luggage carriers developed in line with this need are among the crucial equipment that ensure the safe and practical transportation of loads. In the design of roof carrier systems that create an additional load on the vehicle, deformation, equivalent (Von Mises) stress, and safety factor are among the most important evaluation criteria to determine structural adequacy (Kumlu et al., 2023).

The complex geometries, diverse material properties, and various loading conditions of automotive structures make it difficult to accurately evaluate structural behavior during the design process. Although experimental methods offer reliable results, they pose significant limitations during design development due to high costs, long testing periods, and the requirement for prototypes. For this reason, finite element analysis (FEA) is widely used as an effective engineering tool that enables the numerical evaluation of the structural performance of automotive components prior to production. The reliability of the results obtained from numerical analyses directly depends on the accuracy of the geometric model, the correct definition of material properties, the representation of real operating conditions by the boundary conditions, and the creation of appropriate loading scenarios. Therefore, an accurate modeling approach representing real operating conditions is considered one of the fundamental elements determining the success of finite element analyses (Melosh, 1974).

In studies aimed at developing vehicle roof carrier systems, increasing the carrying capacity, ensuring user safety, and improving ease of use are among the primary design goals. In a study conducted within this scope, an innovative bicycle roof carrier with sliding rail technology was developed to enhance the system's usage ergonomics and structural reliability. The study revealed that roof carrier systems need to be developed not only in terms of load-carrying capacity but also regarding safety and functionality (Jawad et al., 2000).

Lightweight design approaches have come to the fore in roof carrier systems in recent years, and studies aimed at reducing weight without compromising structural strength have gained momentum. Mandadapu et al. performed the robust design of a lightweight roof rack system mounted flush to the vehicle roof, demonstrating that structural performance and weight optimization must be evaluated together. This approach highlights the importance of lightweight design strategies in terms of reducing material consumption in carrier systems, improving fuel economy, and maintaining structural safety (Mandadapu et al., 2011).

In the study about carrier, a random vibration fatigue analysis of a vehicle roof luggage carrier was conducted and the long-term usage performance of the system was examined. As a result of the study, it was stated that the carrier system has a safe operating life under specified load conditions (Gülsevinçler, 2021). In another study, the design and numerical analysis of a bicycle carrier mounted on a vehicle roof were carried out. The maximum stress regions occurring in the carrier system were determined. In that study, structural safety was evaluated using the finite element method (Ptak et al., 2016).

Although various studies exist in the literature review regarding the design and structural analysis of vehicle roof carrier systems, no research has been encountered in which the effects of connection leg height, internal structure geometry (solid/hollow), and the number of connection legs on structural performance are evaluated comparatively within the same scope.

In this respect, the present study aims to contribute to this gap in the literature by simultaneously examining the effects of design parameters on the maximum Von Mises stress, total deformation, safety factor, and weight. Within this framework, six different vehicle roof luggage carrier connection leg models with varying heights, internal structural geometries, and numbers of connection legs were designed, and their structural analyses were performed under a 100 kg (981 N) static load using the finite element method. By comparing the analysis results, it is aimed to determine the effects of carrier dimensions on structural performance.

MATERIALS and METHODS

Aluminum alloys used in similar applications have a critical role in part lightening strategies due to their low specific gravity and high specific strengths. The recyclable structure, thermal/electrical conductivity, ductility, and spark-free properties of the material make it stand out in the industry. Aluminum, whose mechanical properties are limited in pure form, is reinforced with alloying elements to achieve high strength and is thus used as a building material in structural engineering projects. In this study, an aluminum alloy was used for vehicle roof rack bracket designs. Material information is given in Table 1 (Gökçe, 2013; Karaçor et al., 2025).

Table 1. Material properties (Karaçor et al., 2025)

Material	**Density (kg/m³)**	**Young's Modulus (GPa)**	**Tensile Ultimate Strength (MPa)**	**Tensile Yield Strength (MPa)**	**Poisson's Ratio**
Aluminum Alloy	2770	71	280	310	0.33

Within the scope of this study, six different vehicle roof rack models with varying dimensions were created. The model codes and names are given in Table 2. Computer-aided engineering methods were used to investigate the structural behavior of the roof rack systems designed in different sizes. Static analyses of the models were performed. The design models were created using CATIA V5R21 software. The 3D representation of the roof rack supports is shown in Figure 1-6.

Table 2. Code names of the models

Codes	Explanation
3FD	3 cm high solid-filled design
3ED	3 cm high hollow-filled design (wall thickness 1 mm)
2FD	2 cm high solid-filled design
2ED	2 cm high hollow-filled design (wall thickness 1 mm)
2FD4	2 cm high design with 4 connection legs
2ED4	2 cm high, hollow-core design (wall thickness 1 mm) with 4 connection legs

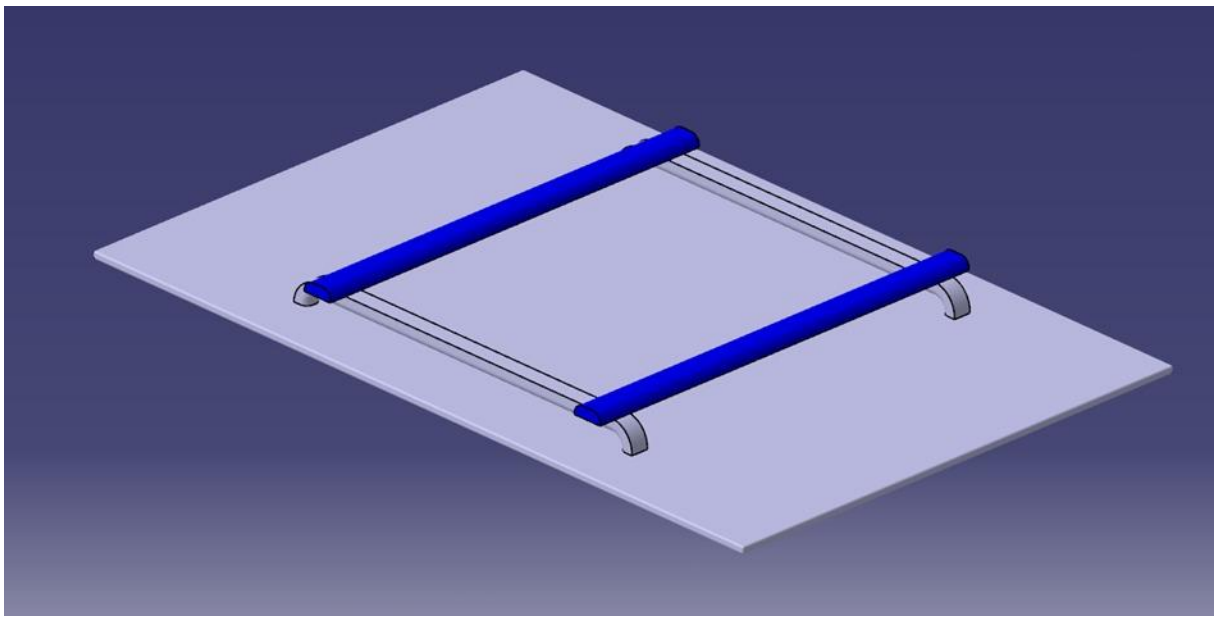

Figure 1. General view of 3FD ceiling carriers designed and the ceiling support system design

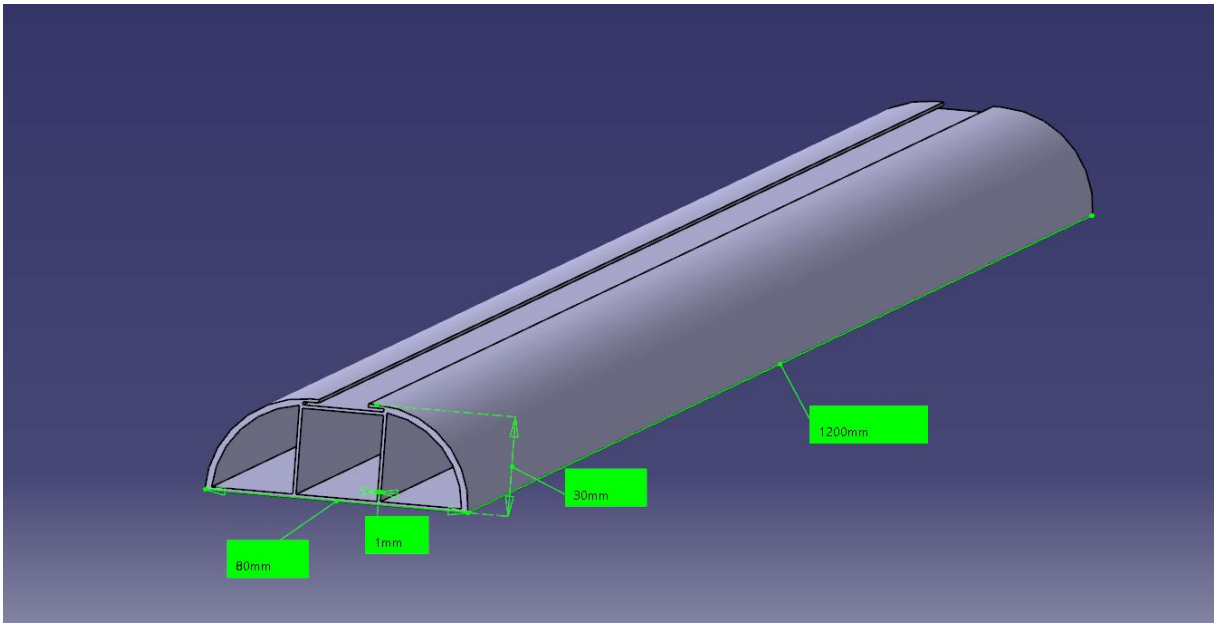

Figure 2. View of the 3ED ceiling carrier's design

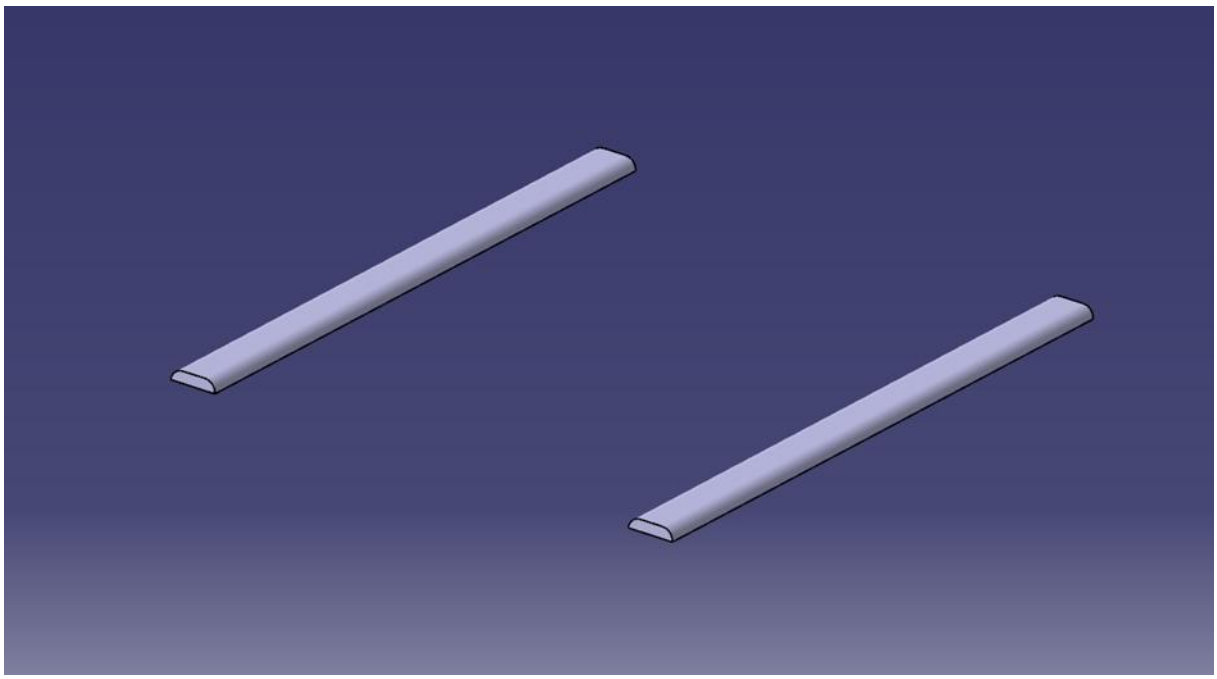

Figure 3. View of 2FD ceiling carriers designed

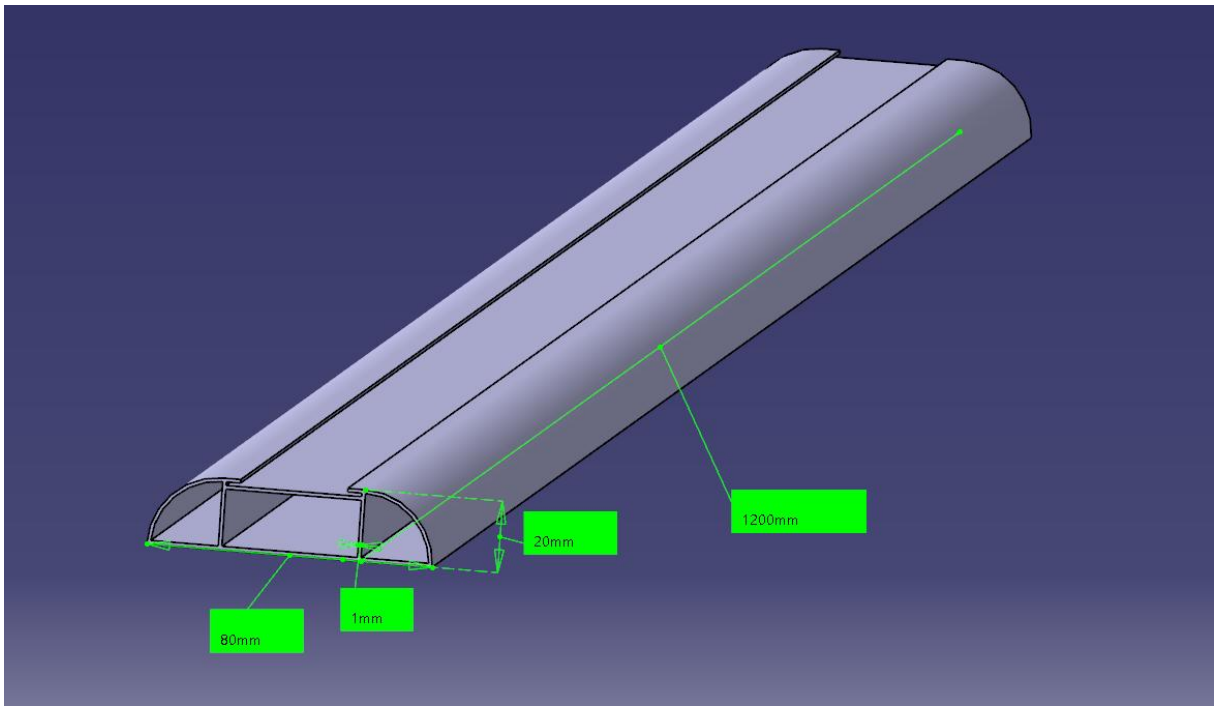

Figure 4. View of 2ED ceiling carriers designed

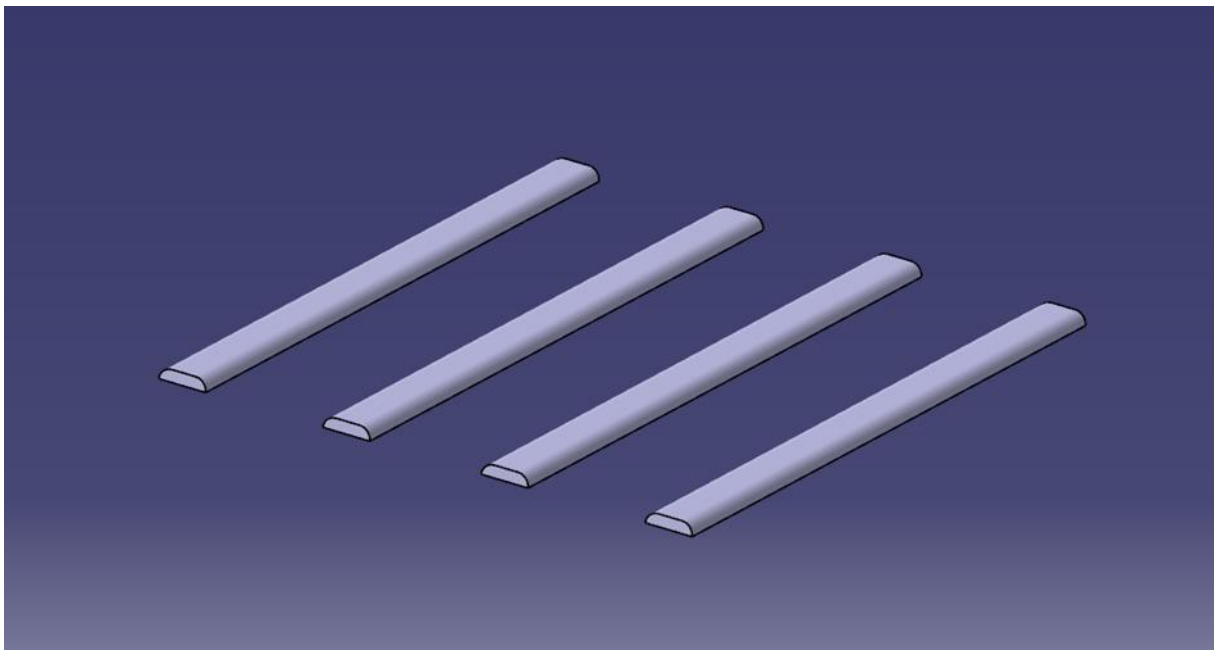

Figure 5. View of 2FD4 ceiling carriers designed

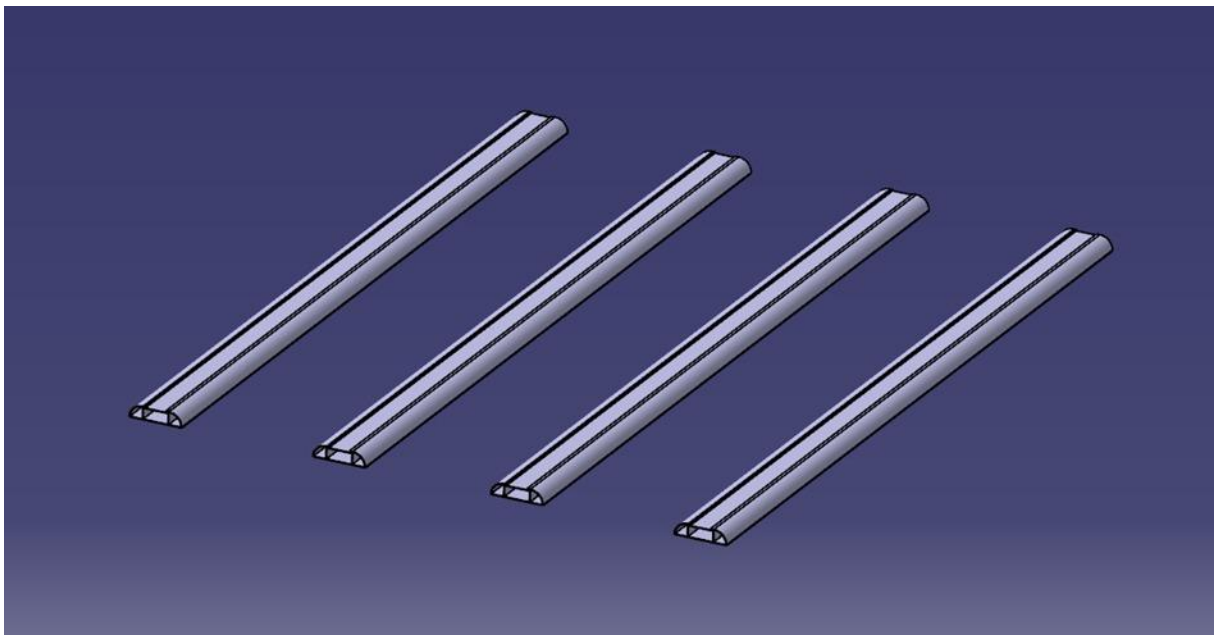

Figure 6. View of the 2ED4 ceiling carrier's design

Finite element analysis (FEA) was performed using ANSYS 18.0 to evaluate the structural behavior of the designs. The static module was used to evaluate the total deformation, equivalent Von-Mises stresses and safety factors affecting the system under a vertical load of 100 kg (981 N), taking into account the fixing points on the surfaces where the roof trunk connection legs are mounted on the vehicle.

In the automotive industry, passenger vehicle roofs are generally limited to 75-100 kg. In the analysis, the vertical load of 100 kg was selected as the worst-case scenario to test the structural safety Factor and limit strength of the connection legs under maximum load and overload conditions (Erkul Oto, 2026.; Thule Group, 2025).

In order to simulate load transfer in the most accurate way within the geometric limits of the design and to capture stress accretions precisely, a finite element network suitable for the connection pillar geometry has been created. Local network improvement has been applied by using smaller element sizes

in thin-walled regions, sharp corners, and geometric transitions where stress accretions may occur. A network independence study was conducted to evaluate the accuracy of the analysis.

The number of elements was gradually increased, and changes in the maximum Von Mises stress and total deformation values were monitored. After a significant change in the analysis results was not observed when the network density was increased above a certain level, it was accepted that the existing network structure provides network independence.

The quality of the finite element network created is considered ideal, the average Element quality is close to 1, and values above certain limits indicate a high-quality network structure. Similarly, when the distortion values measuring the geometric deformity of the elements were examined, it was found that all the models remained within the excellent and very good quality limits. All the network statistics and quality metrics obtained prove that the finite element network structure created is sufficient and reliable for producing high-accuracy and stable results in static structural analyses (ANSYS Inc., 2017). The total number of nodes and elements in the models, along with the average element quality and average skewness values from the network quality parameters, are given in Table 3. Figure 7-12 shows the finite element mesh generated for the ceiling support design geometries

Table 3. Mesh information and quality parameters of models

	3FD	3ED	2FD	2ED	2FD4	2ED4
Nodes	42980	2293266	53712	1713532	77636	3427064
Elements	8400	372800	10268	249600	14580	499200
Element quality	0.85749	0.83262	0.89058	0.82254	0.85929	0.82498
Skewness	0.24287	0.23371	0.25949	0.2593	0.2349	0.25685

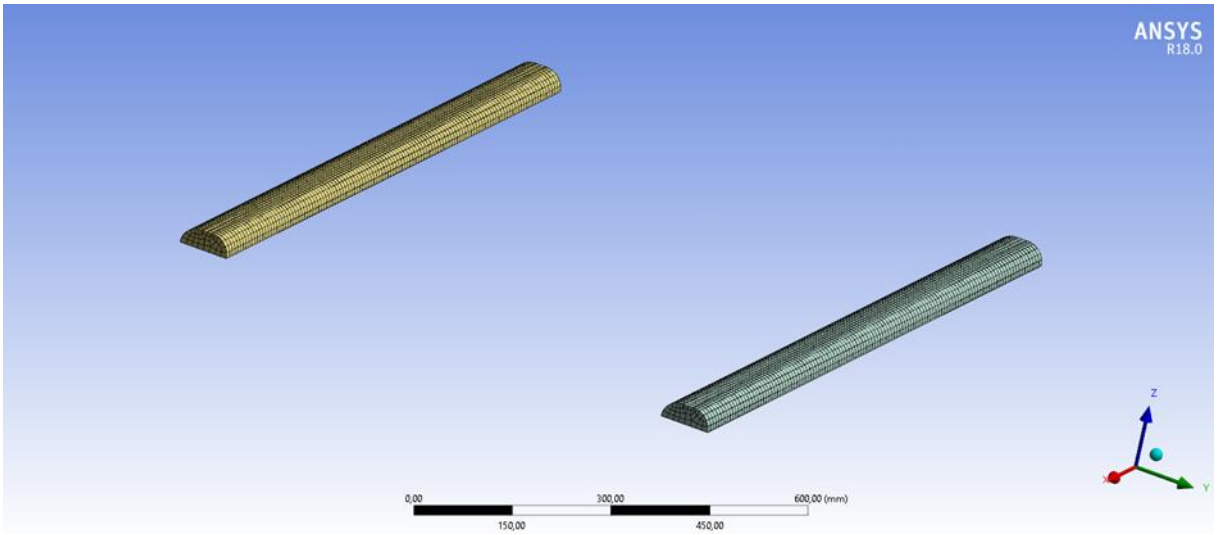

Figure 7. Mesh view of 3FD ceiling carriers

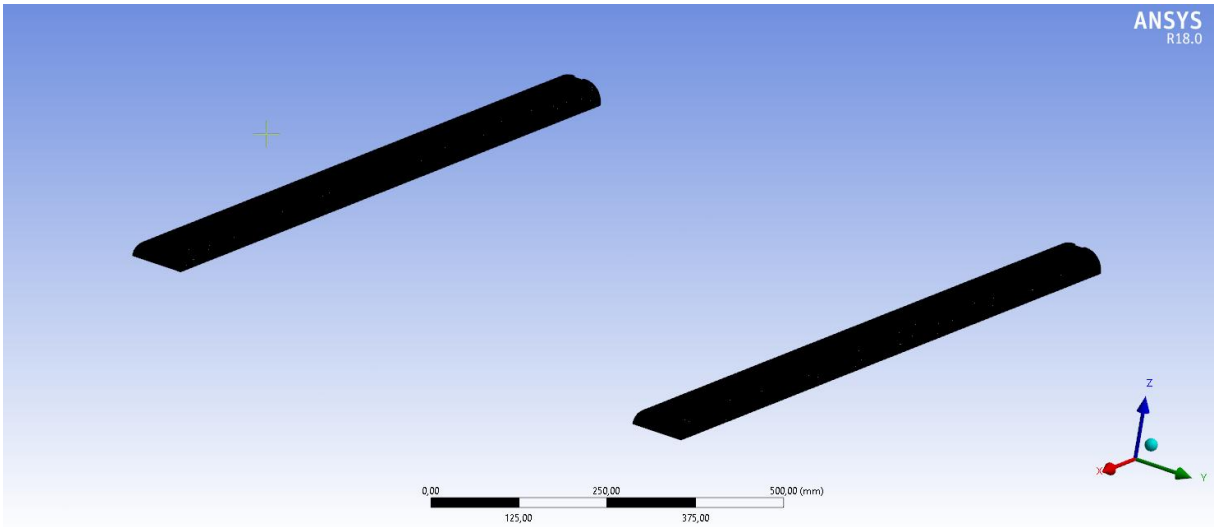

Figure 8. Mesh view of 3ED ceiling carriers

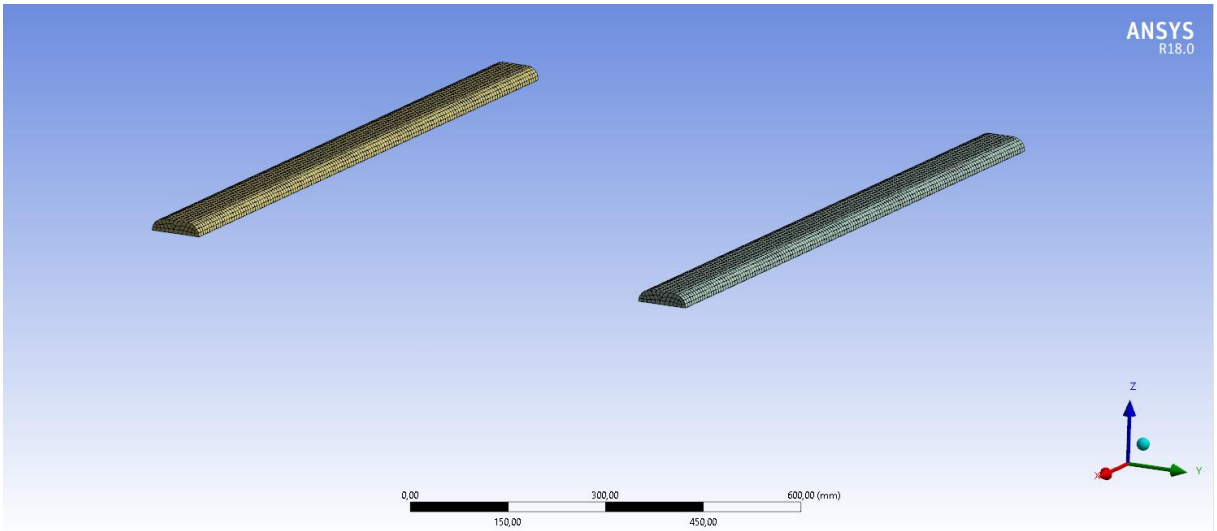

Figure 9. Mesh view of 2FD ceiling carriers

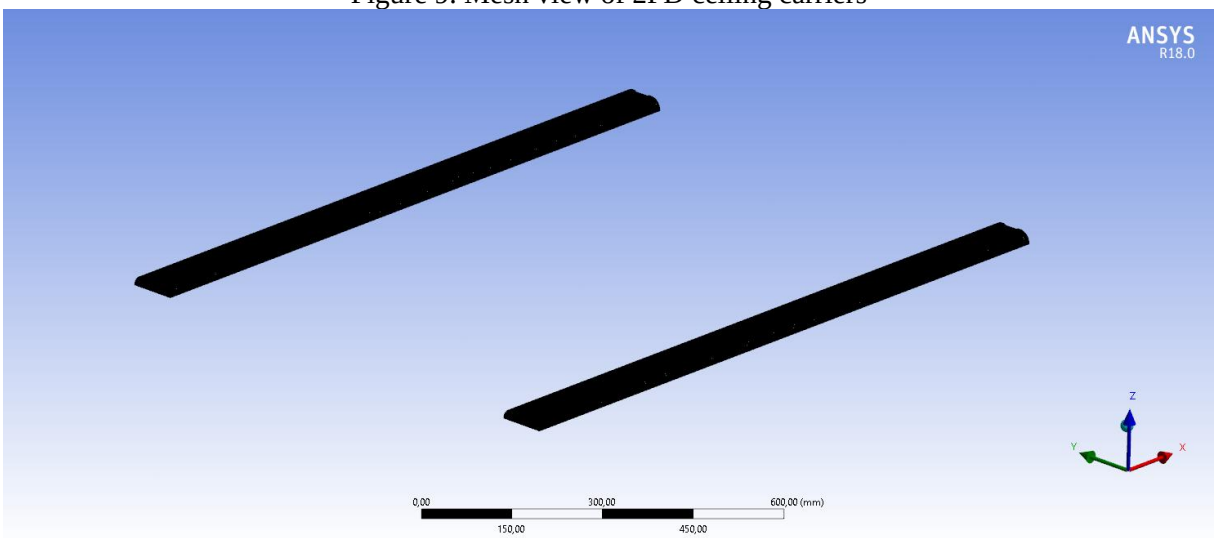

Figure 10. Mesh view of 2ED ceiling carriers

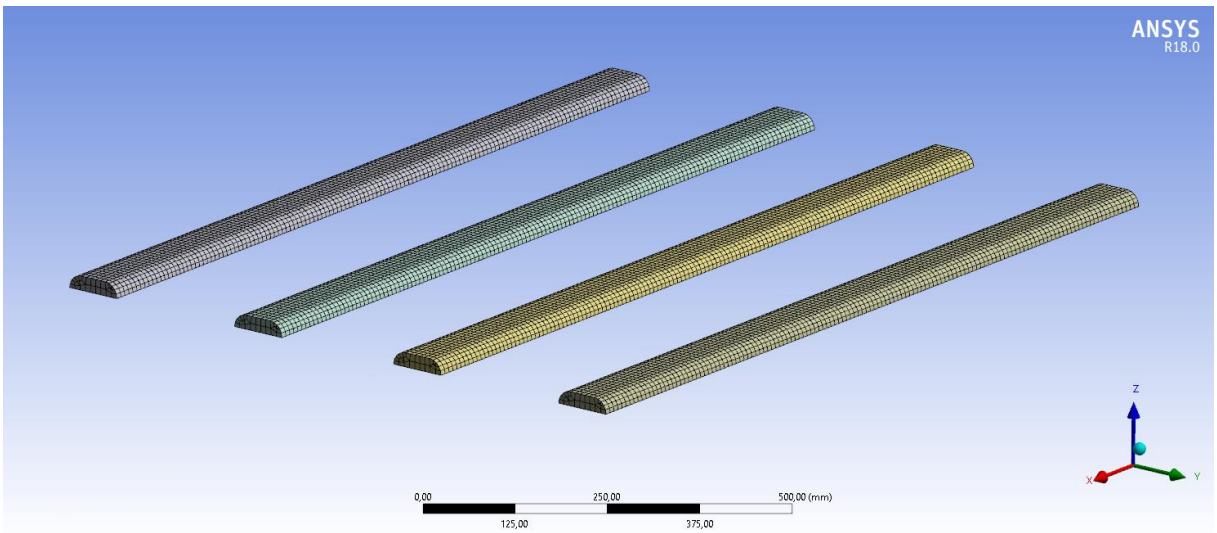

Figure 11. Mesh view of 2FD4 ceiling carriers

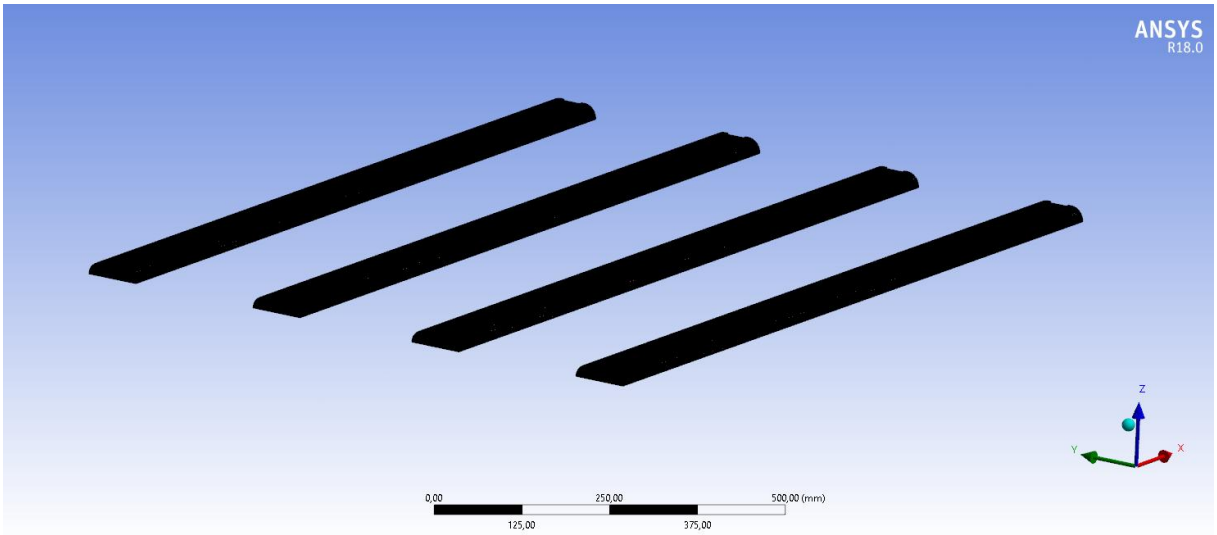

Figure 12. Mesh view of 2ED4 ceiling carriers

The lower surfaces and bolt holes where the fasteners are mounted on the vehicle roof rails are defined as fixed supports by limiting them at all degrees of freedom in such a way as to simulate the actual installation situation. Figure 13-18 shows the fixed support regions. A homogeneous force was applied in the vertical direction based on the maximum anticipated carrying capacity and standard of the roof rack system. Figure 19-24 shows the areas where force is applied.

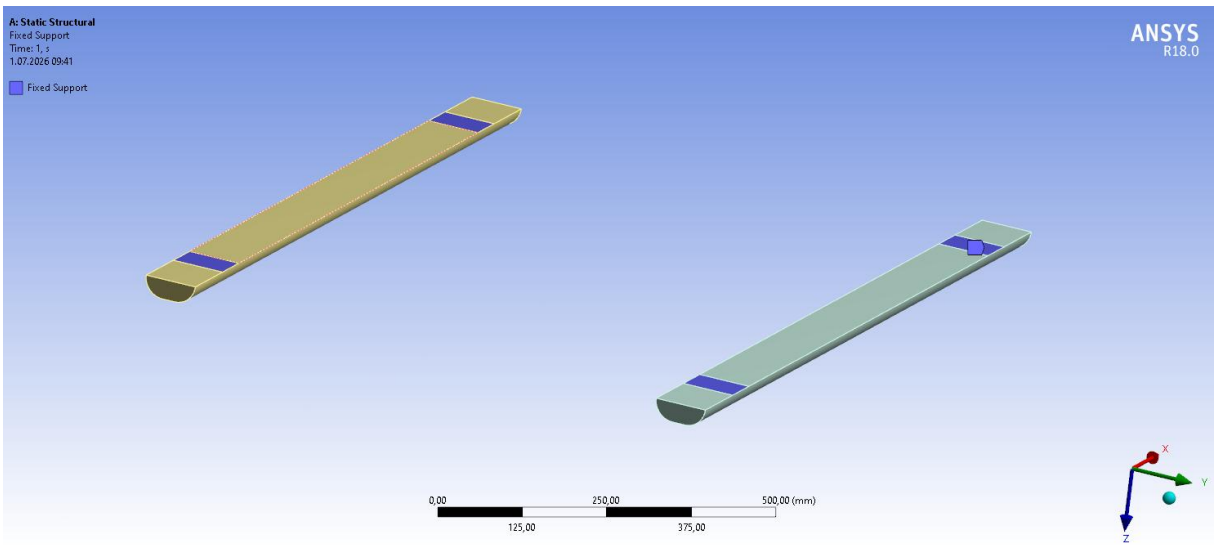

Figure 13. Fixed support zones of the 3FD model

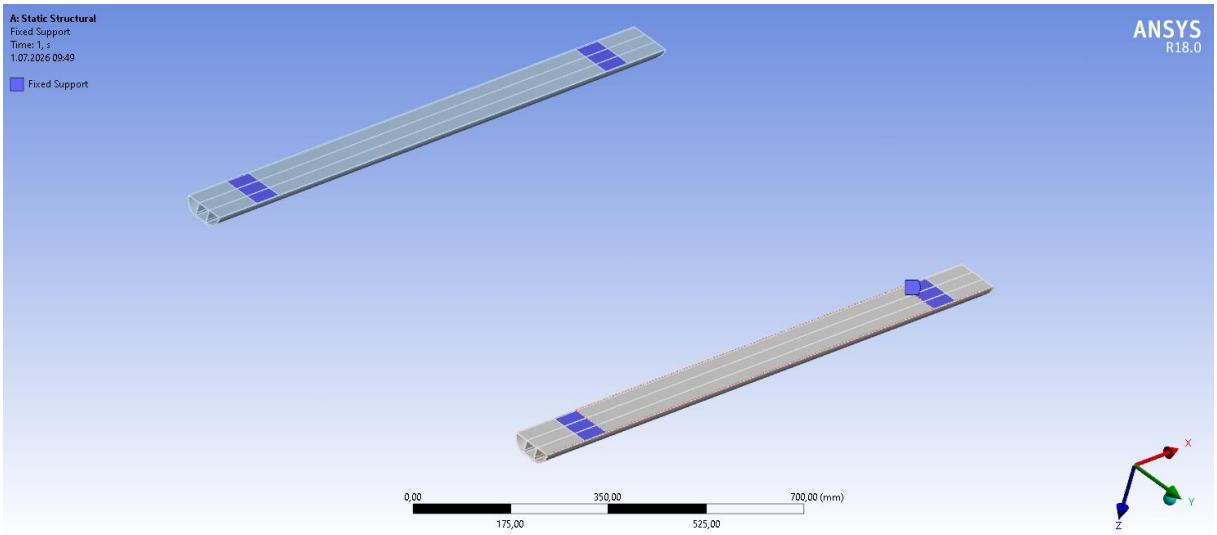

Figure 14. Fixed support zones of the 3ED model

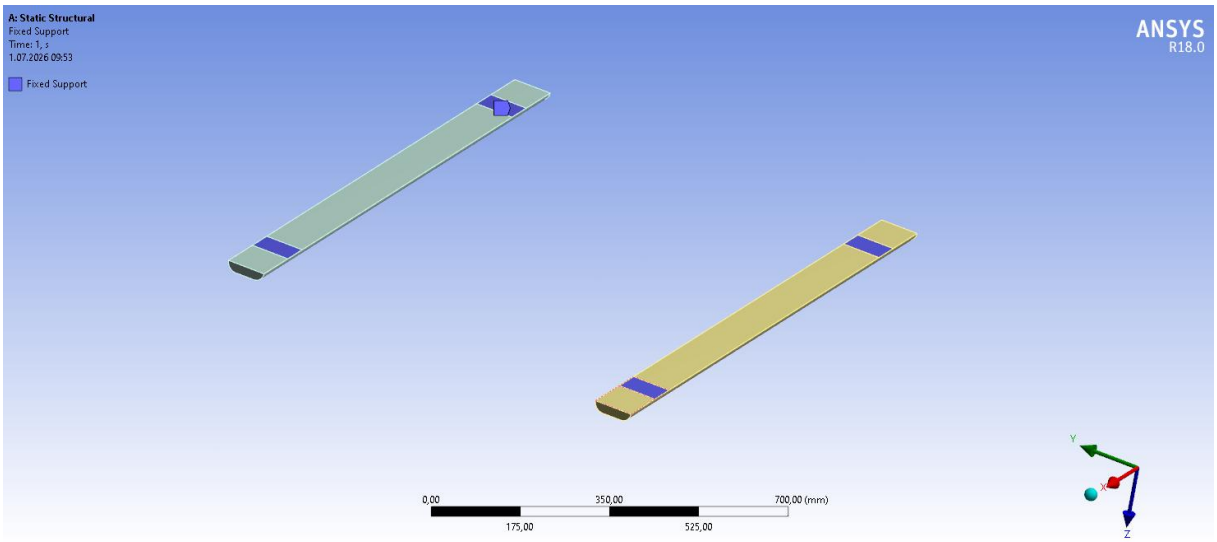

Figure 15. Fixed support zones of the 2FD model

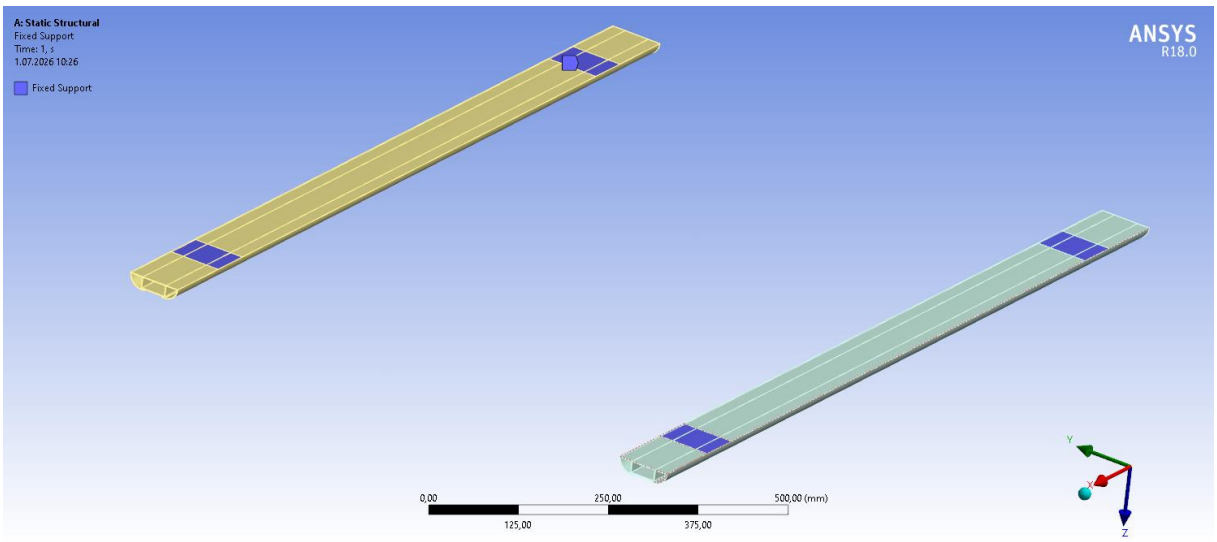

Figure 16. Fixed support zones of the 2ED model

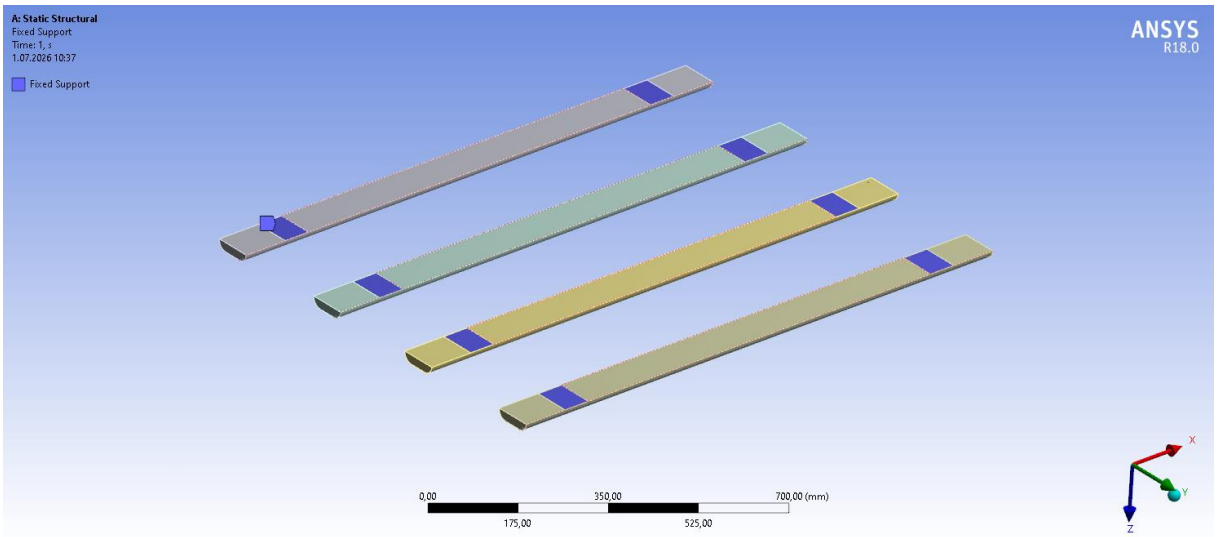

Figure 17. Fixed support zones of the 2FD4 model

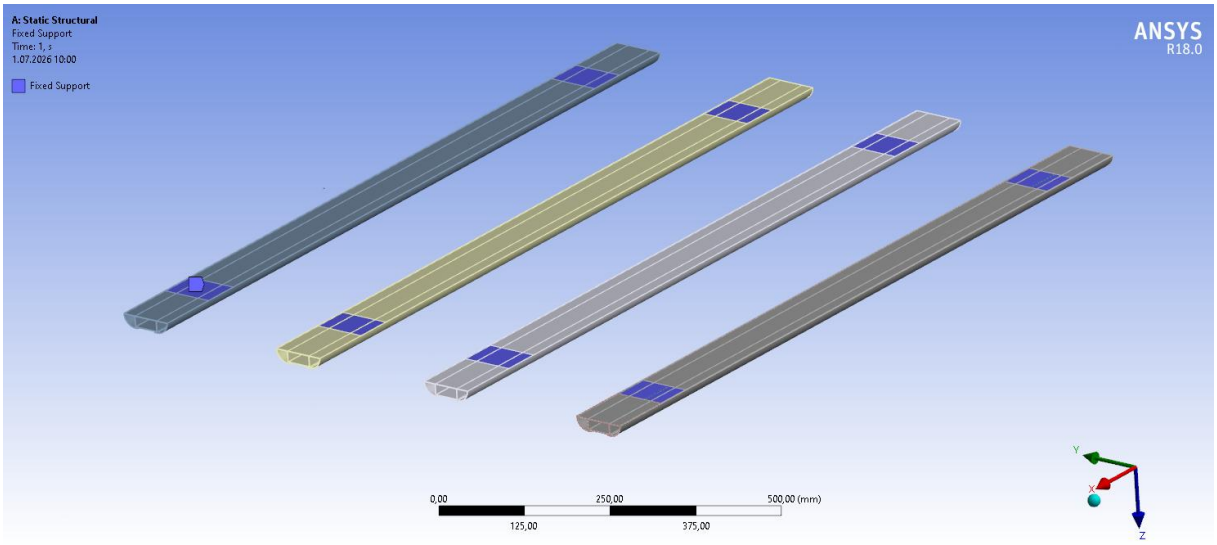

Figure 18. Fixed support zones of the 2ED4 model

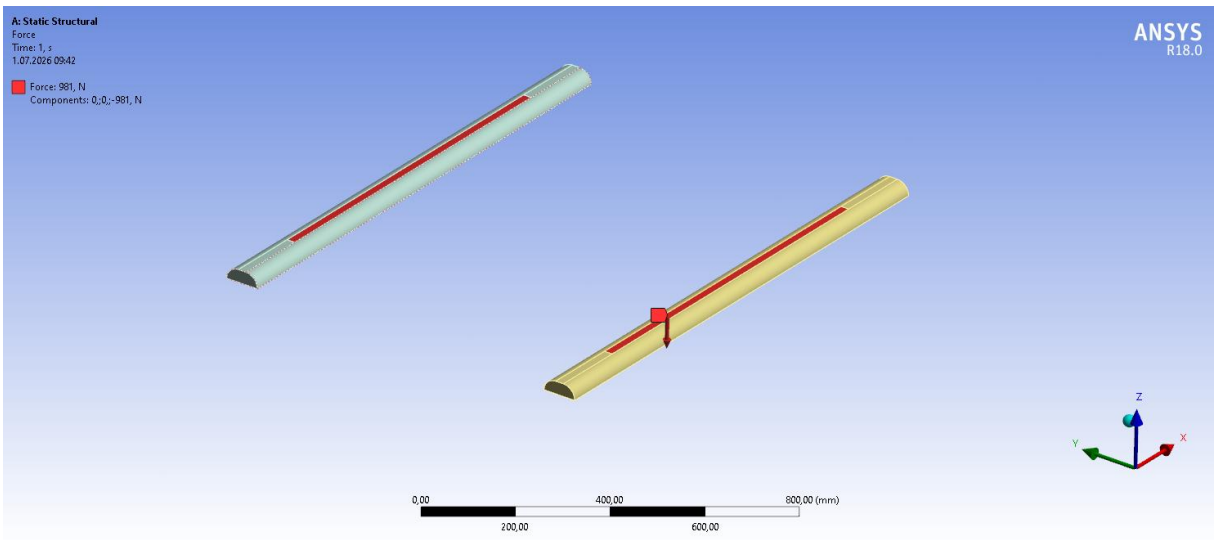

Figure 19. Applied force regions of the 3FD model

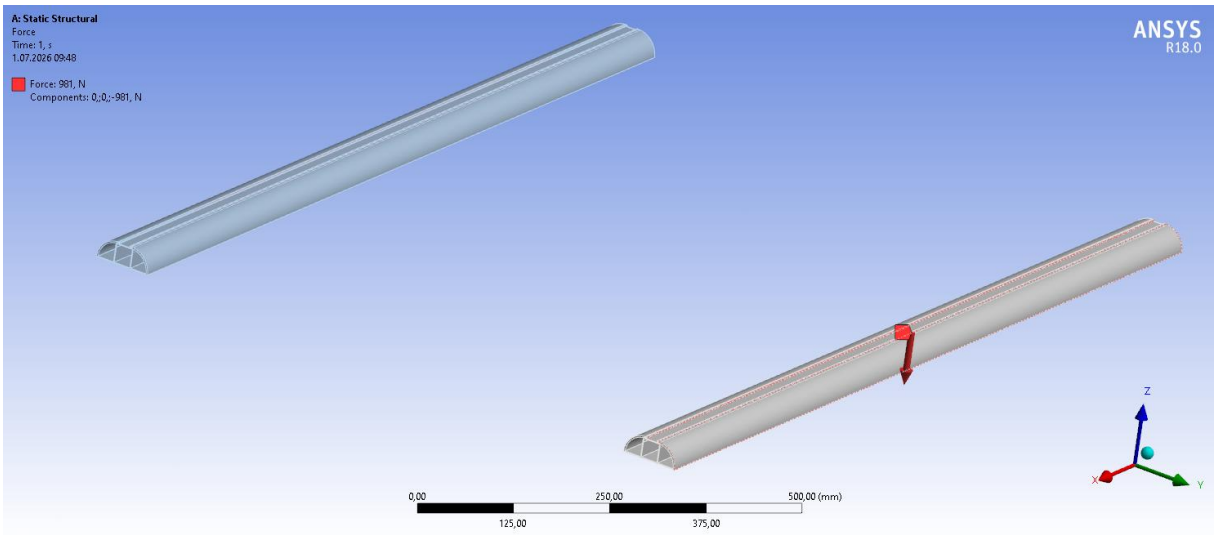

Figure 20. Applied force regions of the 3ED model

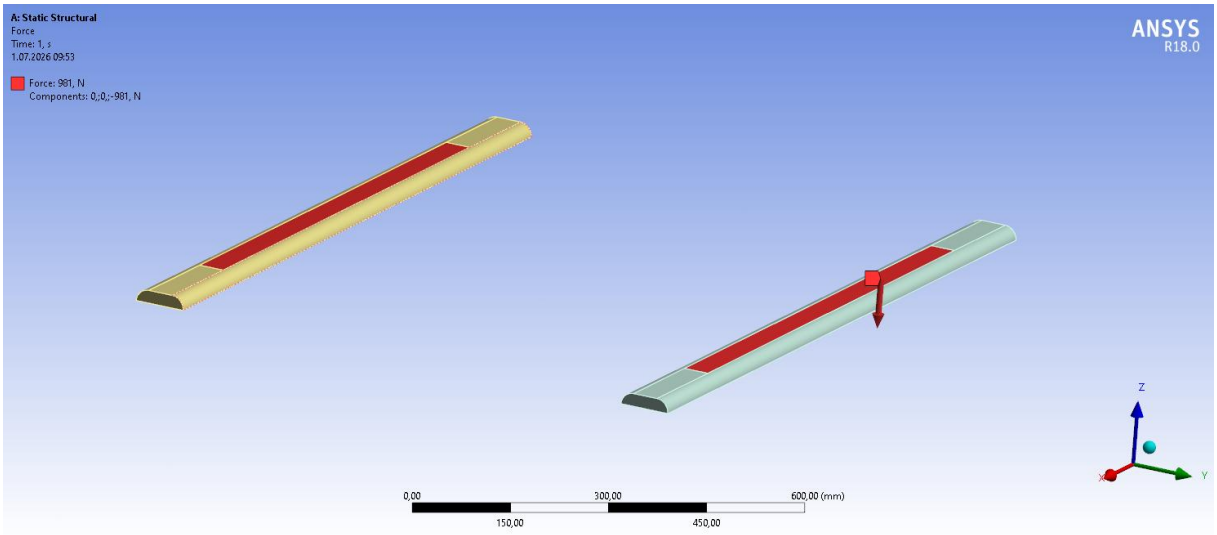

Figure 21. Applied force regions of the 2FD model

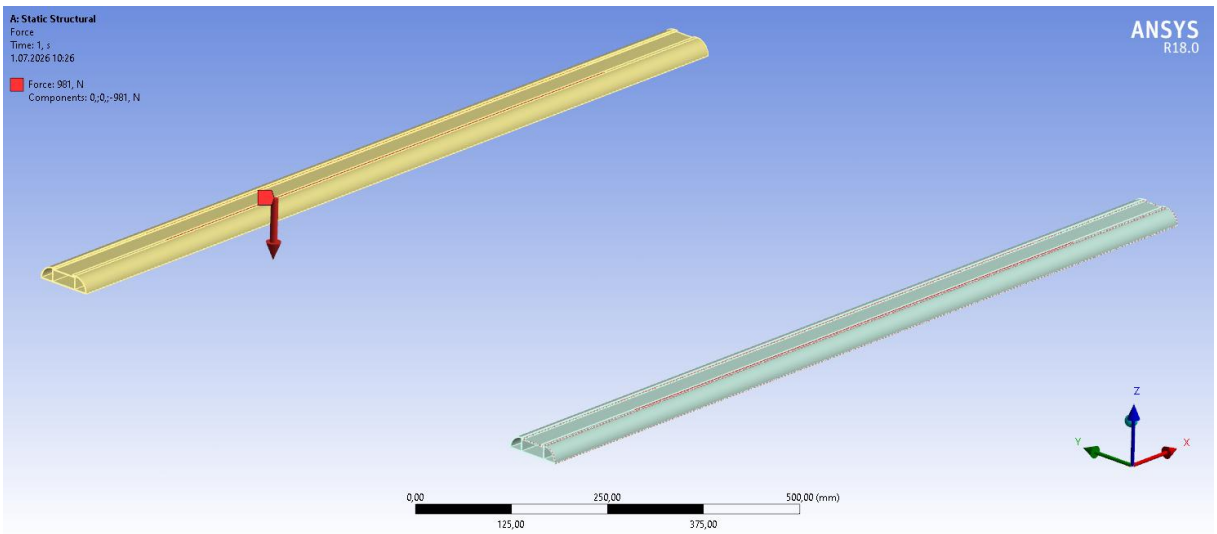

Figure 22. Applied force regions of the 2ED model

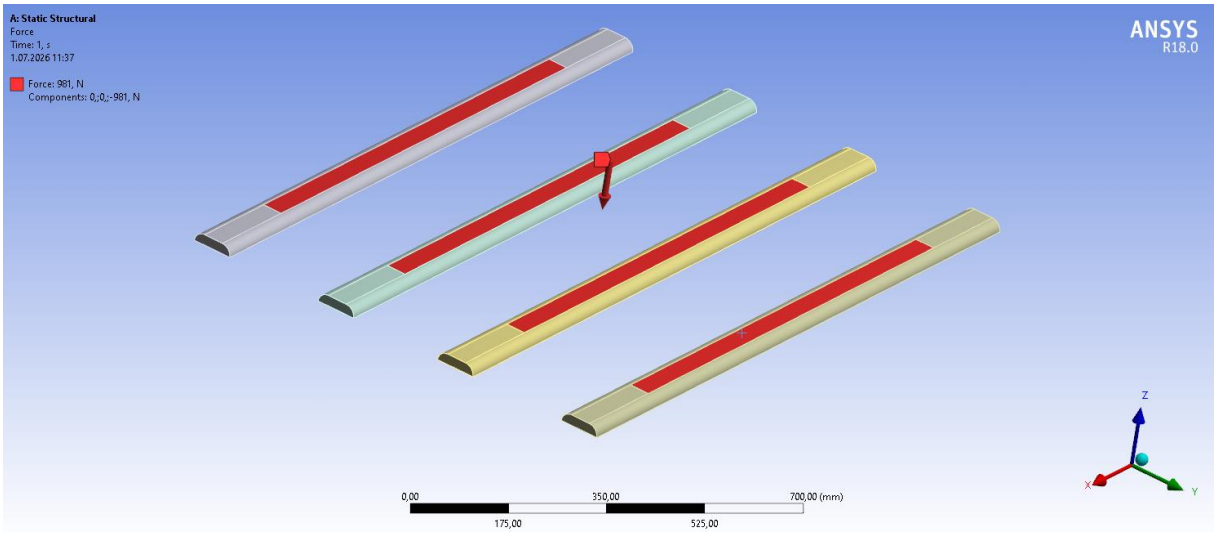

Figure 23. Applied force regions of the 2FD4 model

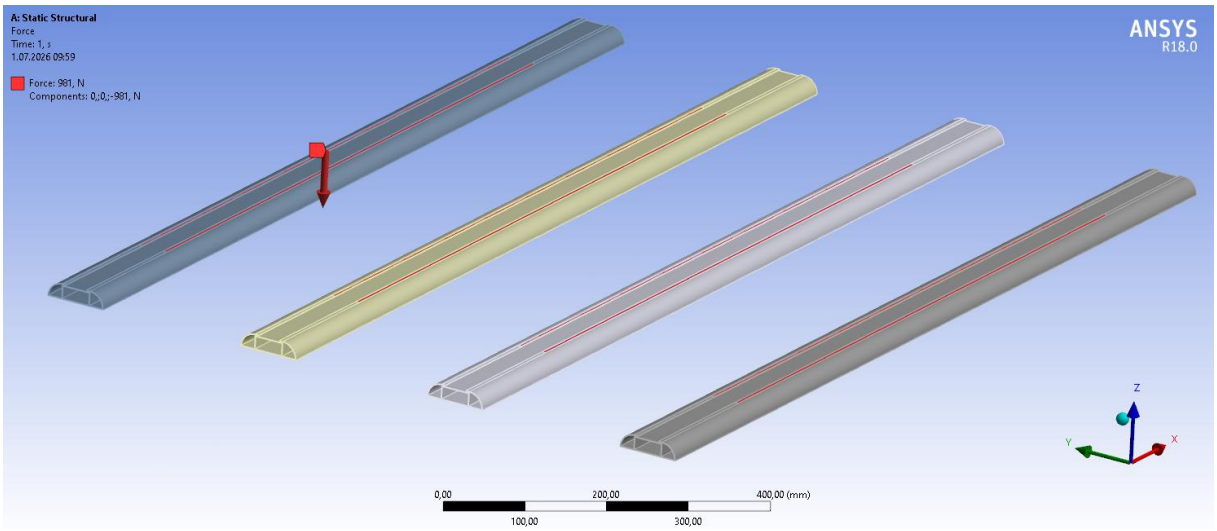

Figure 24. Applied force regions of the 2ED4 model

RESULTS

The weights of the models are given in Table 4. It was observed that the lowest weight was in the 2ED model (1.484 kg). It has been determined that this is followed by the 3ED (2.239 kg) and 2ED4 (2.968 kg) models. The highest weight was achieved in the 2FD4 model with 18.991 kg. Filled-core models offer advantages in structural strength, but result in a significant increase in weight.

Table 4. Weights of the designed models

	3FD	3ED	2FD	2ED	2FD4	2ED4
Kg	13.387	2.2388	9.4955	1.4841	18.991	2.9682

Six different models designed for vehicle roof rack mounting brackets were evaluated using finite element analysis under a static load of 981 N. As a result of the analyses, total deformation, equivalent (Von Mises) stress, and safety factor values were obtained; these results are presented in Table 5. The total deformation results are shown in Figures 25-30, the equivalent stress results in Figures 31-36, and the safety factor results in Figures 37-42.

Table 5. Static analysis results

	3FD	3ED	2FD	2ED	2FD4	2ED4
Total Deformation (mm)	0.1035	0.41108	0.29922	1.1549	0.10583	0.57861
Equivalent Stress (MPa)	4.4912	83.513	8.3333	120.76	2.8534	62.647
Safety Factor	15	3.3528	15	2.3186	15	4.4695

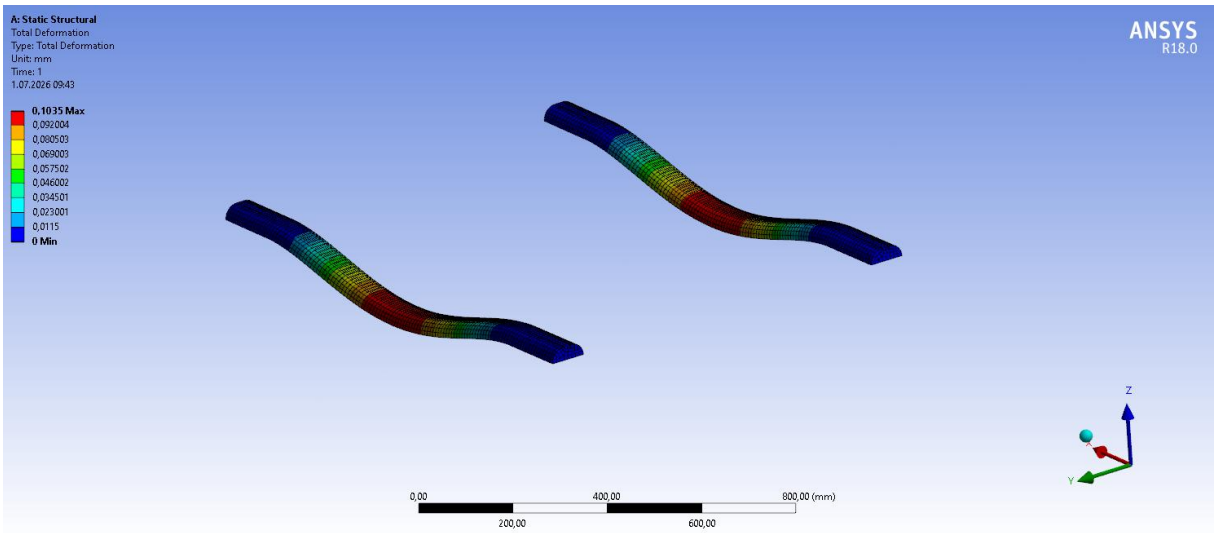

Figure 25. Total deformation value for the 3FD model

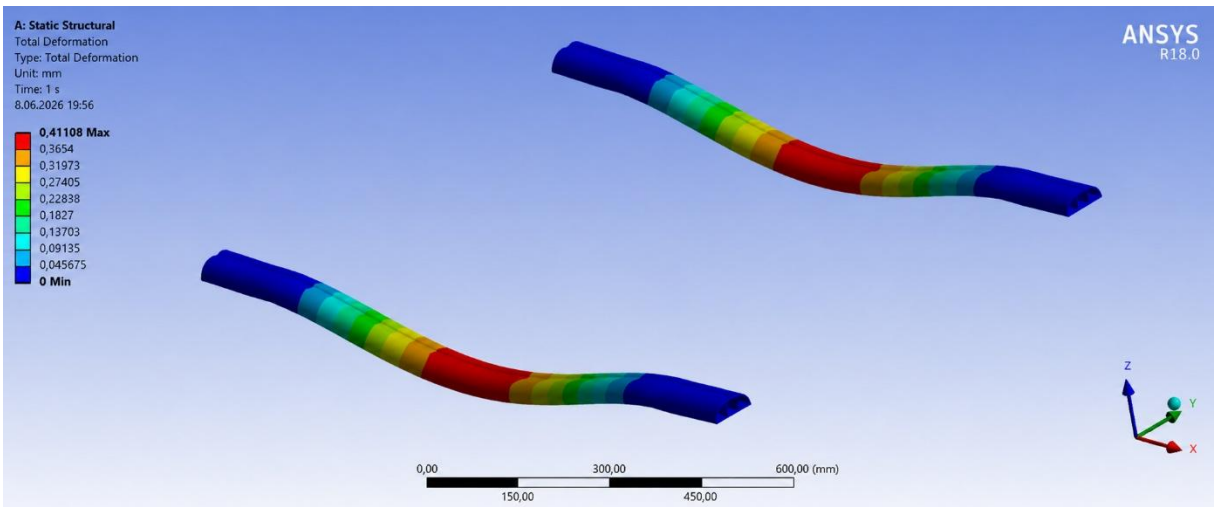

Figure 26. Total deformation value for the 3ED model

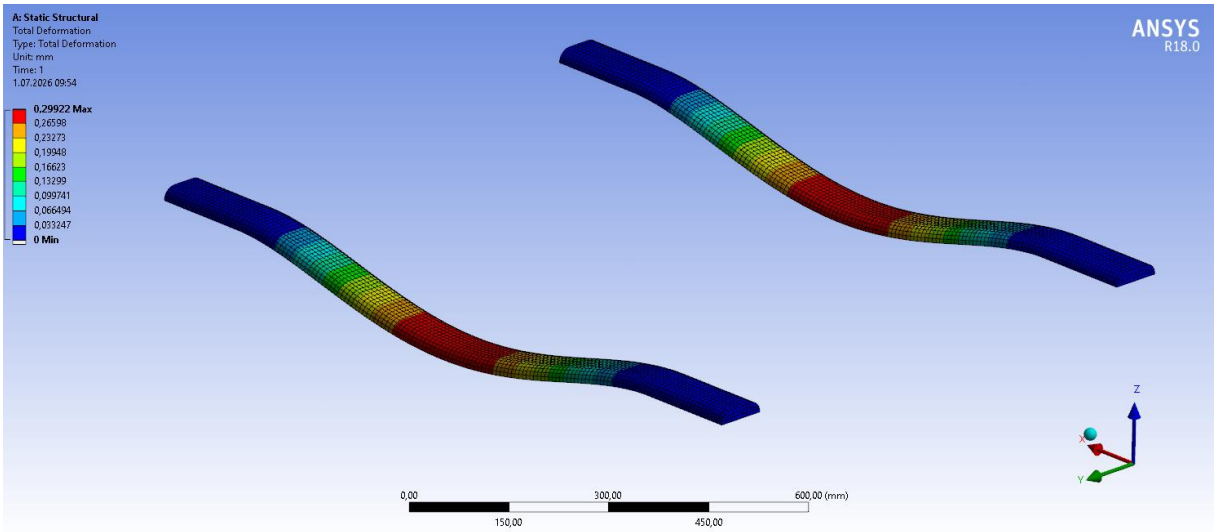

Figure 27. Total deformation value for the 2FD model

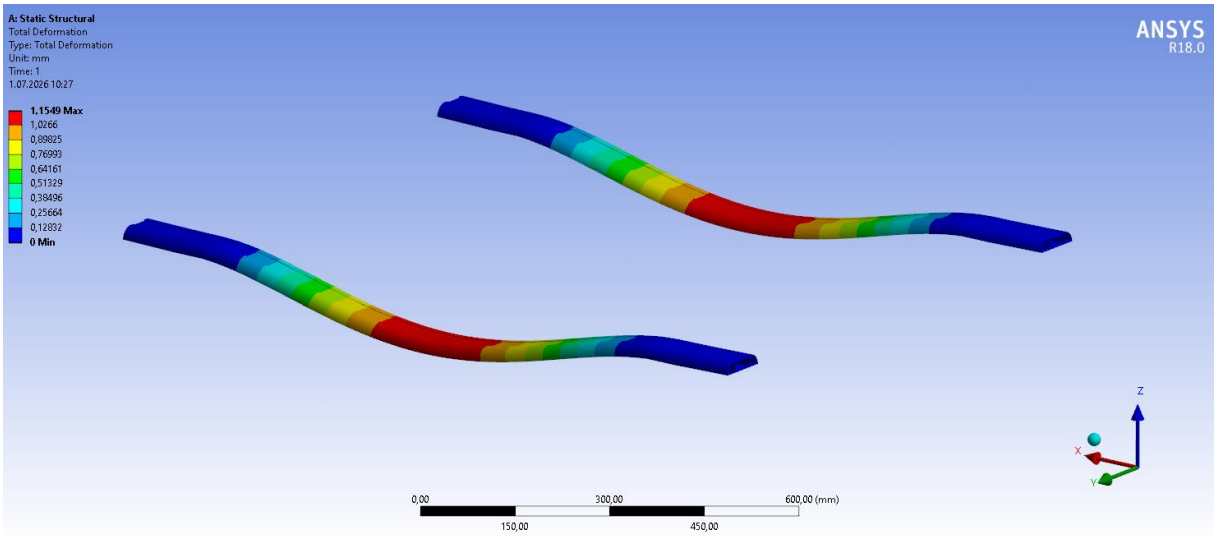

Figure 28. Total deformation value for the 2ED model

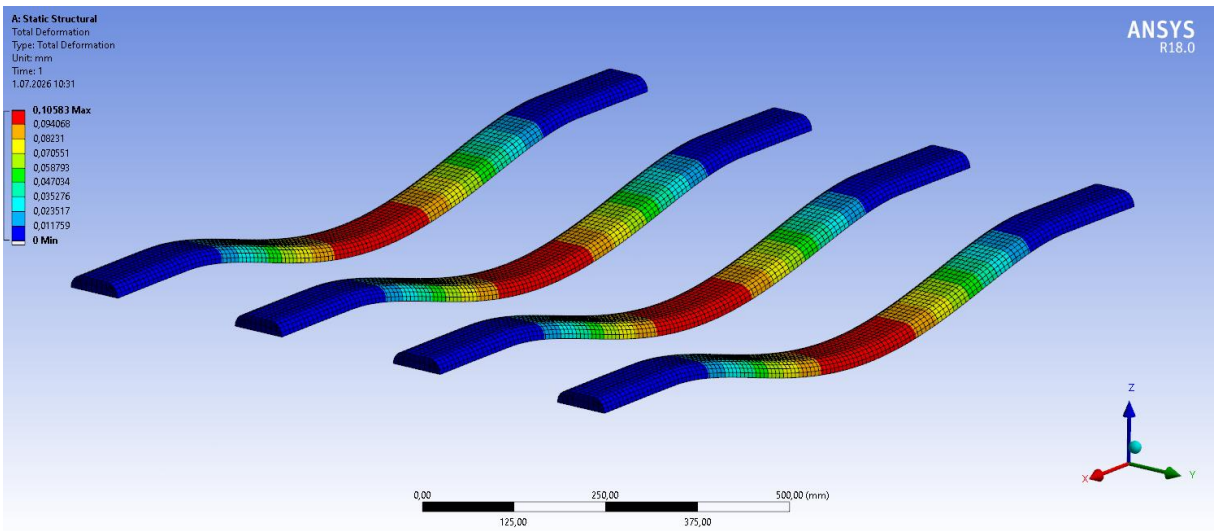

Figure 29. Total deformation value for the 2FD4 model

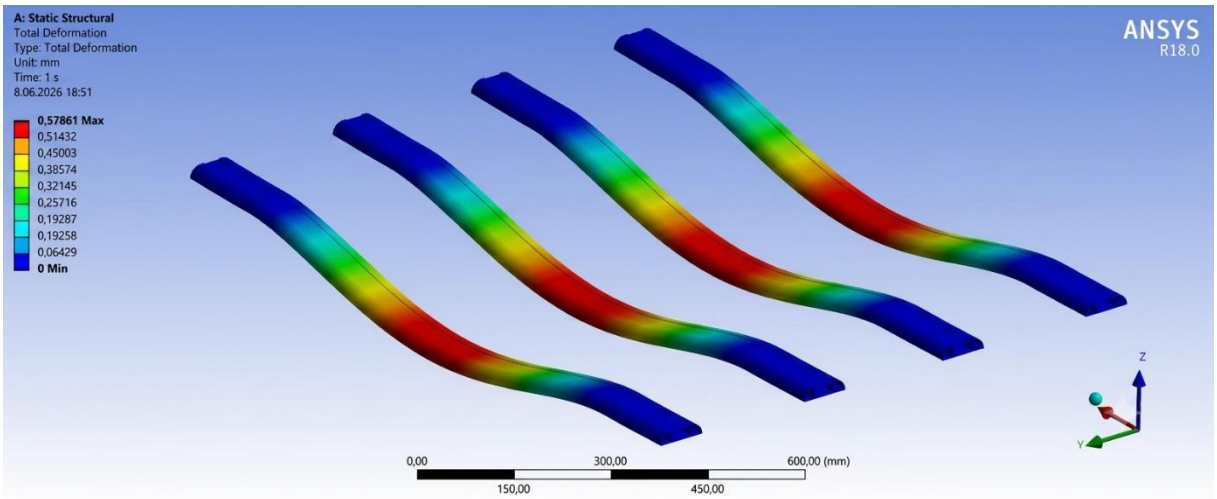

Figure 30. Total deformation value for the 2ED4 model

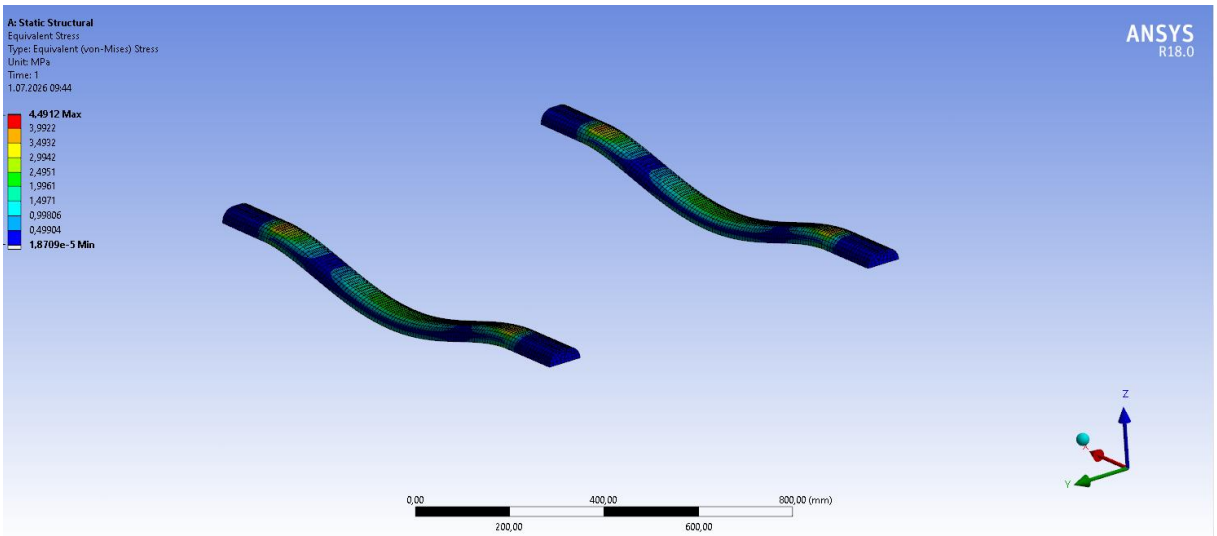

Figure 31. Equivalent von-Mises stress value for the 3FD model

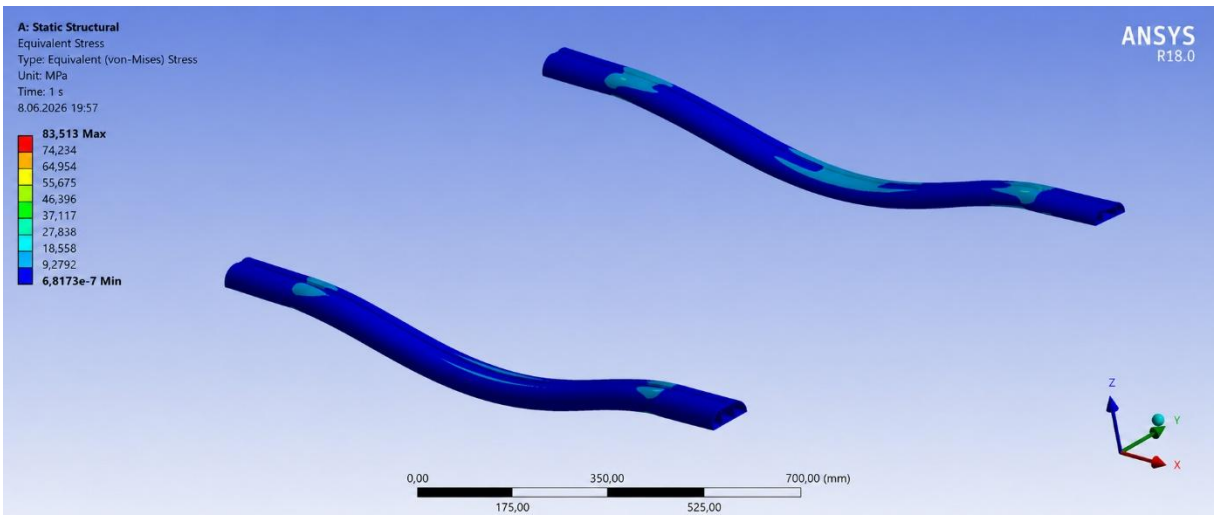

Figure 32. Equivalent von-Mises stress value for the 3ED model

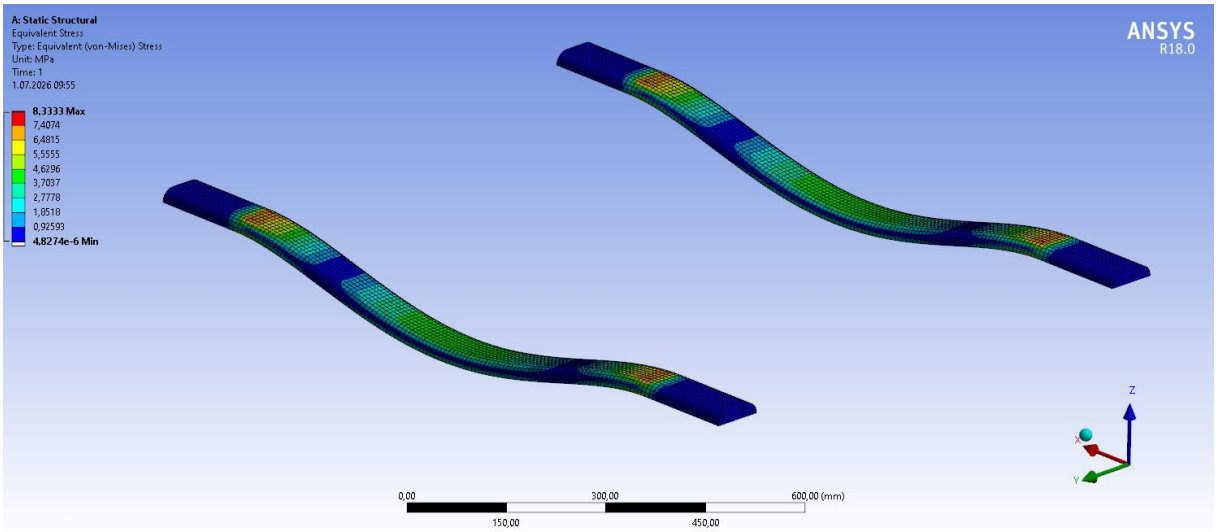

Figure 33. Equivalent von-Mises stress value for the 2FD model

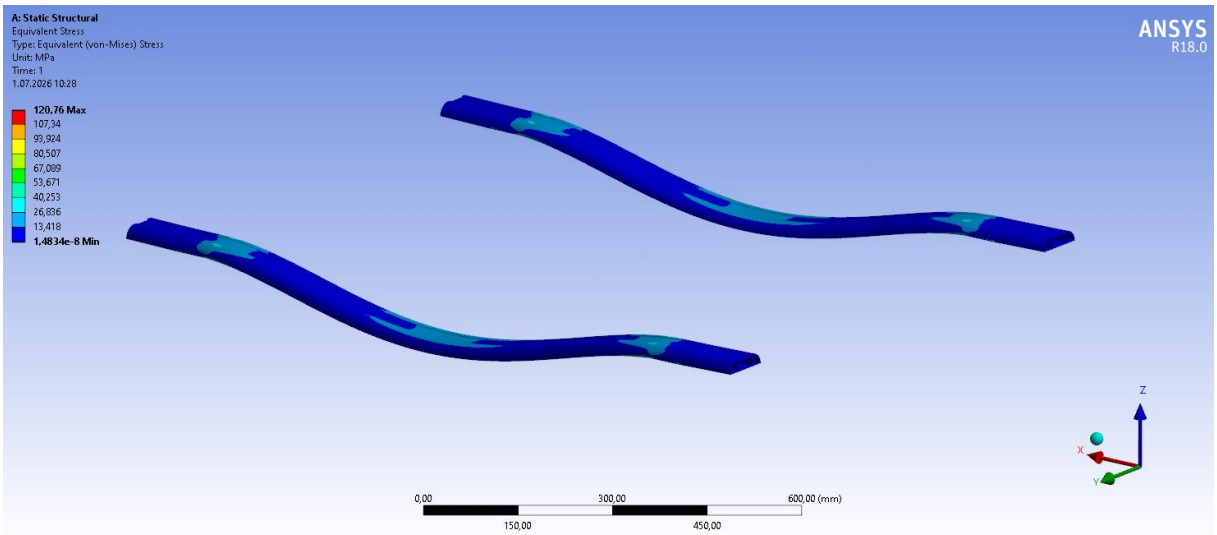

Figure 34. Equivalent von-Mises stress value for the 2ED model

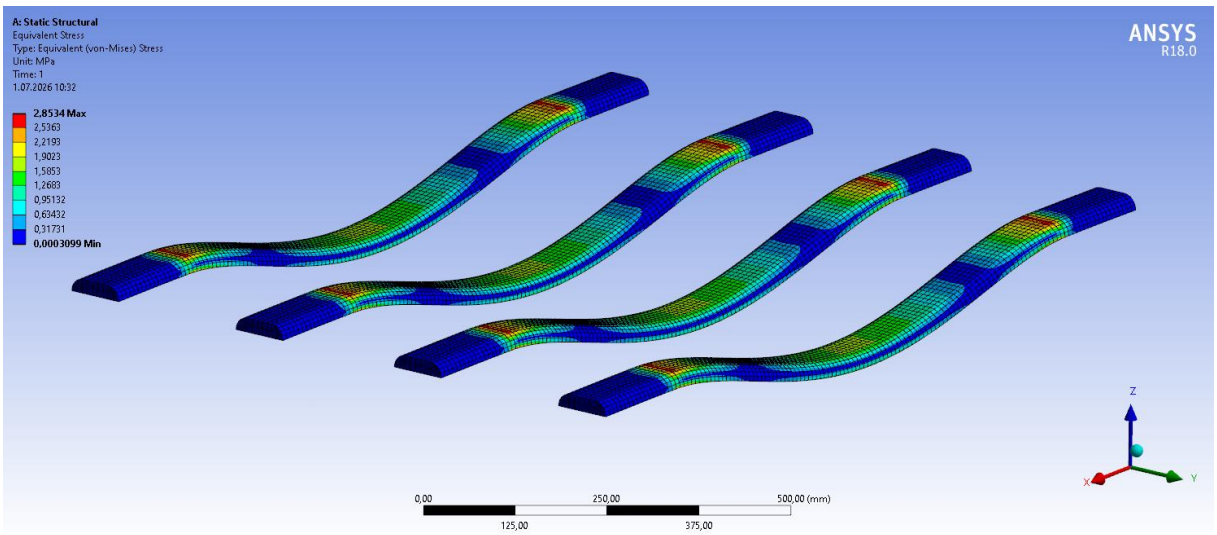

Figure 35. Equivalent von-Mises stress value for the 2FD4 model

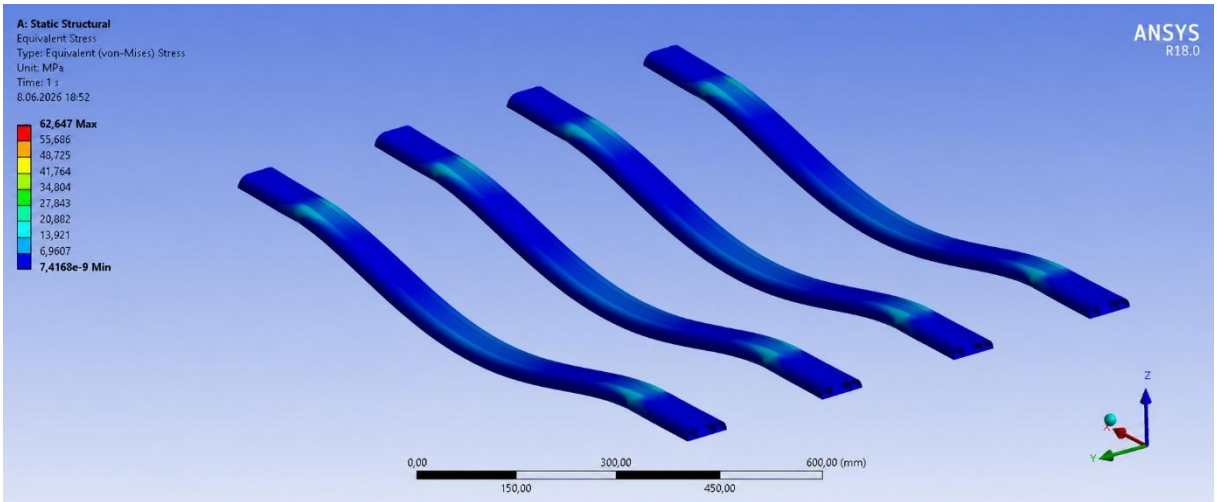

Figure 36. Equivalent von-Mises stress value for the 2ED4 model

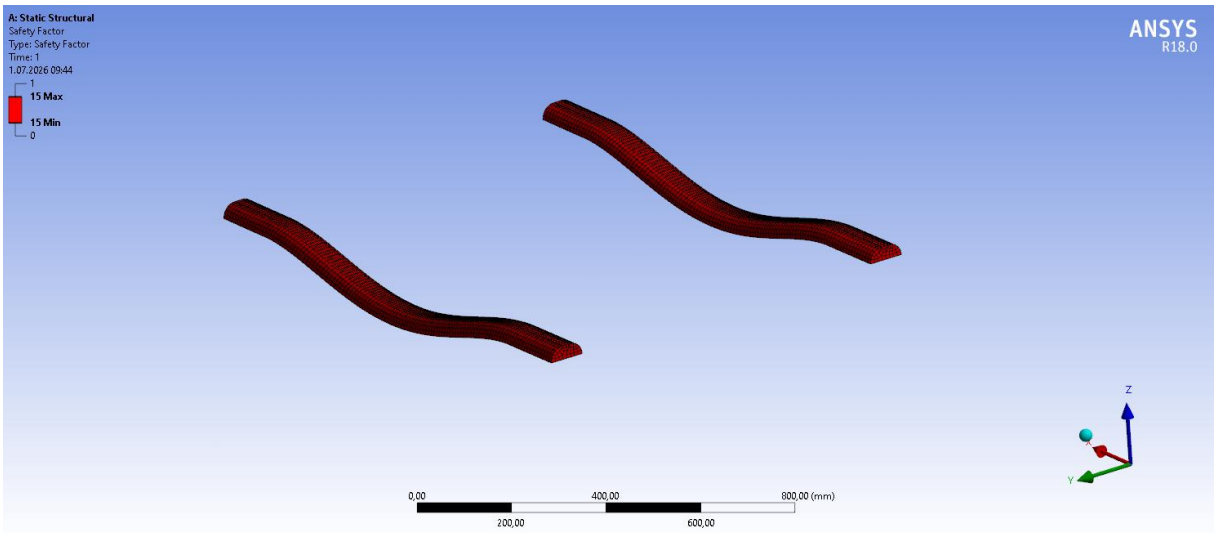

Figure 37. Safety factor value for the 3FD model

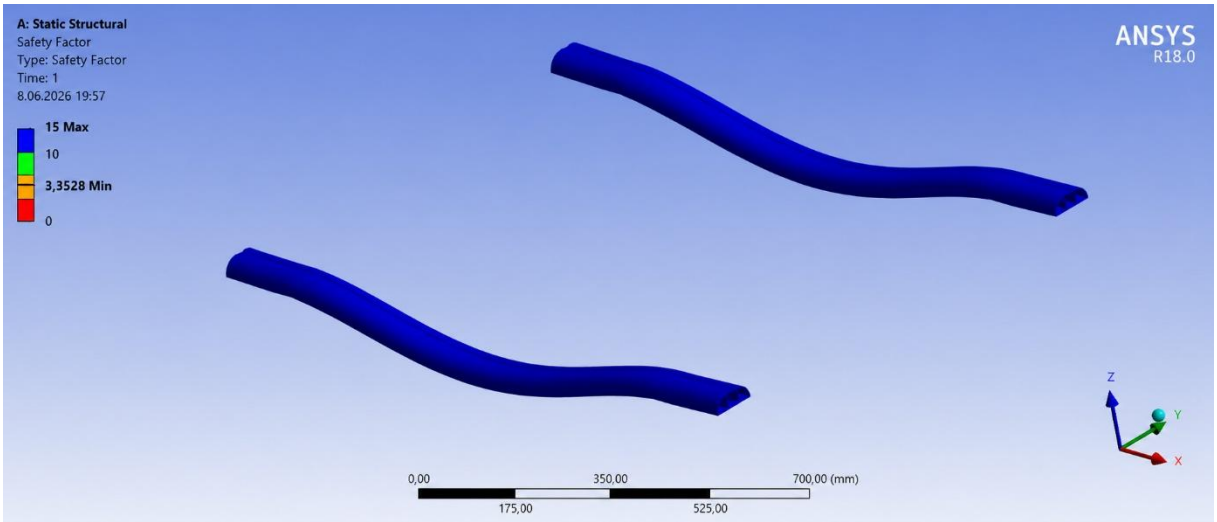

Figure 38. Safety factor value for the 3ED model

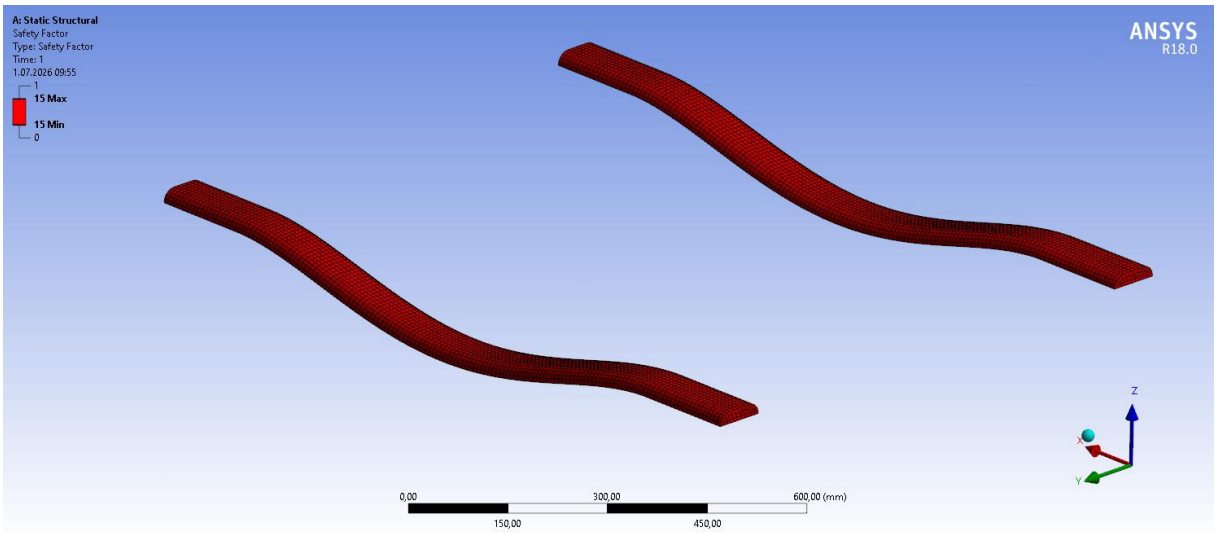

Figure 39. Safety factor value for the 2FD model

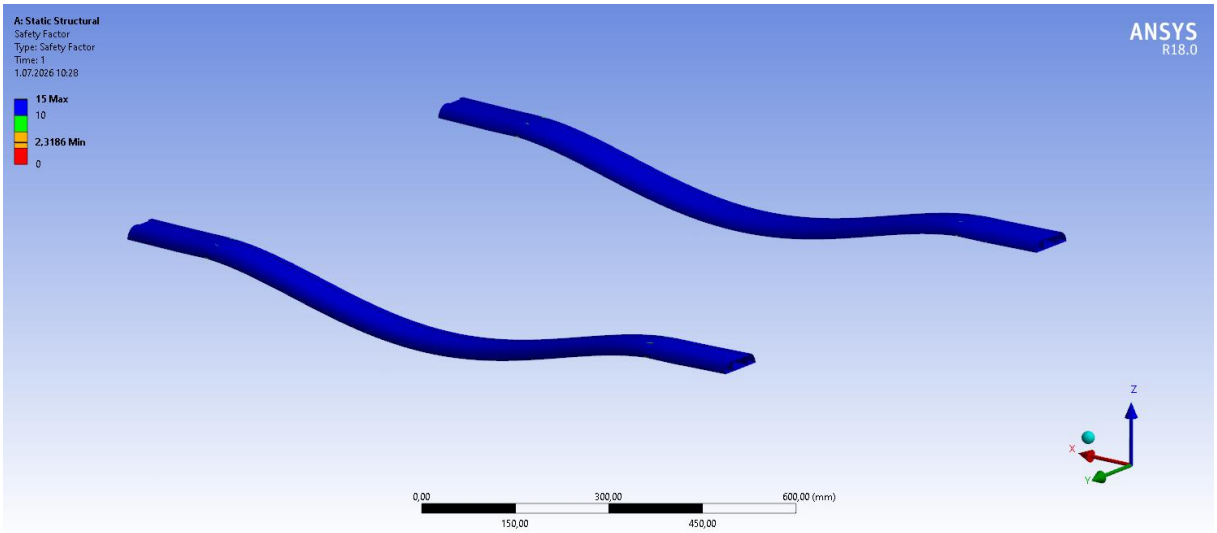

Figure 40. Safety factor value for the 2ED model

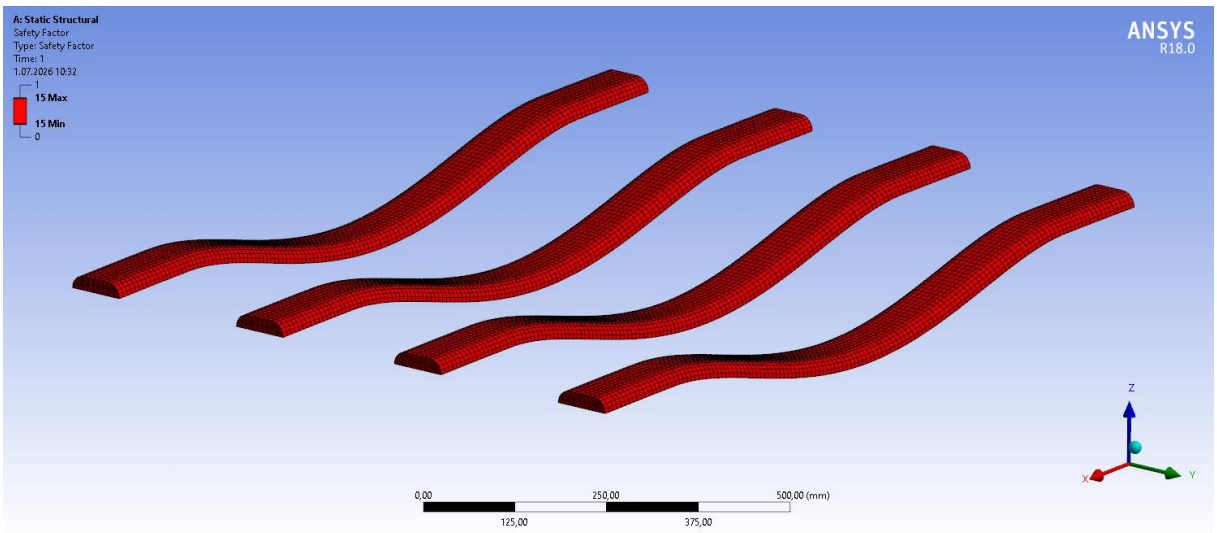

Figure 41. Safety factor value for the 2FD4 model

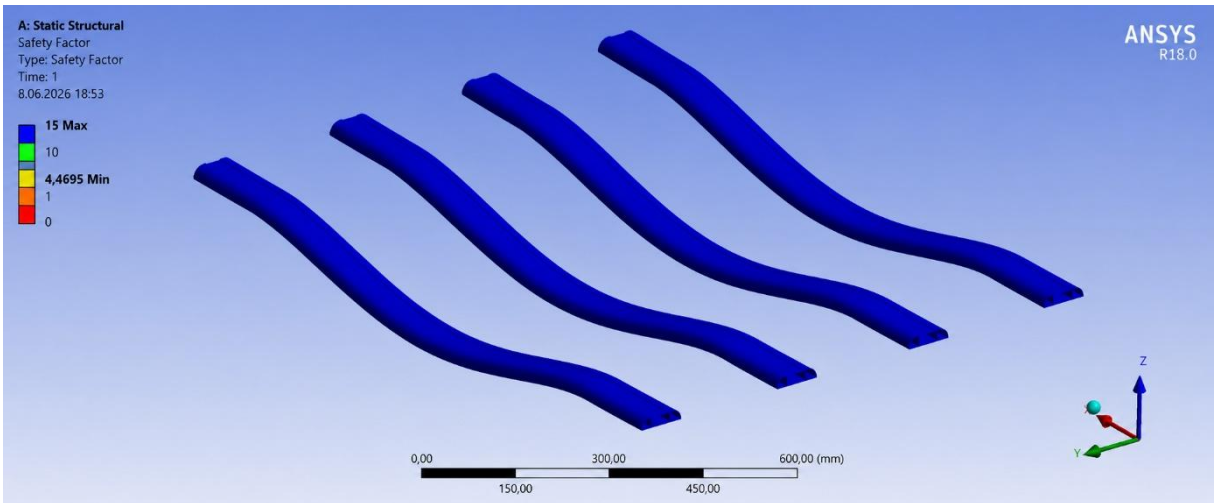

Figure 42. Safety factor value for the 2ED4 model

When the total deformation results were examined, the lowest deformation value was obtained as 0.1035 mm in the 3FD model, while a value quite close to this was determined as 0.1058 mm in the 2FD4 model. The highest deformation occurred in the 2ED model, measuring 1.1549 mm. It is observed that hollow-core designs exhibit greater deformation than solid-core models. The obtained deformation values are within an acceptable level for all models.

According to the equivalent stress results, the lowest stress value was obtained as 2.853 MPa in the 2FD4 model. This is followed by the 3FD (4.491 MPa) and 2FD (8.333 MPa) models, respectively. In hollow-core models, stress values increase significantly. The highest equivalent stress occurred in the 2ED model at 120.76 MPa. In the 3ED and 2ED4 models, values of 83.513 MPa and 62.647 MPa were obtained, respectively. Despite this, the stresses generated in all models remained below the aluminum alloy's yield strength of 280 MPa.

When the safety factors are evaluated, the safety factor is calculated as 15 for the 3FD, 2FD, and 2FD4 models. This indicates that the designs in question possess a very high level of safety under the current loading conditions. The safety factors of the hollow designs were determined as 3.35 for 3ED, 2.32 for 2ED, and 4.47 for 2ED4, respectively. These values specifically demonstrate that the 2ED4 model provides sufficient structural reliability.

Although the 2ED4 model provides lower stress and a higher safety coefficient, it is estimated that material consumption, production, and installation costs will increase due to the two additional connecting legs. A safety factor of 2.3186 indicates that the design maintains structural adequacy under static loading conditions.

DISCUSSION and CONCLUSION

In this study, six models with varying heights, internal structures and numbers of connecting legs for vehicle roof rack connection were examined using finite element analysis. The results showed that the filled-in models gave lower stress and deformation values but had significantly higher weight. Hollow-core models, although they exhibit higher stress and deformation value, offer a significant weight advantage. It was determined that the maximum equivalent stresses formed in all models remained below the yield strength of the aluminum alloy used by 280 MPa and that the designs maintained their structural adequacy under static loading.

Thanks to the use of two connecting legs in the 2ED model, it is estimated that it will provide less material consumption, lower production complexity and lower installation costs compared to models with four connecting legs. For this reason, when light weight, production cost and adequate structural safety criteria are evaluated together, it is concluded that the 2ED model is a suitable and optimal design that can be used in vehicle roof carrier systems.

In future studies, it is proposed to evaluate the performance of the design under real use conditions by conducting dynamic loading, fatigue analysis, and experimental verification.

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OKUL ÖNCESİ DÖNEM ÇOCUKLARININ AKRAN İLİŞKİLERİNİ ETKİLEYEN FAKTÖRLERİN CHAID ANALİZİ İLE İNCELENMESİ

AN EXAMINATION OF FACTORS INFLUENCING PEER RELATIONSHIPS AMONG PRESCHOOL CHİLDREN USING CHAID ANALYSIS

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ÖZET

Bu araştırmanın amacı okul öncesi dönem çocuklarının akran ilişkilerini etkileyen faktörlerin belirlenmesi ve bu faktörlerin önem sırasının ortaya konulmasıdır. Araştırma nicel araştırma yöntemlerinden ilişkisel tarama modeliyle yürütülmüştür. Çalışma grubunu Ankara ili Etimesgut ilçesinde bulunan 2024-2025 eğitim-öğretim yılında okul öncesi eğitim kurumlarında öğrenim gören ve kolay ulaşılabilir örnekleme yöntemiyle seçilen 340 çocuk oluşturmaktadır. Araştırma verileri "Çocuk Bilgi Formu" ve "Okul Öncesinde Akran İlişkileri Ölçeği (öğretmen formu)" kullanılarak toplanmıştır. Araştırmada veri analizi sürecinde sınıflandırma yöntemlerinden biri olan CHAID analizi yöntemi kullanılmıştır. Araştırmadan elde edilen bulgulara göre okul öncesi dönem çocuklarının akran ilişkilerini etkileyen en önemli faktörlerin cinsiyet, yaş, okula devam süresi, günlük ekran kullanım süresi olduğu belirlenmiştir. Araştırma sonuçlarına göre zorba çocuk alt boyutunu etkileyen en önemli faktörün cinsiyet olduğu ve 48-60 aydan büyük kız çocuklarının zorba çocuk düzeyinin düşük olduğu gözlenmiştir. Arkadaşlık ve etkileşim alt boyutunu etkileyen en önemli faktörün okula devam süresi olduğu ve 1 yıldan fazla okula devam eden çocukların arkadaşlık ve etkileşim düzeylerinin daha yüksek olduğu görülmüştür. Mağdur çocuk alt boyutunu etkileyen en önemli faktörün cinsiyet olduğu ve 1-3 saat veya daha az ekran kullanan kız çocuklarının mağdur çocuk düzeylerinin daha düşük olduğu belirlenmiştir. Akran ilişkileri toplamını etkileyen en önemli faktörün cinsiyet olduğu ve 1 yıldan fazla okula devam eden, 1-3 saat veya daha az ekran kullanan erkek çocuklarının akran ilişkisi düzeylerinin daha yüksek olduğu tespit edilmiştir.

Anahtar Kelimeler: Okul öncesi dönem, akran ilişkileri, zorbalık, mağduriyet, arkadaşlık ve etkileşim, CHAID analizi.

ABSTRACT

The purpose of this study is to identify the factors influencing peer relationships among preschool-aged children and to determine the order of importance of these factors. The study was conducted using the correlational survey model, one of the quantitative research methods. The study group consists of 340 children enrolled in preschool education institutions in the Etimesgut district of Ankara during the 2024–2025 academic year, selected using a convenience sampling method. Research data were collected using the "Child Information Form" and the "Preschool Peer Relationships Scale (teacher form)." The CHAID analysis method, one of the classification methods, was used in the data analysis process of the study. According to the findings of the study, the most significant factors influencing peer relationships among preschool-aged children were determined to be gender, age, duration of school attendance, and daily screen time. According to the research results, the most significant factor influencing the "bully" sub-dimension was gender, and it was observed that girls aged 48–60 months had lower levels of bullying behavior. The most significant factor influencing the "friendship and interaction" sub-dimension was duration of school attendance, and it was found that children who had attended school for more than one year had higher levels of friendship and interaction. It was determined that gender is the most significant factor influencing the victimization subscale, and that girls who use screens for 1–3 hours or less have lower levels of victimization. It was also found that gender is the most significant factor influencing the total peer relationship score, and that boys who have been attending school for more than one year and use screens for 1–3 hours or less have higher levels of peer relationships.

Keywords: Preschool years, peer relationships, bullying, victimization, friendship, and social interaction, CHAID analysis.

GİRİŞ

Okul öncesi dönem, çocuğun kişilik gelişiminin temellerinin oluşturulduğu, farklı gelişim alanlarında hızlı ilerlemelerin kaydedildiği, yaşanılan deneyimlerin bireyin hayatında kalıcı izler bıraktığı kritik bir süreçtir (Gülay, 2009). Bu dönemde çocuk ilk sosyal çevresi olan aile ortamının dışına çıkarak okul öncesi eğitim kurumlarında akranlarıyla yoğun ve sürekli etkileşimler kurmaya başlamaktadır (Şahin ve Turan, 2025). Akran ilişkileri, aynı yaş, olgunluk veya gelişim düzeyine sahip olan, ortak geçmişe, değerlere, deneyimlere, yaşam biçimine ve sosyal ortama sahip bireyler arasında devam eden karşılıklı etkileşimlerdir (Avcı, Tan Selçuk ve Kaynak, 2019).

Okul öncesi dönemde akran ilişkileri çocukların paralel oyun döneminden çıkarak iş birlikli oyuna geçiş şeklinde bir ilerleme göstermektedir. Üç yaş civarında artan akran etkileşimleri, dört yaş civarında akran kabulü ve akran reddi deneyimleri ile şekillenmektedir (Ünlüer, 2024). Akran ilişkileri, yakınlık, arkadaşlık, iş birliği, rekabet, çatışma ve uzlaşma gibi birçok boyutu kapsayan bir yapı olmakla birlikte gelişim dönemlerine göre farklı özellikler göstermektedir (Hanish vd., 2023). 3-6 yaş döneminde çocuklar arkadaşlık kurma, arkadaş seçme, grup oyunlarına katılma, sosyal kuralları benimseme, karşılıklı etkileşim sürdürme becerilerinde önemli ilerlemeler kaydetmektedir. Çocuklar akran etkileşimleri sayesinde iletişim yeteneklerini ilerletmekte, farklı bakış açılarını gözlemlemekte ve sosyal sorunları çözme deneyimi elde etmektedir (Akçakır vd., 2024). Küçük çocuklar akran ilişkileri aracılığıyla kendilerini tanıma, sosyal yaşam ve kültürle ilgili önemli tecrübeler kazanmaktadır (Wang, Kajamies, Hurme & Palonen, 2021). Akran ilişkileri çocuğun aidiyet duygusu geliştirmesinde, duygu düzenleme becerileri edinmesinde, iş birliği yapma, empati kurma, sıra bekleme, paylaşma, yardımlaşma ve çatışma çözme gibi sosyal becerilerde ilerlemeler kaydetmesi için önemli bir öğrenme ortamıdır (Rubin, Bukowski & Parker, 2006). Akran ilişkileri sayesinde çocuk duygularını ifade etme, başkasının duygularını fark etme ve anlama, akranının duygusuna uygun şekilde tepki vermeyi öğrenmektedir (Denham vd., 2003). Ayrıca dikkat ve odaklanma becerisinin artması ve neden sonuç ilişkisi kurma becerisinin gelişiminde etkili olmaktadır (Hay, Caplan & Nash 2009). Olumlu akran ilişkileri çocuğun okula adaptasyon sürecini kolaylaştırmakta ve akademik başarısında artış olmasını sağlamaktadır. Akranları tarafından kabul gören çocukların okul ortamına daha kolay uyum sağladığı, etkinliklere daha fazla katılım gösterdiği, sosyal yeterlik düzeylerinin yüksek olduğu görülmüştür (Wentzel, 2017). Buna karşın akran reddi ve mağduriyet yaşayan çocukların davranış problemleri gösterdikleri, psikolojik olarak yalıtılmışlık duygusu yaşadıkları ve öz benlik algılarının olumsuz etkilendiği belirtilmektedir. Bu sebeple olumlu akran ilişkileri çocuğun psikolojik iyi oluşu, özgüven gelişimi ve sosyal uyumu açısından önem arz etmektedir. (Kucaba & Monks, 2022).

Akran ilişkilerinin gelişiminde bireysel, ailesel ve çevresel birçok faktör etkili olmaktadır. Yapılan çalışmalar akran ilişkilerinin yaşla birlikte artış gösterdiği, kız çocuklarının erkek çocuklarına göre daha fazla olumlu ve duyarlı davranışlar sergilediği belirtilmektedir (Beyazkürk, Anlıak, Dinçer, 2007; Toplu, 2022). Literatür incelendiğinde, sosyal beceri düzeyi yüksek olan çocukların olumlu akran ilişkilerine sahip olduğu (Önder ve Gülay Ogelman, 2011); duygu düzenleme becerisi yüksek olan çocukların akran ilişkilerinin de olumlu yönde ilerlediği (Walker, Berthelsen & Irving, 2013); kardeşi olan çocukların akran ilişkilerinde pozitif tutum sergilediği (Durualp ve Aral, 2016); davranış problemi olan çocuklarda davranış problemi arttıkça akran reddi yaşama olasılığının da arttığı (Yılmaz ve Tepeli, 2019); ekran kullanım süresinin artmasının akran ilişkilerini olumsuz yönde etkilediğini (Madigan vd., 2019); ebeveynleri tarafından demokratik tutumla yetiştirilen çocukların olumlu akran ilişkilerinin olduğunu (Pinquart, 2017); akran mağduriyetinin psikolojik iyi oluş ve sosyal uyum üzerinde olumsuz etkisinin olduğunu (Kucaba & Monks, 2022); çocuğun cinsiyeti ve yaşının akran ilişkilerinde sosyal etkileşim boyutunda etkili olduğunu (Göktaş, Gülay Ogelman ve Ok, 2024) belirten çalışmalara rastlanmıştır.

Literatürde okul öncesi dönem çocuklarının akran ilişkilerini inceleyen çok sayıda çalışma bulunmasına karşın, bu araştırmaların büyük çoğunluğunda akran ilişkilerinin belirli değişkenler ile ilişkisi incelenmiş ve genellikle korelasyon, regresyon ya da grup karşılaştırmalarını içeren analizler kullanılmıştır. Akran ilişkilerini etkileyen faktörlerin önem sırasını ortaya koyan ve değişkenler arası etkileşimleri birlikte değerlendiren çalışmaların sınırlı olduğu tespit edilmiştir.

Özellikle aynı çalışmada akran ilişkileri üzerinde cinsiyet, yaş, kardeş sayısı, doğum sırası, bedensel veya ruhsal rahatsızlığa sahip olma durumu, okula devam süresi, ekran kullanım süresi gibi güncel ve gelişimsel yönden önemli faktörlerin birlikte incelendiği ve önem sırasının ortaya çıkarıldığı çalışmalara

rastlanmamıştır. Bu araştırma okul öncesi dönem çocuklarının toplam akran ilişkilerini ve akran ilişkilerinin alt boyutlarını CHAID analizi ile inceleyerek hangi değişkenlerin hangi durumlarda daha belirleyici olduğunu ortaya koyması açısından mevcut çalışmalardan ayrılmaktadır. Bu çalışma CHAID analizi sayesinde çocukların akran ilişkilerini etkileyen faktörlerin etkileşimli yapısını ortaya koyması bakımından özgün ve önemlidir. Ayrıca araştırmada arkadaşlık ve etkileşim, zorba çocuk ve mağdur çocuk gibi akran ilişkilerinin farklı boyutları ayrı ayrı incelenerek risk ve koruyucu faktörlerin tespit edilmesi, erken müdahale programlarının geliştirilmesine ve okul öncesi eğitimi uygulamalarına katkı sağlayacaktır. Bu kapsamda araştırmada okul öncesi dönem çocuklarının akran ilişkilerini etkileyen faktörlerin tespit edilmesi amaçlanmıştır. Bu genel amaç doğrultusunda çalışmanın alt amaçları şu şekilde sıralanmıştır:

- Okul öncesi dönem çocuklarının zorba çocuk düzeylerini etkileyen en önemli değişkenler nelerdir?
- Okul öncesi dönem çocuklarının arkadaşlık ve etkileşim düzeylerini etkileyen en önemli değişkenler nelerdir?
- Okul öncesi dönem çocuklarının mağdur çocuk düzeylerini etkileyen en önemli değişkenler nelerdir?
- Okul öncesi dönem çocuklarının toplam akran ilişkisi düzeylerini etkileyen en önemli değişkenler nelerdir?

YÖNTEM

Bu bölümde araştırma modeli, çalışma grubu, veri toplama araçları, verilerin toplanması ve analizi başlıklarına yer verilmiştir.

Araştırmanın Modeli

Araştırmada okul öncesi dönem çocuklarının akran ilişkilerini etkileyen faktörleri belirlemek amacıyla nicel araştırma yöntemlerinden ilişkisel tarama modeli kullanılmıştır. İlişkisel tarama modeli, birden çok değişken arasındaki ilişkinin olup olmadığını ve yönünü tespit etmek amacıyla tercih edilen bir araştırma modelidir (Karasar, 2012). Araştırmada akran ilişkileri ile çeşitli değişkenler arasındaki ilişkiler incelenmiş ve bu değişkenlerin akran ilişkileri üzerindeki göreli önem sırası ortaya çıkarılmaya çalışılmıştır.

Çalışma Grubu

Araştırmanın çalışma grubunu 2024-2025 eğitim-öğretim yılında Ankara ili Etimesgut ilçesinde bulunan resmi anaokulu ve anasınıflarında eğitim gören basit seçkisiz örnekleme yöntemiyle seçilen 340 çocuk oluşturmaktadır. Çalışma grubunda bulunan çocuklara ait demografik veriler Tablo 1'de gösterilmiştir.

Tablo 1:Çalışma Grubundaki Çocuklara İlişkin Demografik Bilgilerin Dağılımı

Değişken	Grup	Frekans (f)	%
Cinsiyet	Kız	190	55,9
	Erkek	150	44,1
Yaş	37-47 ay	56	16,4
	48-60 ay	142	41,8
	61-72 ay	142	41,8
Kardeş Sayısı	Tek çocuk	92	27,1
	1 kardeşi var	196	57,6
	2 kardeşi var	38	11,2
	3 ve daha fazla kardeşi var	14	4,1
Doğum Sırası	İlk çocuk	164	48,2
	İkinci çocuk	124	36,5
	Üçüncü ve daha sonraki çocuk	52	15,3

Bedensel veya Ruhsal Rahatsızlığı Olma Durumu	Evet	12	3,5
	Hayır	328	96,5
Okula Devam Süresi	1 yıldan az	148	43,5
	1-2 yıl arası	140	41,2
	2 yıldan fazla	52	15,3
Günlük Ekran Kullanım Süresi	1 saatten az	126	37,1
	1-3 saat arası	160	47,1
	3-5 saat arası	47	13,8
	5 saat üzeri	7	2,1

Tablo 1'e göre çocukların %55,9'u kız, %44,1'i erkektir. Çocukların yaşları incelendiğinde %16,4 oranında 3-4 yaş, %41,8 oranında 4-5 yaş ve 5-6 yaş aralığında çocuk bulunmaktadır. Çocukların %27,1'i tek çocuk, %57,6'sının 1 kardeşi, %11,2'sinin 2 kardeşi, %4,1'inin 3 ve daha fazla kardeşi bulunmaktadır. Çocukların %48,2'si ilk sırada, %36,5'i ikinci sırada, %15,3'ü üçüncü ve daha sonraki sırada doğmuştur. Çocukların %3,5'i bedensel veya ruhsal rahatsızlığa sahipken, %96,5'inin herhangi bir rahatsızlığı bulunmamaktadır. Çocukların okul öncesi eğitimi alma sürelerinde %43,5'i 1 yıldan az süredir, %41,2'si 1-2 yıl arası, %15,3'ü 2 yıldan fazla süredir okul öncesi eğitim almaktadır. Çocukların ekran kullanım süresi incelendiğinde %37,1'i 1 saatten az, %47,1'i 1-3 saat arası, %13,8'i 3-5 saat arası, %2,1'i 5 saat üzerinde ekran kullandıkları görülmektedir.

Veri Toplama Araçları

Bu araştırmada çocukların demografik bilgilerine ulaşmak için çocuk bilgi formu kullanılmıştır. Araştırmacı tarafından oluşturulan çocuk bilgi formu, çocuğun cinsiyeti, yaşı, kardeş sayısı, doğum sırası, bedensel veya ruhsal rahatsızlığa sahip olma durumu, okula devam süresi ve ekran kullanım süresi olmak üzere 7 maddeden oluşmaktadır.

Araştırmada çocukların akran ilişkilerini değerlendirmek amacıyla "Okul Öncesinde Akran İlişkileri Ölçeği" kullanılmıştır. Kanmaz ve Tezel Şahin (2022) tarafından geliştirilen ölçme aracının geliştirilme sürecinde gerçekleştirilen açıklayıcı ve doğrulayıcı faktör analizi neticesinde öğretmen formu zorba çocuk, arkadaşlık ve etkileşim (sosyal etkileşim), mağdur çocuk şeklinde 3 alt boyuttan ve 37 madde olarak tasarlanmıştır. Öğretmen formunun güvenirlik analizleri sonucunda Cronbach alfa değeri ölçek toplamı için 0,97 olarak belirlenirken; zorba çocuk alt boyutu için 0,98, arkadaşlık ve etkileşim alt boyutu için 0,97, mağdur çocuk alt boyutu için 0,97 olarak tespit edilmiştir (Kanmaz ve Tezel Şahin, 2022).

Verilerin Toplanması ve Analizi

Araştırma verileri toplanmadan önce etik kurul onayı alınmış ve araştırmanın yürütüleceği okulların belirlenmesi ve çalışmanın yapılabilmesi için Milli Eğitim Bakanlığı'ndan gerekli izin alınmıştır. Çalışma grubunda bulunan okulların müdürlerine gerekli bilgilendirme yapıldıktan sonra araştırmaya katılmaya gönüllü olan öğretmenlere ölçekler dağıtılarak doldurmaları istenmiştir.

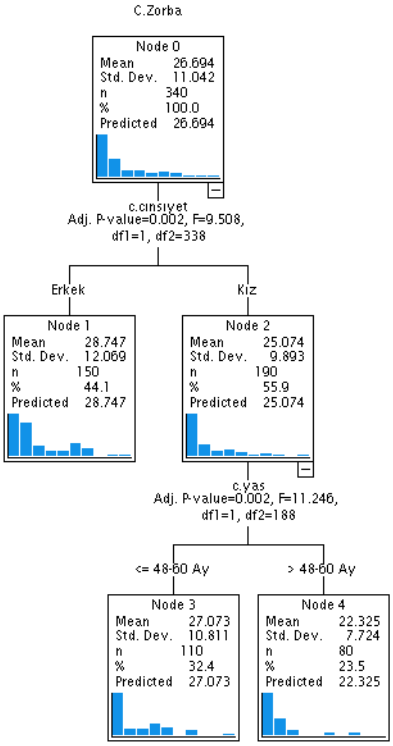
Araştırma verilerinin analiz edilmesinden önce veri setindeki kayıp değer ve uç değer bakımından değerlendirmeler yapılmış ve herhangi bir kayıp değer bulunamamıştır. Daha sonra sınıflandırma yöntemlerinden biri olan CHAID (Chi-squared Automatic Interaction Detector) analizi uygulanmıştır. CHAID, sınıflandırma ve tahmin yöntemleri kapsamında kullanılan karar ağacı tekniklerinden biri olup, karmaşık veri yapılarını daha sistematik ve yorumlanabilir şekle dönüştürmektedir.

Karar ağaçları, geniş veri setlerini belirli karar kuralları açısından alt gruplara ayırarak verilerin daha kolay yorumlanabilir biçimde değerlendirilmesine imkan sağlamaktadır (Ulgen, 2017). Birden fazla değişkenin yer aldığı büyük veri setleri, CHAID analizi sayesinde özetlenebilmekte, bağımlı değişkeni etkileyen en önemli faktör belirlenebilmekte ve değişkenler arasındaki önem sırası belirlenebilmektedir. Ayrıca güvenilir ölçümler sağlarken değişkenlerdeki kayıp verileri tahmin etme ve modeldeki etkisini tespit edebilme açısından etkilidir (Pehlivan, 2006; Şata, 2015). Bu araştırmada akran ilişkileri ölçeği alt boyutları ve ölçek toplamı bağımlı değişken olarak belirlenirken, çocuğun cinsiyeti, yaşı, kardeş sayısı, doğum sırası, bedensel/ruhsal rahatsızlığı olma durumu, okula devam süresi, gün içerisindeki ekran kullanım süresi bağımsız değişken olarak belirlenmiştir. Verilerin analizinde 0,05 anlamlılık değeri olarak belirlenmiştir.

BULGULAR

Okul öncesi dönem çocuklarının zorba çocuk düzeylerini etkileyen faktörlerin belirlenmesi amacıyla yapılan CHAID analizinde maksimum ağaç derinliği 3, minimum örneklem sayısı üst düğümde 30 ve alt düğümde 15 olarak belirlenmiştir. Veri analizi sonucunda 3 düzeyli ve 5 düğümden oluşan ağaç yapısı Şekil 1'de verilmiştir.

Şekil 1. Çocukların Zorba Çocuk Düzeyini Etkileyen Faktörlere Yönelik Karar Ağacı

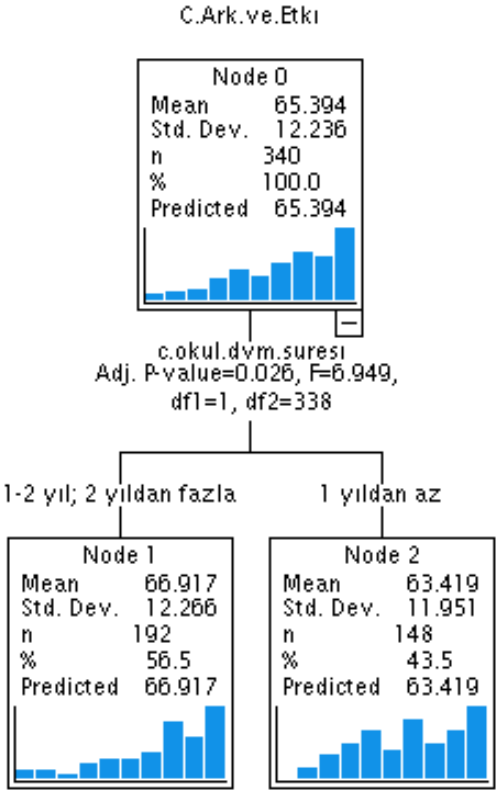


Şekil 1 incelendiğinde çocukların zorba çocuk düzeylerini etkileyen en önemli değişken cinsiyettir ve çocukların zorba çocuk düzeyleri cinsiyet değişkenine göre belirgin düzeyde farklılık göstermektedir (F=9,508; p=0,002). Erkek çocuklarının zorba çocuk puanı 28,747 iken, kız çocuklarının zorba çocuk puanı 25,074'tür. Araştırmanın bu bulgusuna göre erkek çocuklarının zorba çocuk düzeyi kız çocuklardan yüksektir.

Kız çocuklarının zorba çocuk düzeylerini etkileyen en önemli değişken yaş grubudur ve çocukların zorba çocuk düzeyleri yaş grubuna göre belirgin düzeyde farklılık göstermektedir (F=11,246; p=0,002). CHAID analizine göre kız çocuklarının yaşları 48-60 ay veya daha küçük, 48-60 aydan büyük olmak üzere iki gruba ayrılmıştır. 48-60 ay veya daha küçük kız çocuklarının zorba çocuk puanı 27,073 iken, 48-60 aydan büyük kız çocuklarının zorba çocuk puanları 22,325'tir. Bu bulgu, 48-60 aydan büyük kız çocuklarının zorba çocuk düzeylerinin düşük olduğunu göstermektedir.

Okul öncesi dönem çocuklarının arkadaşlık ve etkileşim düzeylerini etkileyen faktörlerin belirlenmesi amacıyla yapılan CHAID analizinde maksimum ağaç derinliği 3, minimum örneklem sayısı üst düğümde 50 ve alt düğümde 25 olarak belirlenmiştir. Veri analizi sonucunda 2 düzeyli ve 3 düğümden oluşan ağaç yapısı Şekil 2'de verilmiştir.

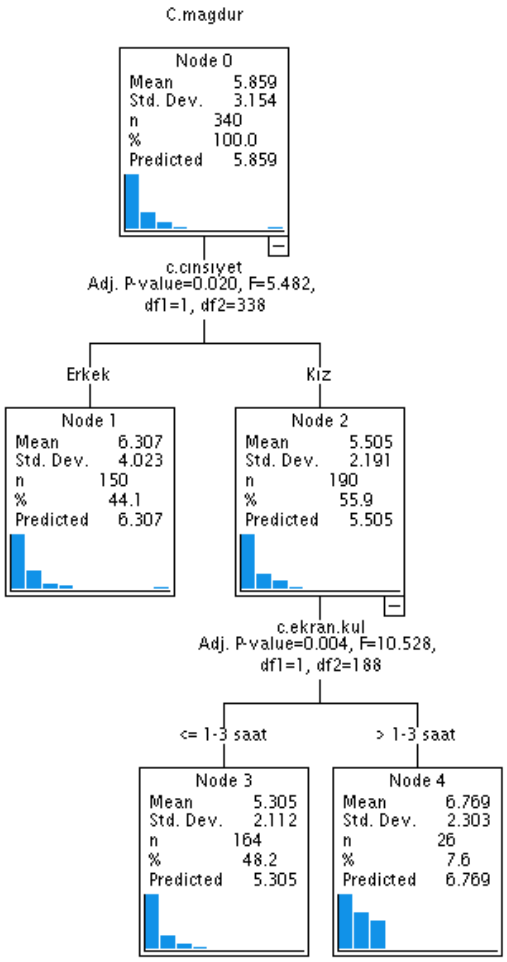
Şekil 2. Çocukların Arkadaşlık ve Etkileşim Düzeyini Etkileyen Faktörlere Yönelik Karar Ağacı



Şekil 2'ye göre çocukların arkadaşlık ve etkileşim düzeylerini etkileyen en önemli değişken okula devam süresidir ve çocukların arkadaşlık ve etkileşim düzeyleri okula devam süresine göre belirgin düzeyde farklılık göstermektedir (F=6,949; p=0,026). CHAID analizi okula devam süresine göre 1 yıldan az ve 1-2 yıl veya 2 yıldan fazla olmak üzere iki gruba ayırmıştır. 1 yıldan az okula devam eden çocukların arkadaşlık ve etkileşim puanları 63,419 iken, 1 yıldan fazla okula devam eden çocukların arkadaşlık ve etkileşim puanı 66,917'dir. Bu durum 1 yıldan fazla okula devam eden çocukların 1 yıldan az okula devam eden çocuklara göre arkadaşlık ve etkileşim düzeylerinin daha yüksek olduğunu göstermektedir.

Okul öncesi dönem çocuklarının mağdur çocuk düzeylerini etkileyen faktörlerin belirlenmesi amacıyla yapılan CHAID analizinde maksimum ağaç derinliği 3, minimum örneklem sayısı üst düğümde 30 ve alt düğümde 15 olarak belirlenmiştir. Veri analizi sonucunda 3 düzeyli ve 5 düğümden oluşan ağaç yapısı Şekil 3' de verilmiştir.

Şekil 3. Çocukların Mağdur Çocuk Düzeyini Etkileyen Faktörlere Yönelik Karar Ağacı

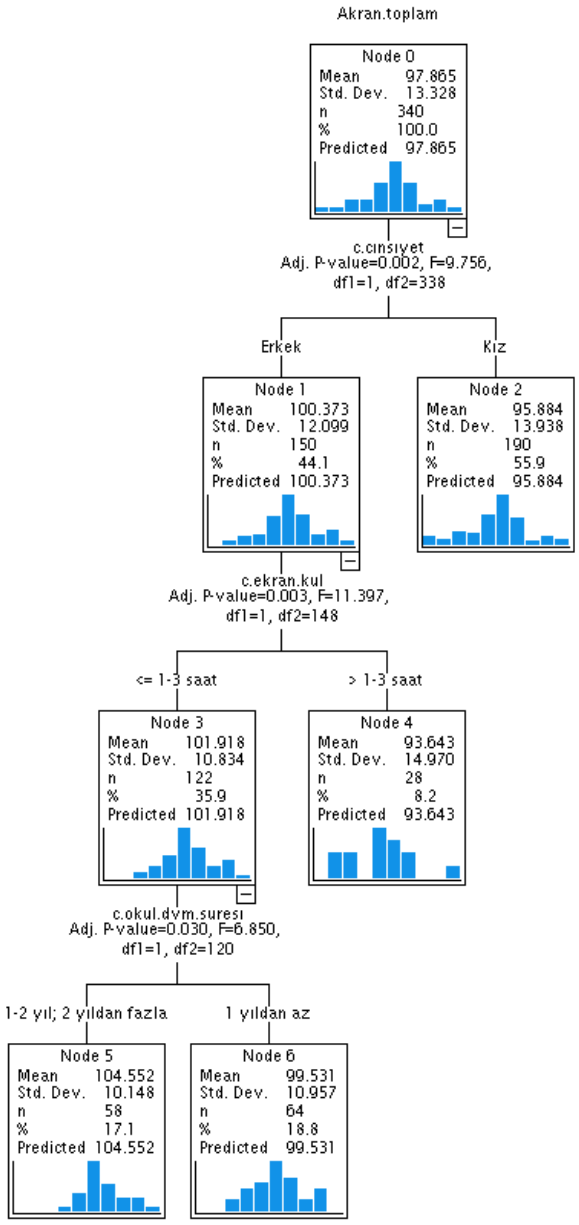


Şekil 3 incelendiğinde çocukların mağdur çocuk düzeylerini etkileyen en önemli değişken cinsiyettir ve çocukların mağdur çocuk düzeyleri cinsiyete göre belirgin düzeyde farklılık göstermektedir (F=5,482; p=0,020). Erkek çocuklarının mağdur çocuk puanı 6,307 iken, kız çocuklarının mağdur çocuk puanı 5,505'tir. Araştırmanın bu bulgusuna göre erkek çocuklarının mağdur çocuk düzeyi kız çocuklardan yüksektir.

Kız çocuklarının mağdur çocuk düzeylerini etkileyen en önemli değişken günlük ekran kullanım süresidir ve çocukların mağdur çocuk düzeyleri günlük ekran kullanım süresine göre belirgin düzeyde farklılık göstermektedir (F=10,528; p=0,004). CHAID analizine göre kız çocuklarının günlük ekran kullanım süresi 1-3 saat veya daha az, 1-3 saatten fazla olmak üzere iki gruba ayrılmıştır. 1-3 saat veya daha az ekran kullanan çocukların mağdur çocuk puanları 5,305 iken, 1-3 saatten fazla ekran kullanan çocukların mağdur çocuk puanları 6,769'dur. Bu durum 1-3 saat veya daha az ekran kullanan kız çocuklarının mağdur çocuk düzeylerinin düşük olduğunu göstermektedir.

Okul öncesi dönem çocuklarının akran ilişkisi düzeylerini etkileyen faktörlerin belirlenmesi amacıyla yapılan CHAID analizinde maksimum ağaç derinliği 3, minimum örneklem sayısı üst düğümde 30 ve alt düğümde 15 olarak belirlenmiştir. Veri analizi sonucunda 4 düzeyli ve 7 düğümden oluşan ağaç yapısı Şekil 4' de verilmiştir.

Şekil 4. Çocukların Akran İlişkisi Düzeyini Etkileyen Faktörlere Yönelik Karar Ağacı



Şekil 4 incelendiğinde çocukların akran ilişkisi düzeylerini etkileyen en önemli değişken cinsiyettir ve çocukların akran ilişkisi düzeyleri cinsiyete göre belirgin düzeyde farklılık göstermektedir (F=9,756; p=0,002). Erkek çocuklarının akran ilişkisi puanı 100,373 iken, kız çocuklarının akran ilişkisi puanı 95,884'tür. Araştırmanın bu bulgusuna göre erkek çocuklarının akran ilişkisi düzeyi kız çocukların akran ilişkisi düzeyinden yüksektir.

Erkek çocuklarının akran ilişkisi düzeylerini etkileyen en önemli değişken günlük ekran kullanım süresidir ve çocukların akran ilişkisi düzeyleri günlük ekran kullanım süresine göre belirgin düzeyde farklılık göstermektedir (F=11,397; p=0,003). CHAID analizine göre erkek çocuklarının günlük ekran kullanım süresi 1-3 saat veya daha az, 1-3 saatten fazla olmak üzere iki gruba ayrılmıştır. 1-3 saat veya daha az ekran kullanan erkek çocuklarının akran ilişkisi puanı 101,918 iken, 1-3 saatten fazla ekran kullanan erkek çocuklarının akran ilişkisi puanı 93,643'tür.

Bu durum 1-3 saat veya daha az ekran kullanan erkek çocuklarının akran ilişkisi düzeylerinin 1-3 saatten fazla ekran kullanan erkek çocuklarına göre daha yüksek olduğunu göstermektedir.

1-3 saat veya daha az ekran kullanan erkek çocuklarının akran ilişkisi düzeylerini etkileyen en önemli faktör okula devam süresidir ve akran ilişkisi düzeyleri okula devam süresine göre belirgin düzeyde farklılık göstermektedir (F=6,850; p=0,030). CHAID analizi okula devam süresine göre 1 yıldan az, 1-2 yıl veya 2 yıldan fazla olmak üzere iki gruba ayırmıştır. 1 yıldan az okula devam eden çocukların akran ilişkisi puanı 99,531 iken, 1 yıldan fazla okula devam eden çocukların akran ilişkisi puanı 104,552'dir. Bu durum 1 yıldan fazla okula devam eden çocukların 1 yıldan az okula devam eden çocuklara göre akran ilişkisi düzeylerinin yüksek olduğunu göstermektedir. Bu bulgu sonucunda 1 yıldan fazla okula devam eden, 1-3 saat veya daha az ekran kullanan erkek çocuklarının akran ilişkisi düzeylerinin yüksek olduğu saptanmıştır.

TARTIŞMA, SONUÇ VE ÖNERİLER

Okul öncesi dönem çocuklarının akran ilişkilerini etkileyen değişkenlerin belirlenmesi ve bu değişkenleri önem sırasına göre ortaya çıkarmak amacıyla yapılan bu çalışmada, akran ilişkileri ölçeğinin alt boyutları ve ölçek toplamı kapsamında değerlendirilmiştir.

Araştırmanın bulgusuna göre çocukların zorba çocuk düzeylerini etkileyen en önemli faktörün cinsiyet olduğu saptanmıştır. Erkek çocuklarının zorba çocuk puanları kız çocuklarının puanlarından daha yüksektir. Erkek çocuklarının zorba çocuk puanlarının yüksek çıkmasında toplumsal cinsiyet rolleri açısından erkek çocuklarının güç, rekabet, hakimiyet gibi davranışlarla ilişkilendirilmesi, kız ve erkek çocuklarının yetiştirilme tarzındaki farklılık, akran grupları arasında liderlik ve güçlü olma isteğinin yüksek olması, erkeklerin vurma, ütme, tekmeleme gibi fiziksel saldırganlığa daha yatkın olmaları etkili olabilir. Yapılan çalışmalar araştırmanın bulgusuna paralel olarak erkek çocuklarının zorbalık veya saldırgan davranışlar sergileme düzeylerinin kız çocuklardan daha yüksek olduğunu belirtmektedir (Hanish, Hill, Gosney & Fabes, 2010; Ertürk Kara ve Gürgen, 2016; Avcı, Selçuk & Kaynak, 2019).Araştırmada kız çocuklarının zorba çocuk düzeylerini etkileyen en önemli değişkenin yaş grubu olduğu ve 48-60 aydan büyük kız çocuklarının zorbalık puanlarının düşük düzeyde olduğu, yaş arttıkça zorbalık düzeylerinin düştüğü görülmüştür. Bu durumun oluşmasında gelişimsel açıdan küçük yaş grubundaki çocukların daha dürtüsel davrandığı ancak yaş ilerledikçe dürtü kontrolü, kurallara uyöa gibi davranışların daha fazla artması etkili olabilir. Bunun yanı sıra çocukların yaşları ilerledikçe iş birliği yapma, empati kurma, sosyal problem çözme becerileri gelişmektedir ve bu durumun zorbalık davranışlarının azalmasına katkı sağladığı düşünülmektedir. Yapılan çalışmalar yaşın ilerlemesiyle birlikte zorbalık davranışlarının azaldığı bulgusunu desteklemektedir (Özözen-Danacı ve Çetin, 2019; Ateş, 2022).Araştırmada çocukların arkadaşlık ve etkileşim düzeylerini etkileyen en önemli değişkenin okula devam süresi olduğu ve 1 yıldan fazla okula devam eden çocukların 1 yıldan az okula devam eden çocuklara göre arkadaşlık ve etkileşim düzeylerinin daha yüksek olduğu görülmüştür. Bu sonuç okul öncesi eğimin çocukların sosyal gelişimlerine katkı sağladığını ve arkadaşlık ilişkilerini güçlendirdiğini göstermektedir. Çocuklar okul öncesi eğitim kurumlarında iş birliği yapma, paylaşma ve yardımlaşma, iletişim kurma, çatışma çözme gibi birçok sosyal beceriyi deneyimleme fırsatı elde ederler. Okula devam süresi arttıkça çocukların sınıf ve okul kurallarına uyum sağlaması kolaylaşmakta, akran grubuna dahil olma ve sosyal ilişkilerini güçlendirme becerisi gelişmektedir.

Literatür incelendiğinde araştırma bulgusuna paralel olarak, okul öncesi eğitime devam süresinin artmasının çocukların akran ilişkilerinde sosyal uyum ve düzenleyici beceriler ile ilişkili olduğunu (Acar vd., 2015), sosyal katılım ve akranlarla olumlu etkileşimi desteklediğini (Clopet & Bulotsky-Shearer, 2016), akranlarla uzun süreli etkileşimlerin sosyal ağ içerisinde merkezi konuma ulaşmada kolaylık sağladığını (Akçakır vd., 2024) belirten çalışmalar mevcuttur.

Araştırmada mağdur çocuk düzeylerini etkileyen en önemli değişkenin cinsiyet olduğu ve erkek çocuklarının mağdur çocuk düzeyinin kız çocuklardan yüksek olduğu görülmüştür. Erkek çocuklarının daha kalabalık gruplarla etkileşim kurması hareketli, rekabetçi ve fiziksel etkileşimli oyunlar sonucunda daha fazla çatışma yaşaması, zorbalık davranışını uygulayan ve maruz kalan taraf olmasına neden olabilir. Erkek çocuklarının akran baskısı ve kendine yönelik saldırganlığa yine saldırgan bir davranışla dönüt vermesi mağduriyet durumunun yaşanmasına da neden olabilir. Yapılan çalışmalar zorbalık davranışlarında erkek çocuklarının kız çocuklarından daha fazla risk altında olduğunu (Navarro vd., 2024; Zhou vd., 2024), doğrudan saldırganlık durumlarına erkek çocuklarının daha fazla maruz kaldığını (Georgiou & Phaedonos, 2020) ortaya koymaktadır.

Araştırmada kız çocuklarının mağdur çocuk düzeylerini etkileyen en önemli değişkenin günlük ekran kullanım süresi olduğu görülmüştür. 1-3 saat ve daha az ekran kullanan kız çocukların mağdur çocuk düzeyleri 1-3 saatten fazla ekran kullanan çocuklara göre daha düşük düzeyde olduğu görülmüştür. Bu durum ekran karşısında kısa süreli vakit geçirmenin akranlarla oyun oynama, problem çözme, iletişim kurma, duygu düzenleme gibi sosyal becerilerin artması için deneyim fırsatı edinme ile ilişkilendirebilir. Sınırlı ekran süresinin çocukların akran ilişkileri açısından koruyucu faktör olabileceği düşünülmektedir. Ekran süresinin sınırlı olması çocukların oyun etkinliklerine, grup çalışmalarına ve akran etkileşimlerine daha fazla zaman ayırmalarını sağlayabilir. Bu durumun çocukların akranları tarafından kabul görme durumunu arttırabileceği ve mağduriyet yaşama olasılıklarını azaltabileceğini düşündürmektedir. Yapılan çalışmalar araştırma bulgusunu destekler nitelikte, ekran süresinin az olmasının çocukların olumlu sosyal ilişkiler kurmasına imkan sağladığı, sosyal yeterlik ve duygu düzenleme becerilerinin yükseldiği yönündedir (Hinkley, Brown, Carson & Teychenne, 2018; McArthur, Tough & Madigan, 2022). Literatürde ekran süresinin fazla olmasının çocukların psikososyal iyi oluş düzeylerini olumsuz etkilediğini (Tezol vd., 2022), duygusal dengesizlik ve davranışsal problemler oluşturduğunu (Oflu vd., 2021; Madigan vd., 2019) gösteren çalışmalar mevcuttur.

Araştırmanın bulgusuna göre çocukların akran ilişkisi düzeylerini etkileyen en önemli değişkenin cinsiyet olduğu görülmüştür. Erkek çocuklarının akran ilişkisi düzeylerinin kız çocuklarından yüksek olduğu görülmüştür. Bu sonuç erkek çocuklarının grup oyunlarına daha fazla katılması, daha geniş arkadaşlık ağlarının bulunması ve akranlarıyla daha fazla zaman geçirmeleriyle ilişkili olabilir. Erkek çocuklarında grup çatışmalarının hızlı yaşanıp kısa sürede çözülmesi, kız çocuklarında ise çatışma durumlarında küsme, gruptan dışlama gibi ilişkisel saldırganlık davranışlarının görülmesi erkeklerin kızlara oranla akran ilişkisi düzeylerinin yüksek çıkmasında etkili olabilir. Literatürde araştırmanın bulgusunu destekleyecek yönde çalışmalar mevcuttur. Erkek çocuklarının kız çocuklarına göre akranlarıyla oyun kurma ve oyuna katılma konusunda daha girişken olduklarını belirtilmektedir (Gülay, 2011; Gülay ve Önder, 2013).

Araştırmada erkek çocuklarının akran ilişkisi düzeylerini etkileyen en önemli değişkenin günlük ekran kullanım süresi olduğu görülmüştür. Araştırmanın bu bulgusu, ekran maruziyetinin akran ilişkilerinin niteliğini ve yoğunluğu üzerinde belirleyici rol oynayabileceğini düşündürmektedir. Okul öncesi dönemde akran ilişkileri yüz yüze etkileşim, oyun, grup etkinlikleri aracılığıyla geliştiği için ekran süresinin artması akranlarla geçirilen zamanı ve iş birliği, çatışma çözme, sıraya uyma, paylaşma, ortak oyun kurma gibi sosyal deneyim fırsatlarını azaltabilir.

Bunun sonucu olarak grup etkinliklerine aktif katılım gösteren erkek çocuklarının akran ilişkileri zayıflayabilir. Buna karşın ekran süresi sınırlı olan erkek çocukları yüz yüze etkileşime açık olmaları, grup etkinliklerine aktif katılım sağlamaları, sosyal ipuçlarını fark etme ve kullanma becerisi sergilemeleri akran ilişkilerini güçlendirebilir. Literatürde yer alan çalışmalar ekran süresinin düşük olmasının, sosyal beceri gelişimi ve olumlu akran etkileşimleriyle ilişkili olduğunu belirterek araştırmanın bulgusunu desteklemektedir (Tamana vd., 2019; Oflu vd., 2021; McArthur, Tough & Madigan, 2022).

Araştırmada ekran kullanım süresini etkileyen en önemli değişkenin okula devam süresi olduğugörülmüştür. 1 yıldan fazla okula devam eden çocukların akran ilişkisi düzeylerinin 1 yıldan az okula devam eden çocuklara göre daha yüksek düzeyde olduğu tespit edilmiştir. Çocukların okula devam süresi arttıkça iletişim kurma, iş birliği yapma, problem çözme, oyun kurma, sıra bekleme, paylaşma ve yardımlaşma davranışlarının artacağı ve grup etkinliklerine katılan çocukların akran ilişkisi düzeylerinin yükseleceği düşünülmektedir. Çocukların okul öncesi eğitim ortamlarında geçirdikleri zamanın fazla olması sosyal etkileşim fırsatları edinmeleri açısından katkı sağlayabilir. Bu durum çocukların ekran kullanımına ayıracakları zamanı akran gruplarıyla etkileşime ayırarak ekran kullanım süresinin azalması ve akran ilişkilerinin güçlenmesiyle sonuçlanabilir. Literatürde okul öncesi eğitime devam süresinin artmasının akran ilişkilerini olumlu yönde etkilediğini, akran kabulü oranının arttığını, sosyal beceri ve sosyal uyum düzeylerinin yükseldiğini belirten çalışmalar mevcuttur (Gülay, 2011; Hinkley, Brown, Carson & Teychenne, 2018).

Araştırma sonucunda 48-60 aydan büyük kız çocuklarının zorbalık düzeylerinin düşük olduğu belirlenmiştir. 1 yıldan fazla okula devam eden çocukların arkadaşlık ve etkileşim düzeylerinin yüksek olduğu bulunmuştur. Günlük ekran kullanım süresi 1-3 saat veya daha az olan kız çocuklarının mağduriyet düzeylerinin düşük olduğu belirlenmiştir. 1 yıldan fazla okula devam eden, günlük ekran

kullanım süresi 1-3 saat veya daha az olan erkek çocuklarının akran ilişkisi düzeylerinin yüksek olduğu tespit edilmiştir.

Araştırma sonuçlarına göre şu öneriler sunulmuştur:

- Bu araştırmada okul öncesi dönem çocuklarının akran ilişkilerini etkileyen faktörler arasında cinsiyet, yaş, ekran kullanım süresi ve okula devam süresi bulunmuştur. Gelecek çalışmalarda bu faktörlerin akran ilişkileri üzerindeki etkileri boylamsal çalışmalarla incelenebilir.
- Araştırma bulguları ekran kullanım süresinin mağduriyet ve akran ilişkisi düzeyleri ile bağlantılı olduğunu belirtmektedir. Bu nedenle ebeveynlerin çocuklarının günlük ekran kullanım süreleri için yaşa uygun şekilde sınırlar belirlemeleri, çocuklarını ekran yerine akran oyununa yönelten spor ve sosyal etkileşimin yoğun olduğu etkinliklere yönlendirmeleri önerilmektedir.
- Okul öncesi öğretmenlerinin sınıf ortamında, iş birliğine dayalı, akran etkileşiminin yoğun olduğu, sosyal becerileri güçlendirici etkinliklere yer vermeleri önerilmektedir. Ayrıca okula yeni başlayan veya akran ilişkileri konusunda güçlük yaşayan çocukları destekleyici uygulamalar ile sürece dahil etmeleri ve ebeveynleri akran etkileşimi, zorbalık ve mağduriyet konularında bilinçlendiren seminerler vermeleri önerilmektedir.

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NİTROTİYOFEN İÇEREN BİR SCHİFF BAZININ MOLEKÜLER YÜZEY ANALİZİ, MOLEKÜLER KENETLENME VE ADME ARAŞTIRMASI

MOLECULAR SURFACE ANALYSIS, MOLECULAR DOCKING, AND ADME INVESTIGATION OF A NITROTHIOPHENE-CONTAINING SCHIFF BASE

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ÖZET

Tiyofen halkaları içeren Schiff baz türevleri, çok yönlü biyolojik aktiviteleri ve elverişli elektronik özellikleri nedeniyle büyük ilgi görmüştür. Bu çalışmada, $C_{12}H_9N_3O_3S$ Schiff bazının moleküler yapısı, elektronik davranışı, moleküllerarası etkileşimleri ve potansiyel farmasötik özellikleri, hesaplama teknikleri kullanılarak sistematik olarak incelenmiştir. Geometri optimizasyonu ve elektronik yapı hesaplamaları, B3LYP fonksiyoneli ve 6-311G(d,p) temel seti kullanılarak Yoğunluk Fonksiyonel Teorisi (DFT) çerçevesinde gerçekleştirilmiştir. Moleküler elektrostatik potansiyel (MEP) analizi, nitro ve karbonil oksijen atomlarının en yüksek elektron yoğunluğuna sahip olduğunu ve bu atomların en olası elektrofilik etkileşim bölgeleri olduğunu gösterirken, hidrazon hidrojen atomlarının nükleofilik saldırıya duyarlı elektron eksikliği olan bölgeleri temsil ettiğini ortaya koymuştur. Kristal paketleme özellikleri, Hirshfeld yüzey analizi ile daha ayrıntılı olarak incelendi ve O···H/H···O temaslarının en büyük katkıyı (%32) sağladığı, bunu H···H (%22), C···H/H···C (%12) ve S···H/H···S (%7) etkileşimlerinin izlediği gösterildi. ADME ve ilaç benzerliği hesaplamalarından tahmin edilen farmakokinetik profil, kan-beyin bariyeri geçirgenliğinin olmamasına rağmen, yüksek insan bağırsak emilimi ve temel ilaç benzerliği kriterlerine uyum da dahil olmak üzere olumlu oral ilaç özelliklerini ortaya koydu. Ayrıca, insan asetilkolinesterazına (AChE, PDB ID: 4EY7) karşı moleküler kenetlenme hesaplamaları, esas olarak TRP286 kalıntısını içeren π–π etkileşimleri yoluyla stabilize edilen -10,6 kcal/mol'lük güçlü bir bağlanma afinitesi ortaya koydu. Bu bulgular, $C_{12}H_9N_3O_3S$'nin potansiyel bir Alzheimer karşıtı ajan olarak daha da geliştirilmesi için umut vadeden bir aday olduğunu göstermekte ve gelecekteki deneysel doğrulama ve biyolojik değerlendirme için teorik bir temel sağlamaktadır.

Anahtar Kelimeler: Schiff bazı, DFT hesaplamaları, Hirshfeld yüzeyi, MEP, ADME profil oluşturma, Moleküler kenetlenme, AChE

ABSTRACT

Schiff base derivatives incorporating thiophene rings have attracted considerable interest because of their versatile biological activities and favorable electronic characteristics. In the present work, the molecular structure, electronic behavior, intermolecular interactions, and potential pharmaceutical properties of the Schiff base $C_{12}H_9N_3O_3S$ were systematically examined using computational techniques. Geometry optimization and electronic structure calculations were carried out within the framework of Density Functional Theory (DFT) employing the B3LYP functional together with the 6-311G(d,p) basis set. Molecular electrostatic potential (MEP) analysis demonstrated that the nitro and carbonyl oxygen atoms possess the highest electron density, identifying them as the most probable electrophilic interaction sites, whereas the hydrazone hydrogen atoms represent electron-deficient regions susceptible to nucleophilic attack.

Crystal packing features were further explored by Hirshfeld surface analysis, which showed that O···H/H···O contacts make the largest contribution (32%), followed by H···H (22%), C···H/H···C (12%), and S···H/H···S (7%) interactions. The pharmacokinetic profile predicted from ADME and drug-likeness calculations suggested favorable oral drug characteristics, including high human intestinal absorption and compliance with the principal drug-likeness criteria, despite the absence of blood–brain barrier permeability. Furthermore, molecular docking calculations against human acetylcholinesterase (AChE, PDB ID: 4EY7) revealed a strong binding affinity of −10.6 kcal/mol, mainly stabilized through π–π interactions involving the TRP286 residue. These findings indicate that $C_{12}H_9N_3O_3S$ represents a promising candidate for further development as a potential anti-Alzheimer agent and provides a theoretical basis for future experimental validation and biological evaluation.

Keywords: Schiff base, DFT calculations, Hirshfeld surface, MEP, ADME profiling, Molecular docking, AChE.

INTRODUCTION

Schiff bases, which are typically formed through the condensation of primary amines with aldehydes or ketones, represent a versatile family of compounds widely studied in organic, medicinal, and coordination chemistry [1-3]. Their characteristic azomethine (–C=N–) functionality is largely responsible for their distinctive physicochemical properties, coordination ability, and biological activity. Because their molecular framework can be readily modified by introducing different functional groups, Schiff bases continue to attract growing interest as promising candidates for pharmaceutical and functional material applications [4, 5]. Among these compounds, thiophene-containing Schiff bases have received particular attention due to the unique electronic contribution of the sulfur-containing heterocyclic ring [6, 7]. The incorporation of electron-withdrawing substituents, such as nitro groups, further modulates the electron-density distribution, enhances molecular polarization, and influences intermolecular interactions within the crystal lattice. As a consequence, these derivatives have demonstrated a broad spectrum of biological properties, including antimicrobial, antioxidant, anticancer, anti-inflammatory, and enzyme inhibitory activities. In addition, the coexistence of hydrogen-bond donor/acceptor sites and aromatic π systems enables these molecules to establish favorable non-covalent interactions with biological macromolecules, making them attractive scaffolds for the design of inhibitors targeting acetylcholinesterase (AChE), an enzyme closely associated with Alzheimer's disease.

To obtain a detailed understanding of the structural and biological characteristics of the title Schiff base, a series of complementary computational investigations was performed. The optimized molecular geometry and electronic properties were evaluated using Density Functional Theory (DFT), and the molecular electrostatic potential (MEP) surface was analyzed to identify regions susceptible to electrophilic and nucleophilic attack. The intermolecular interactions responsible for crystal stabilization were subsequently examined through Hirshfeld surface analysis and two-dimensional fingerprint plots. In addition, in silico ADME and drug-likeness predictions were employed to evaluate the pharmacokinetic behavior and oral drug potential of the compound. Finally, molecular docking calculations against human acetylcholinesterase (AChE) were carried out to investigate the ligand–protein binding mode and binding affinity. The combined computational results provide a comprehensive description of the electronic structure, crystal packing features, and pharmacological potential of the investigated Schiff base, thereby offering a theoretical foundation for future experimental and medicinal chemistry studies.

MATERIALS AND METHOD

The molecular geometry of $C_{12}H_9N_3O_3S$ (Fig. 1) was optimized using density functional theory (DFT) at the B3LYP/6-311G(d,p) level of theory with the Gaussian 09W program package [8]. Molecular electrostatic potential (MEP) analysis was subsequently performed based on the optimized geometry, and all calculations were visualized using the GaussView 5.0 interface [9]. The optimized molecular structure was then converted into PDB and PDBQT formats with Discovery Studio Visualizer 4.0 [10] to prepare the ligand for molecular docking calculations. Docking simulations were carried out using AutoDock Vina [11, 12] to investigate the binding mode of the ligand with the target protein (PDB ID: 4EY7) [13], obtained from the RCSB Protein Data Bank [14]. The pharmacokinetic behavior, physicochemical properties, and drug-likeness characteristics of the synthesized compound were further evaluated using the SwissADME web server [15]. In addition, Hirshfeld surface analysis was performed with CrystalExplorer 21 software [16] to examine the intermolecular interactions in the crystal structure.

RESULTS AND DISCUSSION

Optimization

The equilibrium geometry of $C_{12}H_9N_3O_3S$ was optimized at the DFT/B3LYP/6-311G(d,p) level, and the selected bond lengths and bond angles are listed in Table 1. The optimized structure preserves the expected molecular framework of the Schiff base without noticeable geometric distortions, indicating that the adopted computational model provides a reliable description of the molecular geometry. The

azomethine bond (C13=N3) was calculated to be 1.284 Å, confirming its significant double-bond character and the effective conjugation within the hydrazone fragment. Likewise, the N3–N5 bond length of 1.341 Å is characteristic of a conjugated N–N linkage and reflects electron delocalization across the hydrazone moiety. The nitro group exhibits nearly identical N=O bond distances of 1.232 Å (O4=N7) and 1.235 Å (O9=N7), indicating a symmetrical distribution of electron density within the –NO_2 group, which is consistent with resonance stabilization. The thiophene ring is characterized by C10–S1 and C24–S1 bond lengths of 1.741 and 1.749 Å, respectively. These values fall within the expected range for aromatic C–S bonds and demonstrate that the sulfur atom effectively participates in the π-conjugated heteroaromatic system. Furthermore, the C8–N5 bond length of 1.397 Å suggests partial electron delocalization between the hydrazone linkage and the adjacent aromatic ring, whereas the carbonyl bond (C8=O2) of 1.215 Å retains its typical double-bond character. The calculated structural parameters are consistent with those reported for closely related thiophene-based Schiff bases, supporting the accuracy of the optimized geometry and the suitability of the computational methodology employed [17–20].

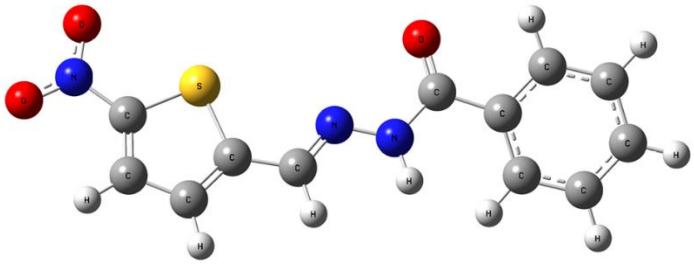

Fig. 1 The optimized structure of $C_{12}H_9N_3O_3S$.

Table 1. Some selected geometric parameters of $C_{12}H_9N_3O_3S$.

Bond lengths (Å)		Bond angles (˚)	
O4=N7	1.232	O4–N7–O9	125.4
O9=N7	1.235	C24–N7–O4	117.0
C10–S1	1.741	C24–N7–O9	117.6
C24–S1	1.749	C10–S1–C24	89.3
C13=N3	1.284	C8–N5–N3	120.6
N3–N5	1.341	C15–C8–O2	123.1
C8–N5	1.397	N5–C8–O2	121.9
C8=O2	1.215	C15–C8–N5	114.9

MEP analysis

To evaluate the charge distribution, reactive sites, and intermolecular interaction capability of the optimized compound, a Molecular Electrostatical Potential (MEP) mapping analysis was performed based on the DFT calculations. The MEP surface maps the total electron density onto the molecular boundary, providing a definitive visual description of the regions prone to electrophilic (electron-deficient) and nucleophilic (electron-rich) actions [21, 22]. The electrostatic potential values across the molecular surface are represented by a standardized color spectrum, ranging from red (strongly negative potential, high electron density) to blue (strongly positive potential, low electron density), with green denoting intermediate/neutral electrostatic regions [23–25]. The molecular electrostatic potential (MEP) surface of $C_{12}H_9N_3O_3S$, depicted in Fig. 2, provides valuable information regarding the electron-density distribution and the reactive regions of the molecule. As expected, the most electron-rich regions are concentrated around the oxygen atoms of the nitro and carbonyl functionalities, where the electrostatic potential reaches its most negative values. These sites are therefore expected to exhibit a strong tendency toward electrophilic interactions. Conversely, the highest positive electrostatic potential is localized mainly on the hydrogen atom of the hydrazone moiety, identifying this region as the most favorable site for nucleophilic attack.

The pronounced separation between electron-rich and electron-deficient regions reflects the polarized nature of the molecule and emphasizes the important role of the oxygen-containing functional groups in governing both intermolecular recognition and non-covalent interactions. Consequently, the MEP distribution provides a useful theoretical basis for understanding the chemical reactivity and potential biological behavior of the investigated Schiff base.

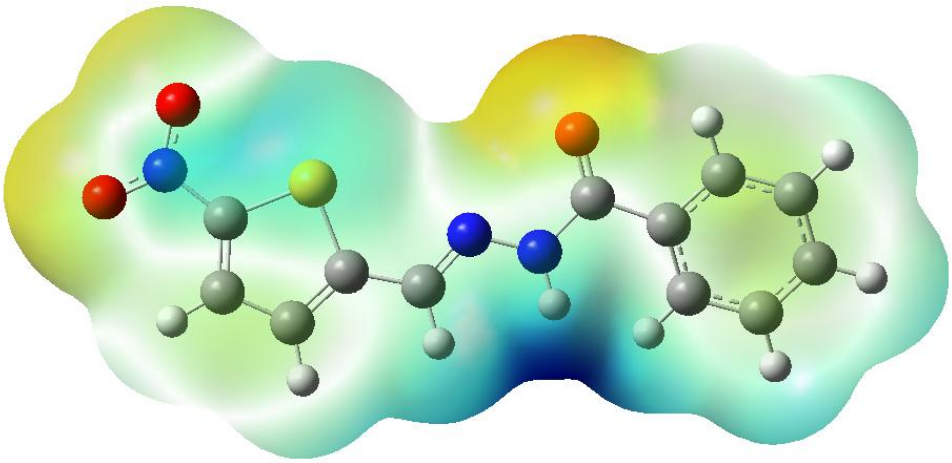

Fig. 2 The optimized structure of $C_{12}H_9N_3O_3S$.

Hirshfeld surface analysis

Hirshfeld surface (HS) analysis is an effective computational tool for visualizing and quantifying intermolecular interactions in crystalline materials [26–29]. Based on the electron-density distribution, the Hirshfeld surface defines the region where neighboring molecules influence the reference molecule within the crystal lattice [30–32]. The normalized contact distance (dnorm) surface distinguishes intermolecular contacts according to their proximity: red regions correspond to contacts shorter than the sum of the van der Waals radii, white regions indicate contacts close to the van der Waals separation, and blue regions represent longer contacts. As illustrated in Fig. 3, the localized red patches on the dnorm surface reveal the presence of close intermolecular interactions, mainly associated with hydrogen bonding. Additional information is provided by the shape index and curvedness surfaces, where complementary red–blue triangular motifs and broad green planar regions are characteristic features of aromatic π···π stacking interactions, offering valuable insight into the crystal-packing arrangement.

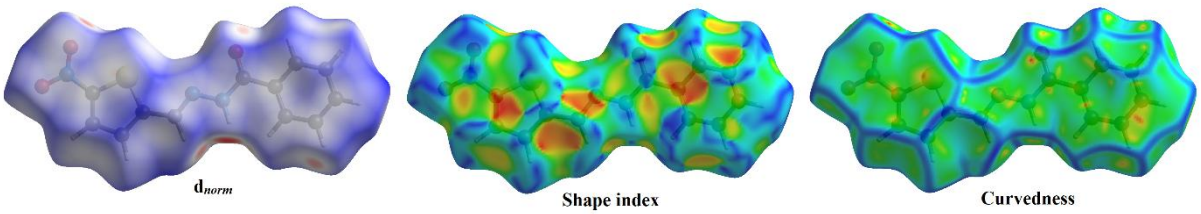

Fig. 3 Hirshfeld surfaces of $C_{12}H_9N_3O_3S$.

The two-dimensional fingerprint plots (Fig. 4) provide a quantitative description of the intermolecular contacts responsible for crystal packing. Among these, O···H/H···O interactions constitute the largest contribution (32%), confirming that hydrogen bonding plays a dominant role in stabilizing the supramolecular structure. The second most abundant contacts are H···H interactions (22%), reflecting the considerable influence of van der Waals forces on the molecular packing. Contributions from C···H/H···C contacts (12%) indicate the presence of weak C–H···π interactions that further support the crystal architecture. In addition, S···H/H···S contacts account for 7% of the Hirshfeld surface, suggesting that sulfur-containing interactions also participate in maintaining the packing arrangement. The remaining N···H/H···N contacts (6%) make a smaller yet noticeable contribution to the intermolecular interaction network, collectively enhancing the overall stability of the crystal structure.

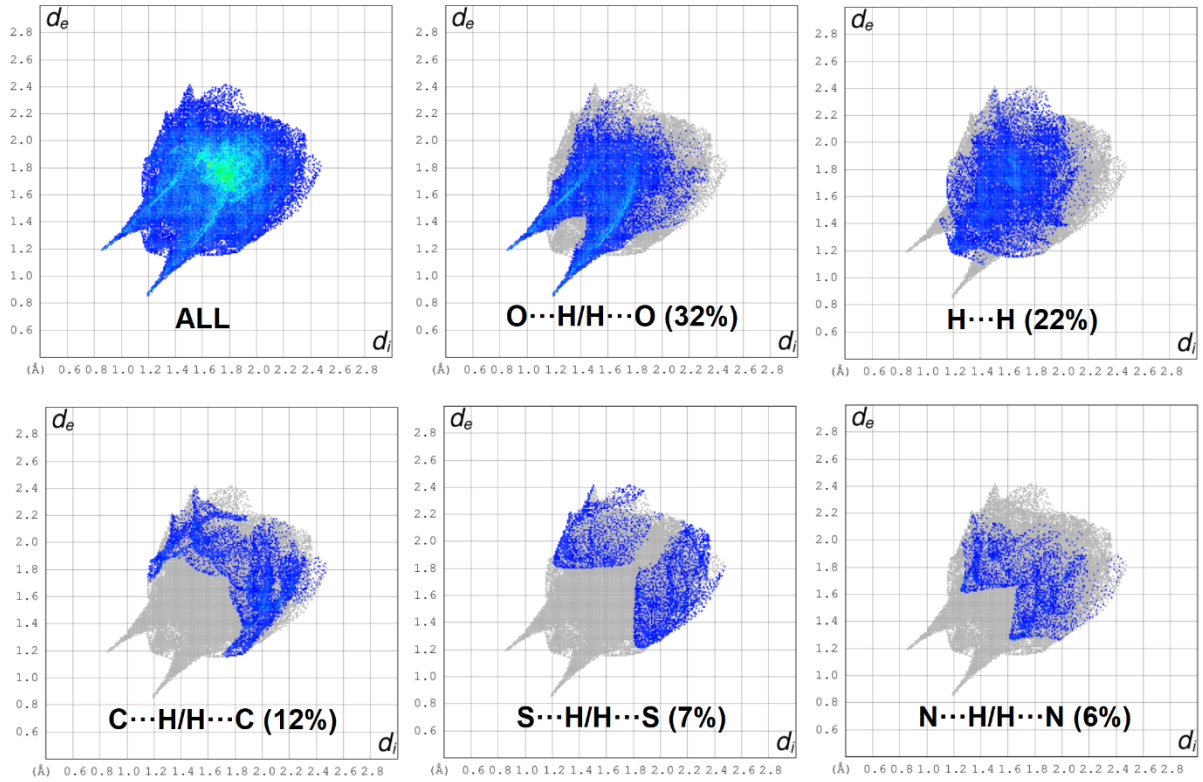

Fig. 4 Fingerprint plots of $C_{12}H_9N_3O_3S$.

Molecular docking analysis

Molecular docking calculations were performed to examine the binding behavior of the ligand within the active site of the human acetylcholinesterase enzyme (PDB ID: 4EY7). The calculated docking scores for all predicted binding poses are presented in Table 2. Among the generated conformations, Mode 1 exhibited the lowest binding energy (−10.6 kcal/mol) together with an RMSD value of 0.000 Å, indicating that this pose corresponds to the most favorable and reliable binding orientation [33–36]. The ligand fits well into the enzyme binding cavity (Fig. 5), where its stabilization is mainly achieved through aromatic interactions in combination with non-covalent contacts.

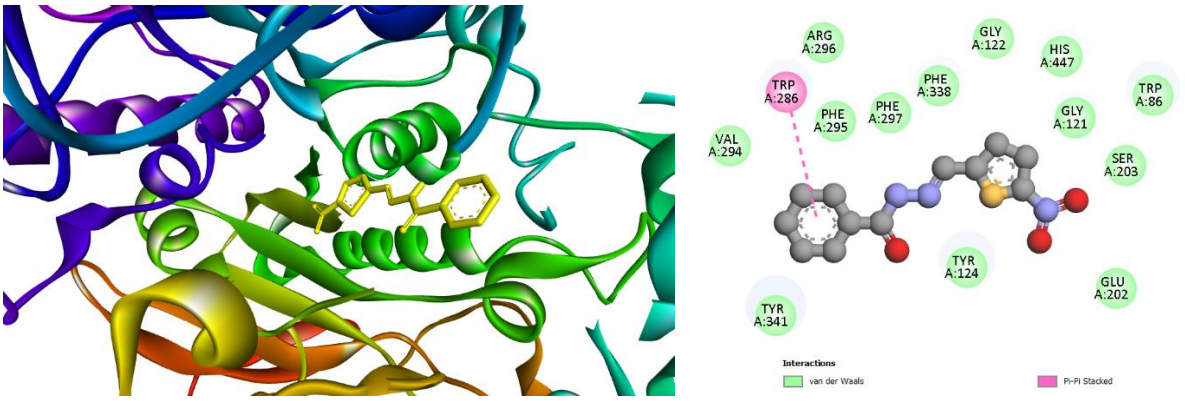

Fig. 5 (a) Showing hydrogen bonds, and (b) 2D molecular docking results of the ligand+PDB:4EY7.

In particular, the phenyl ring of the ligand establishes a π–π stacking interaction with the aromatic residue TRP A:286, which contributes significantly to the strong binding affinity observed for the complex. The remaining docking poses (Modes 2–9) exhibit less favorable binding energies, varying from −9.968 to −7.327 kcal/mol, and are accompanied by progressively larger RMSD values (Table 2). These results indicate greater deviations from the optimal binding geometry and suggest weaker ligand–

protein interactions compared with the best-ranked conformation. The docking study demonstrates that Mode 1 provides the most plausible binding mode for the investigated Schiff base and supports its potential to interact effectively with the catalytic pocket of acetylcholinesterase through stable non-covalent interactions.

Table 2. The binding affinity and RMSD values.

Mode	Affinity (kcal/mol)	rmsd l.b.	rmsd u.b.
1	-10.6	0.000	0.000
2	-9.968	3.6	8.663
3	-9.453	2.284	2.464
4	-9.297	4.316	9.08
5	-8.434	7.002	11.34
6	-8.254	4.436	6.679
7	-8.059	6.212	9.239
8	-7.623	6.512	10.94
9	-7.327	6.478	9.307

ADME analysis

The SwissADME analysis indicates that $C_{12}H_9N_3O_3S$ exhibits favorable physicochemical and pharmacokinetic properties consistent with a drug-like molecule. The calculated molecular weight (275.28 g/mol), consensus LogP (2.42), and TPSA (115.52 Å²) suggest an appropriate balance between lipophilicity and polarity. The compound is predicted to possess high gastrointestinal absorption but lacks blood–brain barrier permeability. It is also classified as water-soluble and complies with the Lipinski, Ghose, Veber, Egan, and Muegge drug-likeness rules without any violations. Moreover, the absence of PAINS and Brenk structural alerts, together with a bioavailability score of 0.55 and a low synthetic accessibility value (2.89), further supports its potential as a promising lead compound (Table 3). The bioavailability RADAR plot (Fig. 6) shows that most of the physicochemical descriptors fall within the optimal region, reflecting a well-balanced molecular profile. The only noticeable deviation is observed for saturation, which is attributable to the aromatic nature of the molecule. Consistent with these results, the BOILED-Egg model predicts efficient intestinal absorption while indicating that the compound is unlikely to cross the blood–brain barrier. In addition, the red marker identifies the molecule as a substrate of P-glycoprotein (P-gp), suggesting that active efflux transport may restrict its accumulation in the central nervous system. The in silico pharmacokinetic evaluation supports good oral bioavailability together with acceptable drug-likeness properties.

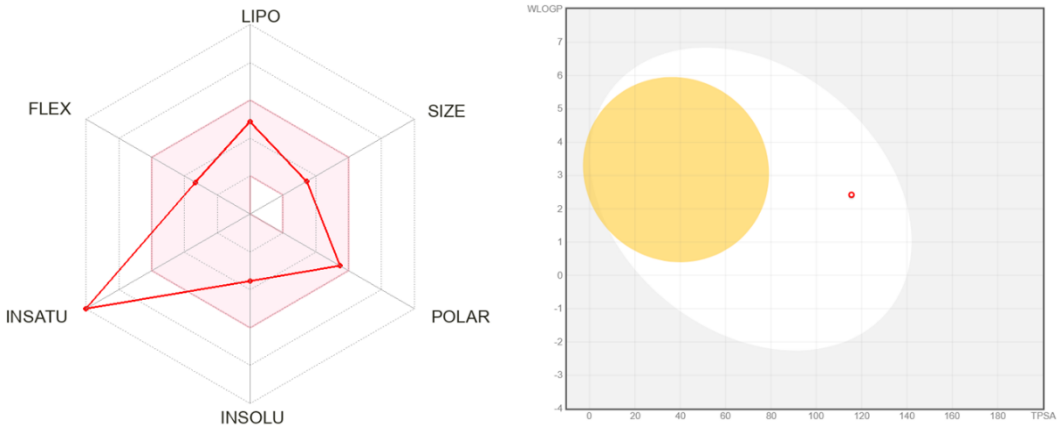

Fig. 6 Showing radar and boiled-egg model.

Table 3. ADME analysis results.

Physicochemical Properties		**Lipophilicity**	
Formula	$C_{12}H_9N_3O_3S$	Log Po/w (XLOGP3)	3.01
Molecular weight	275.28 g/mol	Log Po/w (WLOGP)	2.42
Num. heavy atoms	19	Log Po/w (MLOGP)	0.96

Num. arom. heavy atoms	11	Log Po/w (SILICOS-IT)	1.43
Fraction Csp3	0.00	Consensus Log Po/w	1.95
Num. rotatable bonds	5	**Water Solubility**	
Num. H-bond acceptors	4	Log S (ESOL)	-3.54
Num. H-bond donors	1	Solubility	7.91e-02 mg/ml; 2.87e-04 mol/l
Molar Refractivity	74.31	Class	Soluble
TPSA	115.52 Å²	Log S (Ali)	-5.10
Pharmacokinetics		Solubility	2.18e-03 mg/ml; 7.93e-06 mol/l
GI absorption	High	Class	Moderately soluble
BBB permeant	No	Log S (SILICOS-IT)	-3.66
P-gp substrate	No	Solubility	6.06e-02 mg/ml; 2.20e-04 mol/l
Log Kp (skin permeation)	-5.84 cm/s	Class	Soluble
Medicinal Chemistry		**Druglikeness**	
PAINS	0 alert	Lipinski	Yes; 0 violation
Leadlikeness	Yes	Ghose	Yes
Synthetic accessibility	2.89	Veber	Yes
Brenk	3 alerts: imine1, nitro group, oxygen-nitrogen single bond	Egan	Yes
		Muegge	Yes
		Bioavailability Score	0.55

CONCLUSION

In summary, a comprehensive computational investigation of the Schiff base $C_{12}H_9N_3O_3S$ was carried out to elucidate its structural, electronic, supramolecular, and pharmacological characteristics. The DFT calculations confirmed the stability of the optimized molecular geometry, while the MEP analysis identified the oxygen atoms of the nitro and carbonyl groups as the most electron-rich regions of the molecule. Hirshfeld surface analysis demonstrated that crystal packing is predominantly governed by O···H/H···O and H···H interactions, highlighting the important roles of hydrogen bonding and van der Waals forces in stabilizing the crystal structure. The in-silico ADME evaluation revealed favorable drug-like properties and high predicted intestinal absorption, although limited blood–brain barrier permeability and P-glycoprotein-mediated efflux may restrict central nervous system exposure. Nevertheless, molecular docking against human acetylcholinesterase showed a strong binding affinity, indicating that the title compound constitutes a promising scaffold for further structural optimization. Overall, the present findings provide valuable theoretical insight into the relationship between molecular structure and biological behavior and may serve as a useful foundation for the future design and experimental evaluation of biologically active Schiff base derivatives.

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TASAVVUFUN KOZMİK İNSAN ANLAYIŞI VE MODERN İNSAN FELSEFESİ BAĞLAMINDA İNSAN-DOĞA İLİŞKİSİ

THE HUMAN–NATURE RELATIONSHIP IN THE CONTEXT OF SUFI COSMIC HUMAN UNDERSTANDING AND MODERN HUMAN PHILOSOPHY

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ÖZET

Bu çalışmanın amacı, insan-doğa ilişkisinin felsefi temellerini tasavvufun kozmik insan anlayışı ile modern insan felsefesi arasında karşılaştırmalı bir düzlemde incelemektir. Çalışma, çağdaş ekolojik krizin yalnızca teknik, ekonomik ya da politik bir sorun olmadığını; insanın varlık, doğa, sorumluluk ve anlamla kurduğu ilişkinin dönüşümüyle doğrudan bağlantılı olduğunu ileri sürmektedir. Bu çerçevede araştırma, modern öznenin doğayı araçsallaştıran antroposentrik yaklaşımı ile tasavvuf düşüncesinde insanı kâinatla bütünlük içinde ele alan İnsan-ı Kâmil anlayışı arasındaki ontolojik ve etik farklılıkları ortaya koymayı hedeflemektedir.

Araştırmada nitel araştırma yaklaşımına dayalı karşılaştırmalı kavramsal analiz yöntemi kullanılmıştır. Çalışmanın veri alanını tasavvuf düşüncesinde insan, kâinat, halifelik, emanet, mizan ve İnsan-ı Kâmil kavramları ile modern insan felsefesinde özne, doğa, akıl, Kartezyen düalizm, antroposentrizm ve ekolojik kriz tartışmaları oluşturmaktadır. Bu nedenle çalışma herhangi bir saha örneklemine değil, felsefi ve teorik metinlerden oluşan kavramsal bir veri evrenine dayanmaktadır. İnceleme sürecinde ilgili kavramlar, insanın doğa karşısındaki konumu, doğaya atfedilen değer, sorumluluk biçimi ve etik sonuçlar bakımından analiz edilmiştir.

Analiz sonucunda modern insan felsefesinin, özellikle doğayı insan aklı ve çıkarı doğrultusunda yönetilebilir bir nesne olarak konumlandırdığı; bu yaklaşımın doğanın kutsallıktan, anlamdan ve içsel değerden uzaklaştırılmasına zemin hazırladığı görülmüştür. Buna karşılık tasavvuf düşüncesinde insan, kâinatın dışında veya üzerinde değil; onunla ontolojik bağ içinde bulunan, ilahî isim ve sıfatların tecellisini taşıyan sorumlu bir varlık olarak ele alınmaktadır. İnsan-ı Kâmil anlayışı, doğaya egemen olmayı değil, emanet bilinciyle dengeyi korumayı merkeze almaktadır. Çalışmanın temel bulgusu, tasavvufun kozmik insan anlayışının modern antroposentrik özne anlayışına karşı alternatif bir etik ve ontolojik zemin sunduğudur. Sonuç olarak çalışma, insan-doğa ilişkisinin yeniden düşünülmesinde tasavvufî perspektifin çağdaş çevre etiği tartışmalarına özgün bir katkı sağlayabileceğini göstermektedir.

Anahtar Kelimeler: Tasavvuf, İnsan-ı Kâmil, Modern İnsan Felsefesi, İnsan-Doğa İlişkisi, Ekolojik Etik.

ABSTRACT

The aim of this study is to examine the philosophical foundations of the human–nature relationship through a comparative perspective between the Sufi understanding of the cosmic human and modern human philosophy. The study argues that the contemporary ecological crisis should not be regarded merely as a technical, economic, or political problem.

Rather, it is closely connected with the way human beings understand existence, nature, responsibility, and meaning. Within this framework, the research seeks to reveal the ontological and ethical differences between the anthropocentric orientation of the modern subject, which tends to instrumentalize nature, and the Sufi doctrine of the Perfect Human, which situates the human being within a meaningful cosmic order.

The study is designed as a qualitative inquiry based on comparative conceptual analysis. Its data field consists of key concepts related to Sufi thought, such as human being, cosmos, vicegerency, trust, balance, and the Perfect Human, as well as central concepts in modern human philosophy, including subjectivity, nature, reason, Cartesian dualism, anthropocentrism, and ecological crisis. Accordingly, the study does not rely on an empirical field sample; instead, it is grounded in a conceptual and theoretical corpus. The analysis focuses on how each intellectual framework defines the position of the human being in relation to nature, the value attributed to the natural world, the meaning of responsibility, and the ethical implications that emerge from these assumptions.

The analysis indicates that modern human philosophy, particularly through its subject-centered and dualistic tendencies, has often represented nature as a controllable object to be organized according to human reason and interest. This orientation has contributed to the loss of nature's sacred, meaningful, and intrinsic value. In contrast, Sufi thought does not place the human being outside or above the cosmos, but understands the human as a responsible being whose existence is ontologically connected with the universe. The doctrine of the Perfect Human emphasizes not domination over nature, but the preservation of balance through the consciousness of trust and responsibility. The main finding of the study is that the Sufi understanding of the cosmic human offers an alternative ethical and ontological ground against the anthropocentric model of modern subjectivity. In conclusion, the study suggests that the Sufi perspective may provide a significant and original contribution to contemporary debates on environmental ethics and the reconstruction of the human–nature relationship.
Keywords: Sufism, Perfect Human, Modern Human Philosophy, Human–Nature Relationship, Ecological Ethics.

GİRİŞ

Günümüz dünyası, küresel ısınmadan, doğal kaynakların aşırı tüketimine, hava, su ve toprak kirliliğine kadar uzanan çok boyutlu ve derin bir ekolojik krizle yüzleşmektedir. Bu bunalım, yalnızca teknik önlemlerle giderilemeyecek kadar karmaşık olup, kökeninin insanın doğayla kurduğu ilişkinin felsefi temellerinde aranması gerektiğini göstermektedir. Hâkim modern yaklaşım, özellikle Aydınlanma çağından bu yana, antroposentrik (insan merkezli) bir bakış açısıyla şekillenmiştir.

Bu bakış açısı, insanı doğadan üstün ve ayrı bir varlık olarak konumlandırır, doğayı ise sadece insan refahı ve çıkarları için sınırsızca sömürülecek, yönetilecek ve kontrol edilecek bir araç olarak görür (Catton ve Dunlap, 1978; Maltaş, 2015, s. 328). Bilimsel ve teknolojik ilerlemeler, insanın doğaya hükmetme eğilimini pekiştirmiş ve "İnsan İstisnai Paradigması"nı oluşturarak, doğanın metalaştırılmasına ve kutsallığının yitirilmesine yol açmıştır. Bu seküler ve materyalist zihniyet, doğal çevreyi tahrip eden, insana ve gezegene karşı ahlaki kötülükler işleyen bencil bir tutumu teşvik etmiş ve kadim insan-evren ittifakını yıkmıştır. İnsan-doğa ilişkisindeki bu kopuşun ve yabancılaşmanın, ahlaki bir boşluk yarattığı ve krizin kaynağını oluşturduğu açıktır.

Bu küresel kriz karşısında, insan davranışlarını dönüştürebilecek ve ekolojik bilinci yeniden inşa edebilecek dini ve ruhani dünya görüşlerine olan ihtiyaç giderek artmaktadır. İslam düşüncesi, bilhassa da Tasavvuf felsefesi, insanın mahiyetine ve kâinattaki kozmik konumuna dair benzersiz bir bakış sunar. Tasavvufun merkezi kavramı olan İnsan-ı Kâmil (Yetkin İnsan), yaratılışın gayesi olarak kabul edilir ve Allah'ın yeryüzündeki halifesi sıfatıyla, O'nun tüm isim ve sıfatlarını kemal derecesinde kendinde toplayıp yansıtan ideal varlığı ifade eder. Bu kozmik insan anlayışında, kâinat (makrokozm) büyük insan (insan-ı kebîr) olarak görülürken, insan ise onun küçük bir özeti ve ruhu (âlem-i sağir) olarak telakki edilmiştir. Bu bakış açısı, doğayı rastgele, anlamsız bir varlık olarak gören modern anlayışın aksine, evrendeki her varlığın Allah'ın eserlerinin ve isimlerinin bir yansıması (ayna) olması nedeniyle içsel bir değere ve kutsallığa sahip olduğunu vurgular. Dolayısıyla, İslami çevre etiği, ne sadece insanı merkeze alan (antroposentrik) ne de sadece doğayı merkeze alan (eko-sentrik) bir yaklaşımdır; aksine, Teo-merkezli (Tanrı merkezli) bir etik sunar. Bu teo-merkezli etik, birliğin (Tevhid), sorumluluğun (Halifelik), dengenin (Mizan) ve yaratılışın (fıtrat) korunması ilkeleri üzerine inşa edilmiştir. İnsanın görevi, bu kutsal emanete karşı sorumlu davranmak, doğayı ölçülü kullanmak ve israftan kaçınmaktır.

Çalışma, ekolojik krizi derinlemesine analiz eden ve insan merkezliliği reddeden modern çevre felsefeleri, özellikle de Derin Ekoloji—ki bu akım da doğayı merkeze alan (eko-sentrik) bir değer yönelimi sunar ve mistik geleneklerden etkilenir—ile Tasavvuf'un İnsan-ı Kâmil doktrini arasında kritik bir diyalog kurmayı amaçlamaktadır. Derin Ekoloji ve İslami eko-etik, doğal kaynakların sınırsız sömürüsünün ve israfın reddedilmesi, doğanın içsel değerinin kabul edilmesi gibi konularda benzer sonuçlara ulaşsa da bu değerin kaynağı konusunda temelden ayrılırlar: Derin Ekoloji kutsallığı doğanın içinde (immanent) bulurken, Tasavvuf doğaüstü bir Yaratıcının eseri (transcendent) olması nedeniyle bulur (Yardımcı, 2006, 40; Türkmen, 2008, 270). Bu çalışma, modern zihniyetin yarattığı tahribata karşı, tasavvufun ontolojik ve etik ilkelerinin (tevhid, hilafet, mizan) çağdaş ekolojik bilinçlenmeye ne tür bir itici güç sağlayabileceğini ve kitlesel dönüşümü tetikleme potansiyelini (Yücel, 2017, 72; Yaylı ve Yaslıkaya, 2015, 463) karşılaştırmalı olarak inceleyecektir. Bu diyalog, modern insanın kendini *tek özne*

olarak görme sapmasına karşın, İnsan-ı Kâmil'in kozmik sorumluluğunu ve etik idealini güncel sorunlar bağlamında yeniden değerlendirmenin zeminini oluşturacaktır.

TASAVVUFUN KOZMİK İNSAN ANLAYIŞI

Tasavvuf düşüncesinde kozmik insan anlayışı, temelde İnsan-ı Kâmil öğretisi etrafında şekillenir. İnsan-ı Kâmil, yalnızca ahlaki bakımdan olgunlaşmış bireyi değil; aynı zamanda insanın kâinattaki ontolojik konumunu, varlıkla ilişkisini ve ilahî hakikati yansıtma kapasitesini açıklayan merkezi bir kavramdır. Tasavvuf literatüründe özellikle Muhyiddin İbnü'l-Arabî ile sistematik bir derinlik kazanan bu kavram, insanın felsefi, metafizik ve ahlaki mahiyetini anlamlandırmak bakımından temel bir çerçeve sunar (Durak, 2010, ss. 107-108; Vural, 2017, s. 243; Akot, 2013, s. 61).

Bu anlayışın merkezinde insan ile kâinat arasında kurulan mikrokozm-makrokozm ilişkisi yer almaktadır. Tasavvufî gelenekte insan "âlem-i sağir" yani küçük âlem, kâinat ise "insan-ı kebîr" yani büyük insan olarak değerlendirilir. Bu yaklaşım, insanın kâinattan kopuk bir varlık değil, onun özünü ve anlamını kendinde toplayan bir varlık olduğunu göstermektedir. Buna göre evrende bulunan hakikatlerin insanda da karşılığı vardır; insan, kâinatın küçük bir numunesi ve yoğunlaşmış özeti olarak kabul edilir (Ergül, 2015, s. 209; Konuk, 1994, ss. 325-326, aktaran Ergül, 2015, s. 209; Şahin, 2022, s. 51).

İnsan ile kâinat arasındaki bu bütünlük ilişkisi, tasavvufî metinlerde sembolik anlatımlarla da açıklanmıştır. Bazı sûfîler, insan bedenini yeryüzüne, kemiklerini dağlara, iç boşluklarını denizlere ve damarlarını akarsulara benzeterek insanın kozmik düzenle kurduğu ontolojik bağı somutlaştırmışlardır. Bu benzetmeler, insanın yalnızca doğanın içinde yaşayan biyolojik bir varlık olmadığını; aynı zamanda kâinatın anlamını ve düzenini kendi varlığında taşıyan bir merkez olduğunu göstermektedir. Dolayısıyla insanın doğa ile ilişkisi dışsal ve araçsal değil, varoluşsal ve bütüncül bir ilişki olarak anlaşılmalıdır (Ergül, 2015, ss. 210, 242-243; Durak, 2010, s. 116).

Tasavvuf düşüncesinde İnsan-ı Kâmil'in kozmik konumu, kâinatın yaratılış gayesiyle de ilişkilendirilir. Mutasavvıflara göre kâinat, insanla anlam ve kemal kazanır; beden nasıl ruhla kemale eriyorsa, kâinat da İnsan-ı Kâmil ile tamamlanır. Bu bakımdan İnsan-ı Kâmil, yalnızca yaratılmışlar arasında üstün bir mertebeyi temsil etmez; aynı zamanda evrenin anlamını idrak eden, varlığın güzelliğini takdir eden ve kâinatın ruhu olarak düşünülen ideal varlığı ifade eder (Ergül, 2015, ss. 215, 263; Durak, 2010, ss. 109, 116).

Kozmik insan anlayışının metafizik temelinde Vahdet-i Vücûd düşüncesi yer alır. Bu paradigmaya göre hakiki varlık yalnızca Hakk'ın varlığıdır; kâinat ise ilahî isim ve fiillerin tecellileri olarak anlam kazanır. Varlık, ilahî hakikatin farklı mertebelerde görünür hâle gelmesiyle açığa çıkar ve her bir varlık, kendi istidadı ölçüsünde ilahî isimlerin bir aynası olarak değerlendirilir. Böylece doğa, rastlantısal ve anlamsız bir nesneler toplamı değil, ilahî tecellinin okunabilir bir alanı hâline gelir (Ergül, 2015, ss. 238, 322; Deniz, 2020, s. 3; Sayın, 2017, s. 467).

Bu tecelli anlayışı içinde İnsan-ı Kâmil, ilahî isim ve sıfatların en yetkin biçimde yansıdığı varlık olarak konumlandırılır. Diğer varlıklar ilahî isimleri parça parça ve sınırlı biçimde yansıtırken, İnsan-ı Kâmil bu isim ve sıfatları toplu ve kâmil biçimde kendinde taşır. Bu nedenle insan, ilahî hakikatin idrak edilebilmesi ve kâinatın anlamının açığa çıkabilmesi bakımından merkezi bir yere sahiptir. İbnü'l-Arabîci gelenekte İnsan-ı Kâmil, Hakk ile halk arasında bir berzah; ilahî feyzin âleme yayılmasında ise aracı bir varlık olarak değerlendirilir (Ergül, 2015, ss. 247, 326; Deniz, 2020, s. 3; Akot, 2013, s. 60).

İnsan-ı Kâmil'in bu merkezi konumu, ona yalnızca ontolojik bir üstünlük değil, aynı zamanda ağır bir ahlaki ve kozmik sorumluluk yükler. Kur'an'da insana verilen halifelik görevi, tasavvufî yorumda İnsan-ı Kâmil anlayışıyla ilişkilendirilir. Halifelik, insanın yeryüzünde sınırsız egemenlik kurması anlamına gelmez; aksine, varlık düzenini koruma, emanete riayet etme ve yaratılmışlara karşı adalet, merhamet ve ölçü içinde davranma sorumluluğunu ifade eder (Durak, 2010, ss. 108-109; Ergül, 2015, s. 240; Şahin, 2022, ss. 48-51).

Tasavvufta emanet bilinci, insan-doğa ilişkisinin etik zeminini oluşturan temel unsurlardan biridir. İnsan, kendisine sunulan doğayı mutlak mülk sahibi gibi değil, mülkün asıl sahibinin emri ve izni çerçevesinde değerlendirmekle yükümlüdür. Bu nedenle doğaya yönelik tasarruf, keyfî kullanım ya da sınırsız tüketim şeklinde değil; ölçü, denge ve sorumluluk ilkelerine bağlı olarak gerçekleşmelidir. Emanete riayet etmeyen insan, tasavvufî bakış açısından halifelik bilincinden uzaklaşmakta ve kendi

ontolojik değerini de zedelemektedir (Ergül, 2015, ss. 240, 317, 320; Yılmaz, 2007, s. 198; Şahin, 2022, s. 52).

İnsan-ı Kâmil'in kozmik sorumluluğu, yalnızca doğaya zarar vermeme ilkesiyle sınırlı değildir; aynı zamanda varlıktaki anlamı idrak etme ve bütün yaratılmışların değerini kavrama sorumluluğunu da içerir. Tasavvufî anlayışa göre tüm varlıklar kendi istidatları ölçüsünde Allah'ı tesbih ederken, İnsan-ı Kâmil bu kozmik zikri idrak edebilen ve bütün varlıkların anlamını kuşatabilen yetkin bir varlıktır. Bu bakımdan onun doğayla ilişkisi faydacı değil, hikmet, merhamet ve sorumluluk merkezlidir (Ergül, 2015, s. 331; Durak, 2010, s. 120; Ardoğan, 2009, s. 247).

Tasavvufun kozmik insan anlayışı, insanı doğadan kopuk ve ona egemen bir özne olarak değil; kâinatla ontolojik birlik içinde bulunan, ilahî hakikati yansıtan ve varlık düzenine karşı sorumluluk taşıyan bir varlık olarak konumlandırır. Bu yaklaşım, modern insan felsefesinin doğayı nesneleştiren ve araçsallaştıran yönelimine karşı güçlü bir alternatif sunmaktadır. İnsan-ı Kâmil öğretisi, insanın doğayla ilişkisinde tahakküm yerine emanet bilincini, tüketim yerine ölçülülüğü ve yabancılaşma yerine bütünlük fikrini öne çıkararak çağdaş ekolojik etik tartışmaları için önemli bir felsefi imkân sağlamaktadır (Özdemir, 2016, s. 15; Durak, 2010, ss. 121-122; Ergül, 2015, s. 275).

MODERN İNSAN FELSEFESİNDE DOĞA ANLAYIŞI

Modern insan felsefesinin doğa anlayışı, özellikle Aydınlanma Çağı ve Sanayi Devrimi sonrasında belirginleşen insan merkezli düşünce yapısıyla yakından ilişkilidir. Bu yaklaşımda insan; akıl, teknik üretim ve kültürel örgütlenme kapasitesi nedeniyle doğadan ayrı ve ona üstün bir varlık olarak konumlandırılmıştır. Böylece doğa, kendi başına anlam ve değer taşıyan bir varlık alanı olmaktan çok, insanın faydası ve refahı için kullanılabilecek araçsal bir kaynak olarak değerlendirilmiştir (Maltaş, 2015, ss. 319, 327; Konak, 2010, ss. 274-275; Kılıç, 2008, s. 40).

İnsan merkezli çevre etiği, doğaya yaklaşımda insanı ve insan çıkarını temel ölçüt olarak kabul eder. Bu anlayışta insan dışındaki canlı ve cansız varlıkların değeri, çoğu zaman insana sağladıkları yarar üzerinden belirlenir. Dolayısıyla doğa, korunması gereken bağımsız bir değer alanı olarak değil, insan ihtiyaçlarını karşılayan bir nesne ve kaynak alanı olarak görülür (Kılıç, 2008, s. 40; Maltaş, 2015, s. 327).

Modern felsefenin doğayı araçsallaştıran bu yaklaşımının arka planında katı bir düalizm bulunmaktadır. Özellikle Kartezyen felsefede ruh-beden, özne-nesne ve insan-doğa ayrımı belirginleşmiş; bilinç sahibi insan ile bilinçsiz kabul edilen doğa arasında ontolojik bir mesafe kurulmuştur.

Bu ayrım, insanın kendisini ait olduğu bütünlükten kopuk biçimde algılamasına ve doğayı müdahale edilebilir bir nesne olarak görmesine zemin hazırlamıştır (Descartes, 1988, aktaran Efil, 2018, s. 252; Tatar, 2004, s. 107, aktaran Efil, 2018, s. 254; Maltaş, 2015, s. 162).

Modern dönemde insanın dil, teknoloji ve toplumsal örgütlenme gibi özellikleri, onu doğa karşısında istisnai bir varlık olarak yorumlayan yaklaşımı güçlendirmiştir. "İnsan İstisnai Paradigması" olarak adlandırılan bu anlayış, insanın teknolojik gelişmeler aracılığıyla çevresel sınırlılıkları aşabileceği varsayımına dayanır. Bu varsayım, insanın doğa üzerindeki hâkimiyetini meşrulaştırırken, çevresel sorunların ortaya çıkmasında etkili olan zihinsel zemini de güçlendirmiştir (Catton ve Dunlap, 1978, aktaran Özerkemen, 2002, s. 176; Konak, 2010, s. 275; Özerkemen, 2002, s. 176).

Modern insanın doğa karşısındaki tutumu, doğayı anlama çabasından çok onu kontrol etme ve dönüştürme arzusuyla şekillenmiştir. Bu süreçte doğa, organik ve anlamlı bir bütün olarak değil, insanın üzerinde işlem yapabileceği mekanik bir sistem gibi görülmeye başlanmıştır. Doğayı çözümlemek, sınıflandırmak ve denetlemek, modern öznenin hem bilgi üretme hem de egemenlik kurma stratejisinin parçası hâline gelmiştir (Bowler, 2001, aktaran Maltaş, 2015, s. 317; Ünder, 1996, ss. 40-41, aktaran Efil, 2018, ss. 257-258).

Seküler ve materyalist dünya görüşü, doğanın anlamını büyük ölçüde fiziksel süreçlere ve fayda ilişkilerine indirgemiştir. Naturalist yaklaşımlar, tabiatüstü anlam çerçevelerini reddederek evreni amaçsız, kendine yeterli ve mekanik bir düzen olarak yorumlama eğilimi göstermiştir. Böylece doğa, kutsallık, içsel değer ve aşkın anlam boyutlarından uzaklaştırılmıştır (Düzgün, 1997, ss. 60-64, aktaran Ardoğan, 2022, s. 18; Efil, 2018, ss. 259, 261; Ardoğan, 2022, s. 18).

Bu anlam kaybı, insan ile doğa arasındaki kadim bütünlük fikrinin zayıflamasına yol açmıştır. Evrenin rastlantısal, anlamsız ya da insan dışı değerlerden yoksun bir düzen olarak görülmesi, modern öznenin doğaya karşı etik sorumluluk geliştirmesini de güçleştirmiştir. İnsan ile doğa arasındaki ilişkinin

karşıtlık ve kontrol zeminine taşınması, ekolojik krizin felsefi arka planında önemli bir rol oynamıştır (Monod, 1972, s. 180, aktaran Efil, 2018, s. 256; Prigogine ve Stengers, 1985, s. 56, aktaran Efil, 2018, s. 255; Efil, 2018, s. 256).

Modern insan felsefesinin doğaya yönelik araçsal tutumu, 20. yüzyıldan itibaren yoğun biçimde eleştirilmeye başlanmıştır. Bu eleştiriler içinde Heidegger'in modern teknik anlayışına yönelik değerlendirmeleri önemli bir yere sahiptir. Heidegger'e göre modern teknik, varlığı kendi anlamı içinde değil, kullanılabilir ve tüketilebilir bir kaynak olarak açığa çıkarır. Bu durum, insanın dünyayla kurduğu anlam ilişkisini zayıflatmakta ve doğayı yalnızca teknik müdahalenin nesnesi hâline getirmektedir (Önder, 2003, s. 184; Efil, 2018, ss. 276-277).

Heideggerci bakış açısından modern teknolojinin temel problemi, yalnızca araçların kullanımı değil, varlığın bütünüyle hesaplanabilir ve denetlenebilir bir kaynak alanı olarak kavranmasıdır. Bu anlayış, insanın kendi yaşadığı dünyadan kopmasına ve doğayla olan varoluşsal bağını kaybetmesine neden olur. Bu nedenle modern teknik, ekolojik krizin yalnızca pratik değil, aynı zamanda ontolojik bir boyutu olduğunu göstermektedir (Efil, 2018, ss. 276-277; Konak, 2010, s. 275).

Modernizmin doğayı araçsallaştıran yönelimine karşı postmodern düşünce ve ekolojik hareketler, insanın doğayla yeniden bütünleşmesi gerektiğini vurgulamıştır. Bu bağlamda modernliğin rasyonel-teknik ve ilerlemeci iddiaları sorgulanmış; insanın doğanın dışında değil, onun bir parçası olduğu fikri yeniden önem kazanmıştır. "Doğaya dönüş" çağrısı, insanın ekolojik bağımlılığını ve varoluşsal sınırlılığını fark etmesi gerektiğini ortaya koymaktadır (İnan, 2004, s. 1; Kesgin, 2002, s. 1; Tuna, 2000, s. 69).

Derin Ekoloji yaklaşımı, modern insan merkezci doğa anlayışına yöneltilen en radikal eleştirilerden biridir. Bu yaklaşım, doğanın yalnızca insan için değerli olduğu fikrini reddederek insan dışı varlıkların da kendi başlarına değer taşıdığını savunur. Bu yönüyle Derin Ekoloji, doğayla egemenlik ve kullanım ekseninde değil, özdeşleşme, karşılıklı bağlılık ve bütünlük temelinde ilişki kurulması gerektiğini ileri sürer (Yaylı ve Çelik, 2011, s. 372; Ünder, 1996, s. 203; Önder, 2003, s. 157).

Derin Ekoloji'ye göre ekolojik krizin çözümü yalnızca teknolojik reformlarla veya çevre yönetimi politikalarıyla sağlanamaz. Asıl dönüşüm, insanın doğayı algılama biçiminde, değer anlayışında ve yaşam tarzında gerçekleşmelidir. Bu nedenle sade yaşam, tüketimden uzaklaşma ve insan dışı varlıkların içsel değerini kabul etme gibi ilkeler Derin Ekoloji'nin temel vurguları arasında yer almaktadır (Önder, 2003, ss. 165-166; Gökdayı, 1997, s. 178).

Derin Ekoloji'nin geniş kitleler üzerinde dönüşüm sağlama kapasitesi tartışmalıdır. Bazı eleştiriler, bu yaklaşımın daha çok belirli çevre bilincine sahip gruplarda etkili olabileceğini, fakat toplumsal altyapısı zayıf olduğu için kitlesel dönüşüm üretmekte sınırlı kalabileceğini belirtmektedir. Bu durum, ekolojik krizin çözümünde yalnızca felsefi farkındalığın değil, aynı zamanda güçlü toplumsal ve kültürel dayanakların da gerekli olduğunu göstermektedir (Önder, 2003, s. 182; Yaylı ve Yaslıkaya, 2015, s. 463).

Modern insan felsefesinde doğa, büyük ölçüde insan aklının, teknik gücünün ve ekonomik çıkarlarının nesnesi olarak konumlandırılmıştır. Bu yaklaşım, insan ile doğa arasındaki ontolojik bağı zayıflatmış, doğanın içsel değerini gölgelemiş ve ekolojik krizin felsefi zeminini hazırlamıştır. Modernliğe yöneltilen eleştiriler ve Derin Ekoloji gibi yaklaşımlar bu araçsal doğa anlayışını sorgulamak bakımından önemli olsa da insan-doğa ilişkisinin yeniden kurulabilmesi için daha derin bir ontolojik ve etik dönüşüme ihtiyaç vardır (Efil, 2018, ss. 265, 309; Yaylı ve Çelik, 2011, s. 372; Ergül, 2015, s. 347).

İNSAN-I KÂMİL İLE MODERN ÖZNENİN KARŞILAŞTIRILMASI

İnsan-ı Kâmil ile modern özne arasındaki karşılaştırma, insanın varlık içindeki konumu, evrenle ilişkisi, sorumluluk anlayışı ve ahlaki amacı bakımından iki farklı insan tasavvurunu ortaya koymaktadır. Tasavvuf düşüncesinde İnsan-ı Kâmil, Tanrı, insan ve evren arasındaki bütünlüğü temsil eden kozmik ve ahlaki bir ideal olarak ele alınırken; modern özne çoğunlukla aklı merkeze alan, doğadan ayrışmış ve doğa üzerinde egemenlik kurma eğilimi taşıyan birey olarak tanımlanır. Bu nedenle iki insan modeli arasındaki fark, yalnızca antropolojik değil; aynı zamanda ontolojik, epistemolojik ve etik düzeyde de belirleyicidir (Durak, 2010, s. 107; Maltaş, 2015, s. 384; Efil, 2018, s. 322).

Ontolojik açıdan İnsan-ı Kâmil, tasavvuf düşüncesinde yaratılışın gayesini idrak eden ve ruhî eğitimini tamamlamış yetkin insanı ifade eder. Bu anlayışta insan, kâinattan kopuk bir varlık değil; makrokozm olarak görülen kâinatın küçük bir numunesi, yani mikrokozm olarak konumlandırılır.

Böylece İnsan-ı Kâmil, varlık mertebelerinin en kapsayıcı düzeyinde yer alan, kâinatın anlamını kendinde toplayan ve evrenle derin bir ontolojik bağ içinde bulunan ideal varlık olarak değerlendirilir (Durak, 2010, ss. 107, 116; Ergül, 2015, ss. 209, 280; Şahin, 2022, s. 51).

Modern özne ise özellikle Aydınlanma sonrası düşüncede, aklı ve bilinç yetisi sayesinde doğadan ayrılan ve ona üstün kabul edilen bir insan modelini temsil eder. Kartezyen düalizmin etkisiyle insan, düşünen özne; doğa ise uzamda yer kaplayan, ölçülebilir ve denetlenebilir bir nesne olarak ele alınmıştır. Bu ontolojik ayrım, modern insanın kendisini doğanın parçası olarak değil, onun karşısında konumlanan egemen bir özne olarak algılamasına zemin hazırlamıştır (Maltaş, 2015, s. 162; Konak, 2010, ss. 274-275; Efil, 2018, s. 322).

İnsan-ı Kâmil'in evrenle ilişkisi bütünlük, tecelli ve sorumluluk kavramları üzerinden açıklanır. Tasavvufî anlayışa göre İnsan-ı Kâmil, ilahî isim ve sıfatların en yetkin biçimde tecelli ettiği yegâne ayna olarak görülür; diğer varlıklar ilahî hakikati sınırlı biçimde yansıtırken, İnsan-ı Kâmil bu hakikati daha kapsamlı biçimde taşır. Bu nedenle o, Hakk ile halk arasında bir berzah, yani birleştirici bir vasıta olarak değerlendirilir ve kâinatın ruhu ya da cilası olarak anlamlandırılır (Ergül, 2015, ss. 286, 292; Cebecioğlu, 2004, s. 314; Durak, 2010, ss. 236, 459).

Modern öznenin evrenle ilişkisi ise çoğunlukla araçsal ve faydacı bir karakter taşır. Modern düşüncede doğa, insanın bilgi, teknoloji ve ekonomik çıkarları doğrultusunda dönüştürülebilecek bir kaynak alanı olarak görülür. Bu nedenle modern özne, doğayı kendisiyle ontolojik bağ kurduğu bir bütün olarak değil, üzerinde tasarrufta bulunabileceği ve kontrol edebileceği bir nesne olarak konumlandırır. Böyle bir yaklaşım, insan-doğa ilişkisinde yabancılaşmayı ve ekolojik tahribatı artıran temel zihinsel unsurlardan biridir (Maltaş, 2015, ss. 327, 382; Ünder, 1996, ss. 40-41, aktaran Efil, 2018, ss. 326-327; Konak, 2010, s. 275).

Sorumluluk anlayışı bakımından İnsan-ı Kâmil, halifelik ve emanet bilinciyle hareket eden ahlaki bir varlık olarak öne çıkar. Tasavvufî düşüncede halifelik, insanın yeryüzünde sınırsız egemenlik kurması değil, ilahî düzeni koruma ve yaratılmışlara karşı adalet, merhamet ve ölçü içinde davranma sorumluluğunu ifade eder. Doğa insana mutlak mülk olarak değil, korunması gereken bir emanet olarak verilmiştir; bu nedenle İnsan-ı Kâmil'in görevi doğaya hükmetmek değil, mizanı ve varlık düzenini gözetmektir (Durak, 2010, ss. 422, 450, 466; Ergül, 2015, s. 279; Özdemir, 2006, s. 183).

Modern öznenin sorumluluk anlayışı ise çoğu zaman bireysel özgürlük, fayda, üretim ve ilerleme kavramlarıyla şekillenmiştir. Bu yaklaşımda doğaya yönelik sorumluluk, genellikle insan refahının, ekonomik sürekliliğin ya da teknik sürdürülebilirliğin korunması bağlamında ele alınır. Dolayısıyla modern öznenin çevreye yönelik duyarlılığı çoğu zaman doğanın kendi değerinden değil, insan yaşamının devamı için gerekli olmasından kaynaklanır. Bu durum, doğayı yine insan merkezli bir değer düzeni içinde değerlendirme eğilimini sürdürmektedir (Ardoğan, 2022, s. 18; Konak, 2010, s. 280; Maltaş, 2015, s. 382).

Ahlaki amaç bakımından İnsan-ı Kâmil, yalnızca dış dünyayı düzenleyen değil, öncelikle kendi iç dünyasını arındıran ve Allah'ın ahlakıyla ahlaklanmayı hedefleyen bir insan modelidir. Bu süreçte fenâ ve bekâ gibi tasavvufî mertebeler, insanın nefsani arzulardan uzaklaşmasını ve hakikatle daha derin bir bağ kurmasını ifade eder. İnsan-ı Kâmil'in doğayla ilişkisi de bu ahlaki olgunlaşmanın bir uzantısıdır; çünkü yaratılmışlara merhamet, adalet ve şefkatle yaklaşmak, onun manevi yetkinliğinin göstergelerinden biridir (Durak, 2010, ss. 236, 441; Toprak, 2017, s. 119; Akot, 2013, s. 266).

Modern öznenin ahlaki yönelimi ise çoğu zaman sekülerleşme, bireycilik ve materyalist ilerleme anlayışı tarafından belirlenmektedir. Modernite, bireyi akıl ve özgürlük sahibi bir özne olarak görünür kılsa da onu çoğu zaman metafizik bağlarından ve değer merkezli varoluşundan koparır. Bu durum, insanın kendisini yalnızca üretim, tüketim ve görünür başarılar üzerinden tanımlamasına yol açmakta; manevi derinlik, kozmik sorumluluk ve varlıkla bütünlük fikrini zayıflatmaktadır (Akot, 2013, ss. 248, 253; Efil, 2018, s. 334; Ardoğan, 2022, s. 18).

İnsan-ı Kâmil ile modern özne arasındaki fark, doğaya yönelik tutumda en açık biçimde görünür.

İnsan-ı Kâmil, doğayı ilahî yaratılış düzeninin bir parçası ve kendisine emanet edilmiş bir varlık alanı olarak değerlendirirken; modern özne doğayı çoğu zaman ekonomik, teknolojik ve faydacı amaçlarla dönüştürülebilecek bir kaynak olarak görür. Bu nedenle İnsan-ı Kâmil'in doğayla ilişkisi koruma, merhamet ve dengeye; modern öznenin ilişkisi ise kontrol, kullanım ve tahakküme daha yakındır (Ergül, 2015, s. 292; Maltaş, 2015, s. 327; Efil, 2018, s. 327).

Karşılaştırma, ekolojik krizin yalnızca çevresel değil, aynı zamanda insan tasavvuruyla ilgili bir kriz olduğunu göstermektedir. Modern öznenin doğadan kopuk ve egemenlik merkezli konumu, ekolojik tahribatın zihinsel temelini oluştururken; İnsan-ı Kâmil anlayışı insanı varlıkla bütünlük içinde sorumluluk taşıyan bir özne olarak yeniden düşünmeye imkân verir. Bu bakımdan tasavvufî insan anlayışı, çağdaş ekolojik etik tartışmaları için yalnızca geleneksel bir kavram değil, modern insan felsefesine karşı alternatif bir varlık ve sorumluluk modeli olarak değerlendirilebilir (Durak, 2010, ss. 121-122; Ergül, 2015, s. 275; Yücel, 2017, s. 56).

DOĞA İLE İLİŞKİNİN İKİ PARADİGMADAKİ GÖRÜNÜMÜ

Günümüz küresel medeniyeti, doğal kaynakların aşırı tüketimi, iklim değişikliği, su ve hava kirliliği ile ekolojik dengenin bozulması gibi insan yaşamını tehdit eden çok katmanlı bir krizle karşı karşıyadır. Bu kriz, yalnızca teknik ya da ekonomik önlemlerle çözülemeyecek kadar derindir; çünkü kökeninde insanın doğayla kurduğu ilişkinin felsefi ve ontolojik temelleri bulunmaktadır. Modern çağda güçlenen insan merkezli paradigma, insanı doğadan ayrı, rasyonel ve üstün bir varlık olarak konumlandırmış; doğayı ise insan çıkarı için kullanılabilecek araçsal bir alan olarak değerlendirmiştir (Yücel, 2017, s. 50; Efil, 2018, s. 219; Maltaş, 2015, s. 368).

Modern paradigmada doğa, çoğu zaman insan refahı, ekonomik büyüme ve teknik denetim için kullanılabilecek bir kaynak olarak görülmektedir. Bu yaklaşımda insan, doğanın parçası olmaktan çok, onun karşısında duran ve onu yöneten özne konumundadır. Özellikle Kartezyen düalizm, bilinçli insan ile bilinçsiz kabul edilen doğa arasında keskin bir ayrım oluşturarak insanın kozmik bütünden kopmasına neden olmuştur. Böylece doğal çevre kutsallıktan ve içsel değerden uzaklaştırılmış, mekanik bir evren anlayışı içinde yeniden yorumlanmıştır (Kılıç, 2008, s. 40; Maltaş, 2015, s. 162; Efil, 2018, s. 233).

Teknolojik gelişmeler ve insanın kültürel üstünlüğüne yapılan vurgu, modern öznenin doğa karşısındaki hâkimiyet arzusunu daha da güçlendirmiştir.

"İnsan İstisnai Paradigması", insanın doğal süreçlerden bağımsızlaşabileceği ve teknolojik araçlarla çevresel sorunları aşabileceği varsayımına dayanır. Bu varsayım, doğaya hükmetme, onu fethetme ve sınırsız biçimde dönüştürme eğilimini beslemiş; sonuçta insan-evren arasındaki anlam bağının zayıflamasına ve ekolojik felaketlerin ahlaki bir sorun hâline gelmesine yol açmıştır (Konak, 2010, ss. 274-275; Özerkemen, 2002, s. 176; Efil, 2018, ss. 224, 278).

Tasavvufî paradigmada ise insan-doğa ilişkisi tahakküm değil, bütünlük ve sorumluluk temelinde kurulur. İnsan, kâinatın dışında ya da üzerinde yer alan bağımsız bir özne değil; âlem-i sağir olarak kâinatın özünü kendinde taşıyan bir varlıktır. Kâinat ise insan-ı kebîr olarak değerlendirilir ve bu yaklaşım insan ile doğa arasında derin bir ontolojik bağ bulunduğunu gösterir. Böylece doğa, yalnızca faydalanılacak bir kaynak değil, ilahî düzenin ve hikmetin görünür olduğu anlamlı bir varlık alanıdır (Ergül, 2015, s. 204; Yılmaz, 2007, s. 197; Konuk, 1994, ss. 325-326, aktaran Ergül, 2015, s. 204).

Tasavvufî kozmolojinin temelinde Vahdet-i Vücûd düşüncesi yer alır. Bu anlayışa göre evrendeki her varlık, ilahî isim ve sıfatların bir yansıması olarak değer taşır. İnsan-ı Kâmil ise bu isim ve sıfatların en yetkin biçimde tecelli ettiği varlık olarak, kâinatın ruhu ve cilası kabul edilir. Bu nedenle insanın doğayla ilişkisi mutlak hâkimiyet değil, emanet, halifelik ve mizan ilkeleriyle sınırlandırılmış bir sorumluluk ilişkisidir (Ardoğan, 2009, s. 129; Ergül, 2015, ss. 160, 167; Vural, 2017, s. 243).

Modern antroposentrizme yönelik eleştiriler, Heidegger ve Derin Ekoloji gibi yaklaşımlarda da güçlü biçimde dile getirilmiştir. Heidegger, modern tekniğin varlığı salt kaynak olarak görmesinin insanın dünyayla kurduğu anlam ilişkisini tahrip ettiğini vurgular. Derin Ekoloji ise modern insan merkezci bakışı reddederek doğadaki tüm yaşam formlarına içsel değer atfedilmesi gerektiğini savunur. Bu yaklaşımlar, modern insanın doğayı nesneleştiren ve araçsallaştıran tutumuna karşı önemli eleştirel imkânlar sunmaktadır (Efil, 2018, ss. 276-277; Yaylı ve Çelik, 2011, s. 372; Önder, 2003, s. 162).

Tasavvufî çevre anlayışı ile Derin Ekoloji arasında doğanın değerinin kaynağı bakımından temel bir ayrım bulunmaktadır. Derin Ekoloji doğanın değerini doğanın kendi içkin yapısında temellendirirken, tasavvufî düşünce doğanın değerini onun ilahî yaratılış düzeninin bir yansıması olmasında görür. Bu nedenle her iki yaklaşım doğanın araçsallaştırılmasına ve sınırsız tüketim anlayışına karşı çıksa da tasavvufî perspektif doğaya yönelik sorumluluğu tevhid, emanet ve halifelik ilkeleriyle daha aşkın bir etik zemine yerleştirir (Yardımcı, 2006, s. 40; Yücel, 2017, ss. 86, 153; Şahin, 2022, s. 79).

İki paradigma arasındaki temel fark, insanın doğa karşısındaki konumunu nasıl tanımladığıyla ilgilidir. Modern paradigma insanı doğaya egemen, onu dönüştüren ve kendi çıkarına göre kullanan bir özne olarak görürken; tasavvufî paradigma insanı doğayla ontolojik bütünlük içinde bulunan, onu korumakla yükümlü bir emanet taşıyıcısı olarak değerlendirir. Bu karşılaştırma, ekolojik krizin çözümü için yalnızca teknik araçların değil, insanın varlık anlayışını ve sorumluluk bilincini dönüştürecek daha derin felsefi yaklaşımların gerekli olduğunu göstermektedir (Yücel, 2017, s. 56; Ardoğan, 2012, s. 125; Akot, 2013, s. 178).

ORTAK ZEMİN ARAYIŞI VE YENİ BİR EKO-ETİK SENTEZ İMKÂNI

Ekolojik krizin küresel boyutu, modern insan merkezli düşüncenin doğayı araçsallaştıran, denetim altına alınacak ve sömürülebilecek bir nesne olarak gören temel varsayımlarını yeniden tartışmaya açmıştır. Modern antroposentrik yaklaşım, insanı doğadan ayrı ve ona üstün bir konuma yerleştirirken, doğayı insanın ekonomik ve teknik amaçları doğrultusunda kullanılabilir bir kaynak alanına indirgemiştir. Bu durum, insan-doğa-Tanrı arasındaki kadim bütünlük fikrinin zayıflamasına ve insanın doğa karşısında derin bir yabancılaşma yaşamasına neden olmuştur (Maltaş, 2015, s. 368; Efil, 2018, ss. 237, 298-299; Ardoğan, 2009, s. 244).

Bu kriz karşısında ortak zemin arayışı, çevre sorunlarının yalnızca teknik ya da ekonomik meseleler olarak değil; varlık, değer, ahlak ve anlam alanlarıyla ilişkili derin bir zihniyet problemi olarak değerlendirilmesini gerektirmektedir. Derin Ekoloji ile tasavvufun kozmik insan anlayışı, farklı metafizik temellere sahip olsalar da modern insan merkezci tahakküm düşüncesini ve faydacı materyalist doğa tasavvurunu eleştirme noktasında kesişmektedir. Bu kesişim, çağdaş çevre etiğinin yeniden inşasında önemli bir diyalog zemini oluşturmaktadır (Yücel, 2017, ss. 152-153; Özerkemen, 2002, s. 176; Ergül, 2015, s. 295).

Ortak zeminin en belirgin olduğu alanlardan biri, insan eyleminin etik sınırları ve doğaya saygı ilkesidir. Hem Derin Ekoloji hem de tasavvufî çevre anlayışı, insanın doğa üzerinde mutlak tasarruf hakkı bulunduğu varsayımını reddeder. Doğal kaynakların ölçüsüz biçimde tüketilmemesi, ihtiyaç kadar kullanılması ve doğaya zarar verecek davranışlardan kaçınılması her iki yaklaşımın da temel vurguları arasındadır. Tasavvufî etik bu tutumu israftan kaçınma ve emanete riayet ilkeleriyle temellendirirken, Derin Ekoloji insan dışı varlıkların da kendi başlarına değer taşıdığı düşüncesinden hareket eder (Yücel, 2017, ss. 145, 153; Atalay, 2008, ss. 230-231; Şahin, 2022, s. 80).

Tasavvufî düşüncede doğaya yönelik etik sorumluluğun temelinde mizan, merhamet ve halifelik ilkeleri yer almaktadır. Kâinatın ölçü ve denge içinde yaratıldığı kabulü, insanın doğaya sınırsız müdahale eden bir varlık değil, varlık düzenini korumakla yükümlü bir emanet taşıyıcısı olduğunu gösterir. Bu bağlamda İnsan-ı Kâmil modeli, yaratılanlara karşı şefkat, merhamet ve saygı göstermeyi ahlaki olgunluğun zorunlu bir boyutu olarak değerlendirir. Dolayısıyla tasavvufî çevre anlayışı, ekolojik duyarlılığı yalnızca dışsal bir çevre koruma davranışı değil, insanın manevi yetkinleşme sürecinin bir parçası olarak ele alır (Erkoçoğlu, 2014, ss. 75-76; Ergül, 2015, ss. 292, 295; Özdemir, 2006, s. 183).

Derin Ekoloji de insanın doğanın efendisi değil, ekolojik bütünün bir parçası olduğunu vurgulaması bakımından tasavvufî yaklaşım ile önemli bir ortaklık taşır. Bu yaklaşım, bütün canlıların ve doğal varlık alanlarının kendilerine özgü bir değere sahip olduğunu savunur. Ancak tasavvufî düşüncede bu değer, doğanın kendi içkin yapısından değil, onun ilahî yaratılış düzeninin bir parçası olmasından kaynaklanır. Bu nedenle Derin Ekoloji'nin eko-merkezli bakışı ile tasavvufun teo-merkezli yaklaşımı, doğaya saygı ve tahakküm karşıtlığı bakımından birleşirken, değerin metafizik kaynağı bakımından ayrışmaktadır (Önder, 2003, s. 162; Yaylı ve Çelik, 2011, s. 372; Yücel, 2017, s. 153).

Diyalogun en güçlü potansiyeli, ontolojik ve epistemolojik bütünlük arayışında ortaya çıkmaktadır. Modern düşüncede Kartezyen düalizm, insanı doğadan ve kendi varlık bütünlüğünden ayırmış; doğayla ilişkiyi özne-nesne karşıtlığı üzerine kurmuştur.

Buna karşılık hem Derin Ekoloji hem de tasavvuf, insanın doğadan kopuk değil, daha geniş bir varlık bütünlüğünün parçası olduğu fikrini öne çıkarır.

Tasavvufun Vahdet-i Vücûd anlayışı, varlığı ilahî birlik temelinde yorumlarken; Derin Ekoloji, insan benliğinin daha geniş ekolojik bütünlüklerle özdeşleşmesi gerektiğini savunur (Maltaş, 2015, s. 162; Yaylı ve Çelik, 2011, s. 372; Ergül, 2015, s. 205).

Tasavvufun İnsan-ı Kâmil öğretisi ile Derin Ekoloji'nin kendini gerçekleştirme ilkesi arasında kurulabilecek ilişki, yeni bir eko-etik sentez için dikkat çekici bir imkân sunmaktadır. Derin Ekoloji'de

kendini gerçekleştirme, bireysel benliğin dar sınırlarını aşarak doğayla ve kozmosla bütünleşmesini ifade eder. Tasavvufta ise İnsan-ı Kâmil, nefsin dar sınırlarını aşarak Hakk'ın ahlakıyla ahlaklanan, varlıkla uyum içinde yaşayan ve yaratılmışlara karşı sorumluluk taşıyan ideal insan modelidir. Bu iki yaklaşım, modern bireyin doğadan kopuşunu aşmayı ve insanın varlıkla daha bütüncül bir ilişki kurmasını hedeflemeleri bakımından diyalog kurabilir (Önder, 2003, s. 162; Toprak, 2017, s. 97; Durak, 2010, s. 441).

Diyalog, basit bir özdeşleştirme ya da yüzeysel bir uzlaştırma olarak görülmemelidir. Derin Ekoloji'nin doğayla bütünleşme çağrısı, tasavvufî düşüncede ancak tevhid, emanet, halifelik ve mizan kavramlarıyla yeniden yorumlandığında İslamî bir çevre etiği açısından anlamlı bir zemine kavuşur. Bu nedenle İslamî ilimlerin, modern ekoloji felsefelerinin kavramlarını kendi kaynakları ve ilkeleri açısından sorgulaması önemlidir. Böyle bir sorgulama, hem modern çevre krizine cevap verebilecek hem de tasavvufun özgün varlık ve ahlak anlayışını koruyabilecek bir eko-etik çerçeve geliştirme imkânı sunar (Ardoğan, 2009, ss. 14, 250; Ardoğan, 2012, s. 125; Yücel, 2017, s. 153).

Yeni sentez arayışının temel dayanaklarından biri, tasavvufun teo-merkezli çevre ahlakıdır. Derin Ekoloji doğanın içsel değerini vurgularken, tasavvufî yaklaşım doğanın değerini Allah'ın yaratması, ilahî isimlerin tecellisi ve varlık düzenindeki hikmetle ilişkilendirir. Bu fark, iki yaklaşım arasında bir kopuş sebebi olarak değil, ekolojik sorumluluğun farklı metafizik zeminlerde nasıl kurulabileceğini gösteren verimli bir tartışma alanı olarak değerlendirilmelidir. Tasavvufî çerçevede çevreyi korumak, yalnızca ekolojik bir görev değil, aynı zamanda ahlaki ve uhrevi bir sorumluluktur (Yardımcı, 2006, s. 40; Yücel, 2017, ss. 171-172, 187; Ergül, 2015, s. 217).

Bu noktada tasavvufî perspektif, modern çevre tartışmalarına güçlü bir toplumsal ve manevi motivasyon sağlayabilir. Derin Ekoloji'nin kitlesel dönüşüm üretme kapasitesi sınırlı görülürken, tasavvufun İnsan-ı Kâmil modeli çevreyi korumayı iman, ahlak, ibadet ve sorumluluk bilinciyle ilişkilendirerek daha geniş kitlelere hitap edebilecek bir değer zemini sunmaktadır. Özellikle Müslüman toplumlarda tevhid, emanet, halifelik ve mizan kavramları, ekolojik bilincin yalnızca teorik bir farkındalık değil, gündelik yaşamı dönüştüren ahlaki bir yükümlülük olarak benimsenmesini sağlayabilir (Yaylı ve Yaslıkaya, 2015, s. 463; Yücel, 2017, ss. 55-56; Ardoğan, 2012, s. 125).

Önerilen eko-etik sentez, modern insanın faydacı ve tüketim merkezli yaşam tarzına karşı sade yaşam, ölçülülük, israftan kaçınma ve adalet ilkelerini öne çıkarmaktadır. İslamî çevre etiği, doğanın Allah'ın mülkü olduğu fikriyle insanın mutlak sahiplik iddiasını sınırlandırır; bu da modern öznenin doğa üzerindeki kontrol ve tüketim merkezli yaklaşımına güçlü bir eleştiri sunar.

Böylece insan, doğayı keyfî biçimde kullanan egemen bir özne olmaktan çıkarak, varlık düzeninin korunmasından sorumlu bir emanet taşıyıcısı olarak yeniden konumlandırılır (Atalay, 2008, ss. 230-231; Yücel, 2017, ss. 179, 183; Ardoğan, 2022, s. 53).

Bu sentezin bir diğer önemli boyutu, doğanın Kur'an ve kâinat kitabı bütünlüğü içinde okunmasıdır. Tasavvufî bakışta doğa, yalnızca fiziksel bir çevre değil, Allah'ın sözsüz kelâmı olarak anlam taşıyan bir varlık alanıdır. Bu nedenle doğayı okumak, korumak ve onunla uyum içinde yaşamak, yalnızca çevresel bir duyarlılık değil, aynı zamanda ilahî düzeni anlama ve ona uygun davranma çabasıdır. Böyle bir yaklaşım, çevre etiğini teknik bir yönetim meselesi olmaktan çıkararak manevi, ahlaki ve ontolojik bir sorumluluk alanına taşır (Özdemir, 2007, ss. 44-45; Yıldırım, 2012, ss. 72-73; Ardoğan, 2022, ss. 26-30).

Ortak zemin arayışı, modern insanın doğayla kurduğu araçsal ve faydacı ilişkiyi aşmak için tasavvufî kozmik insan anlayışı ile çağdaş ekoloji felsefeleri arasında eleştirel bir diyalog kurulabileceğini göstermektedir. Bu diyalog, Derin Ekoloji'nin doğanın içsel değerine ilişkin vurgusunu, tasavvufun tevhid, emanet, halifelik ve mizan ilkeleriyle derinleştirerek daha kapsamlı bir çevre ahlakı geliştirme imkânı sunmaktadır. Böylece İnsan-ı Kâmil modeli, modern öznenin yabancılaşmış ve tahakkümcü doğa anlayışına karşı bütüncül, sorumluluk merkezli ve manevi temelli bir alternatif olarak değerlendirilebilir (Yücel, 2017, ss. 73, 184; Toprak, 2017, s. 97; Durak, 2010, s. 452).

SONUÇ

Çalışma, insan-doğa ilişkisinin felsefi temellerini tasavvufun kozmik insan anlayışı ile modern insan felsefesi arasında karşılaştırmalı bir düzlemde incelemiştir. Çalışmanın temel amacı, modern öznenin doğayı araçsallaştıran ve insan merkezli bir değer düzenine yerleştiren yaklaşımı karşısında, tasavvufun İnsan-ı Kâmil öğretisinin insan-doğa ilişkisini yeniden düşünmek için nasıl bir ontolojik ve etik imkân

sunduğunu ortaya koymaktır. Bu doğrultuda çalışma, ekolojik krizin yalnızca teknik, ekonomik ya da yönetsel bir sorun olmadığını; insanın doğayı anlama, değer verme ve onunla ilişki kurma biçiminden kaynaklanan daha derin bir zihniyet problemi olduğunu göstermiştir.

Çalışmada ulaşılan temel sonuçlardan biri, modern insan felsefesinin doğayı çoğunlukla insan aklı, teknik güç ve ekonomik çıkar doğrultusunda dönüştürülebilecek bir nesne olarak konumlandırdığıdır. Bu yaklaşım, insanı doğanın parçası olmaktan çok onun karşısında ve üzerinde duran egemen bir özne hâline getirmiştir. Böylece doğa, içsel anlam ve değer taşıyan bir varlık alanı olarak değil, insan ihtiyaçlarına hizmet eden araçsal bir kaynak olarak değerlendirilmiştir. Bu durum, modern ekolojik krizin arka planında yalnızca çevresel tahribatın değil, aynı zamanda insanın varlıkla kurduğu bağın zayıflamasının da bulunduğunu göstermektedir.

Buna karşılık tasavvufun kozmik insan anlayışı, insanı doğadan kopuk, ona hükmeden ya da onu sınırsızca kullanan bir varlık olarak değil; kâinatla ontolojik bütünlük içinde bulunan, varlık düzeninin anlamını idrak eden ve bu düzen karşısında sorumluluk taşıyan bir varlık olarak ele almaktadır. İnsan-ı Kâmil öğretisi, insanın merkezî konumunu mutlak hâkimiyet şeklinde değil, emanet, halifelik, mizan ve ahlaki sorumluluk çerçevesinde yorumlamaktadır. Bu nedenle tasavvufî perspektifte doğa, tüketilecek bir nesne değil; ilahî düzenin, hikmetin ve anlamın görünür olduğu bir varlık alanıdır.

Çalışmanın karşılaştırmalı değerlendirmesi, modern özne ile İnsan-ı Kâmil arasında temel bir yönelim farkı bulunduğunu ortaya koymuştur. Modern özne, doğayla ilişkisini çoğunlukla kontrol, üretim, tüketim ve fayda üzerinden kurarken; İnsan-ı Kâmil, doğayla ilişkisini sorumluluk, ölçü, merhamet ve bütünlük üzerinden kurmaktadır. Bu fark, ekolojik krizin çözümünde yalnızca teknolojik reformların yeterli olmadığını; insanın kendisini, doğayı ve varlık düzenini nasıl kavradığına ilişkin daha köklü bir dönüşüme ihtiyaç olduğunu göstermektedir.

Derin Ekoloji ile tasavvufî çevre anlayışı arasında kurulan diyalog da bu bağlamda önemli bir sonuç üretmiştir. Her iki yaklaşım, modern insan merkezci doğa anlayışını ve sınırsız tüketim mantığını eleştirmekte; doğanın yalnızca insan çıkarları için var olduğu düşüncesine karşı çıkmaktadır. Ancak bu iki yaklaşım, doğanın değerinin kaynağı konusunda farklılaşmaktadır. Derin Ekoloji doğanın değerini daha çok doğanın kendi içkin yapısında temellendirirken, tasavvufî düşünce doğanın değerini ilahî yaratılış düzeni, tevhid anlayışı ve emanet bilinciyle ilişkilendirmektedir. Bu fark, iki yaklaşım arasında bir kopuştan çok, çağdaş çevre etiği için verimli bir tartışma alanı oluşturmaktadır.

Tasavvufun kozmik insan anlayışının çağdaş ekolojik kriz karşısında güçlü bir felsefi ve etik katkı sunabileceğini göstermektedir. İnsan-ı Kâmil modeli, modern öznenin doğadan kopuk, tahakkümcü ve faydacı konumlanışına karşı; varlıkla bütünlük içinde sorumluluk taşıyan, doğayı emanet olarak gören ve ekolojik dengeyi ahlaki bir yükümlülük şeklinde kavrayan alternatif bir insan tasavvuru önermektedir. Bu yönüyle tasavvufî perspektif, yalnızca bireysel manevi olgunlaşmaya değil, aynı zamanda çevreyle uyumlu, ölçülü ve sorumluluk temelli bir yaşam anlayışının geliştirilmesine de katkı sağlayabilecek niteliktedir.

Bu çalışmanın ana mesajı, ekolojik krizin çözümünde teknik ilerleme kadar insanın varlık anlayışının ve ahlaki sorumluluk bilincinin de dönüştürülmesi gerektiğidir. Modern dünyanın geleceği, yalnızca daha gelişmiş teknolojiler üretmesine değil; insanın doğayla kurduğu ilişkiyi yeniden anlamlandırmasına bağlıdır. Bu bağlamda tasavvufun İnsan-ı Kâmil anlayışı, insan-doğa ilişkisinin yeniden inşasında hem teorik hem de pratik düzeyde değerlendirilebilecek güçlü bir düşünsel imkân sunmaktadır. Gelecek çalışmalarda bu yaklaşımın çevre etiği, sürdürülebilir yaşam, İslam düşüncesinde ekoloji ve çağdaş insan felsefesi bağlamında daha ayrıntılı biçimde ele alınması, alana katkı sağlayacaktır.

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A COMPARATIVE ASSESSMENT OF ALTERNATIVE METHODS FOR *ESTIMATING THE NON-OBSERVED ECONOMY*

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ABSTRAC
The Non-Observed Economy (NOE) encompasses a broad spectrum of economic activities that escape full registration in official national accounts, including informal production, underground transactions, and illegal activities. Its accurate measurement is fundamental to the integrity of macroeconomic statistics, the design of effective fiscal and labour market policies, and the cross-country comparability of national income estimates. Despite decades of methodological development, no single approach has achieved universal acceptance, and the comparative strengths and limitations of competing methods remain a live debate in the empirical and theoretical literature. This paper provides a structured comparative analysis of four principal indirect methods for estimating the NOE: the physical input approach based on electricity consumption, the monetary aggregates approach based on the cash-to-deposit ratio, the monetary transactions approach and the Multiple Indicators Multiple Causes (MIMIC). Each method is examined with respect to its theoretical foundations, data requirements, underlying assumptions, scope of coverage, and analytical limitations. The comparative analysis reveals that no method is universally superior; each captures a distinct dimension of the NOE and operates under assumptions that may be more or less plausible depending on country-specific institutional, structural, and data conditions. The paper argues that the combination of complementary approaches offers the most robust analytical strategy, particularly for transition and developing economies characterised by volatile informal sectors and constrained data environments.
Keywords: Non-Observed Economy; electricity consumption method; cash-to-deposit ratio; monetary transactions; MIMIC model; methodological comparison.

1. INTRODUCTION

The Non-Observed Economy is not a peripheral concern of economic measurement. It represents the heart of national accounting practice, the focal element of fiscal policy design, the core of labour market analysis, and a key point of reference of international economic comparison.

When productive activities, whether informal, underground, or unreported, fall outside the perimeter of official statistics, the resulting distortions are systematic and far-reaching.

Gross Domestic Product is underestimated, tax bases are mismeasured, social expenditure allocation is misaligned, and derived indicators such as public debt ratios, per capita income measures, and poverty indices are rendered unreliable (OECD, 2002). These distorting aspects become problematic in economies where the non-observed sector accounts for a considerable portion of total output since they are no mere calibration errors but fundamental misrepresentations of economic reality.

The challenge is compounded by the inherently covert nature of the phenomenon. The Non-Observed Economy, by definition, resists direct observation. Economic agents operating within it have strong incentives to conceal their activities from tax authorities, regulatory bodies, and statistical offices. This evasion means that standard data collection instruments like: enterprise surveys, household income surveys, administrative tax records, etc, are systematically incomplete with respect to the very activities they are meant to capture. The result is a persistent and structurally measurement gap.

In response to this challenge, economists, statisticians, and national accountants have developed extensive methodological instruments and approaches over the past half-century. These approaches range from direct survey methods, which attempt to elicit information on informal activities from individuals and enterprises, to indirect methods, which infer the presence and scale of the NOE from observable proxies such as energy consumption, monetary aggregates, and labour market indicators.

A third broad class, represented principally by the MIMIC model, adopts an econometric latent variable framework that treats the NOE as an latent variable simultaneously determined by multiple causal forces and manifested through multiple observable indicators.

While the individual methods have each been the subject of extensive attention, comparative assessments that place them side by side, evaluating their theoretical coherence, empirical applicability, and contextual suitability against a common analytical framework, remain less common. The present paper addresses this gap and Its objectives are: ***first***, to provide a rigorous characterisation of the four indirect approaches identified in the literature; ***second,*** to conduct a structured comparative analysis of these methods across a set of analytically meaningful criteria; and ***third,*** to draw methodological implications for the study of the NOE in transition and developing economies, where data constraints and institutional particularities impose specific challenges on researchers and national accountants alike. The paper is structured as follows. Section 2 establishes the conceptual framework, defining the NOE and situating it within the international statistical standards that govern national accounting practice. Section 3 provides an overview of measurement approaches. Sections 4 through 7 characterise each of the four focal methods in detail. Section 8 presents the comparative analysis. Section 9 discusses the methodological implications for transition economies, then the conclusion in Section 10.

2. DEFINING THE NON-OBSERVED ECONOMY

The System of National Accounts is under continuous revision, mainly based on changes in the world economy, new products, new technologies, and the process of globalization. One of the first important legal acts concerning national accounts was the Council Directive 89/130/EEC Euratom on the harmonization of the compilation of Gross National Product in 1989 (European Union, 1989). Five years later, the Commission Decision of 22 February 1994 (94/168/EC) on the measures required for the implementation of Directive 89/130 was adopted. Points 3 and 4 of Decision 94/168/EC refer to a certain degree of exhaustiveness. Commission Decision 98/527/EC concerning the non-reporting of the underground economy includes several important components related to this additional issue.

The term Non-Observed Economy, as codified in the OECD handbook Measuring the Non-Observed Economy (2002), refers to all productive economic activities that are not captured in basic data sources used for the compilation of national accounts. The handbook identifies these principal components:

1. "Underground" activities are defined as those activities which are productive and legal but deliberately concealed from public authorities in order to avoid:

- Payment of income tax, value added tax, and other taxes;
- Payment of social security contributions;
- Compliance with legal standards such as minimum wages, maximum working hours, safety or health standards, etc.;
- Compliance with certain administrative procedures, such as completing statistical questionnaires or other administrative forms.

2. Illegal activities are defined as those productive activities, specifically determined by the boundaries of the System of National Accounts (SNA), which:

- Generate goods and services prohibited by law (e.g. production and distribution of illegal drugs);
- Are unlawful when carried out by unauthorized producers (e.g. unlicensed medical practices).

3. Household production for own final use defines those productive activities that result in goods or services consumed or capitalized by the households that produce them, such as:

- Production of agricultural crops and livestock;
- Production of other goods for own use;
- Construction of their own houses and of others' houses for own-account fixed capital formation;
- Imputed rents of owner-occupied dwellings and paid domestic services.

4. Unobserved informal activities, as part of the informal sector, also cover observed activities undertaken unofficially; in general, informal activities are those productive activities carried out by unincorporated enterprises in the household sector that are unregistered and/or below a certain size in terms of employment, and which have some market production.

This taxonomy is important for method selection because different estimation approaches do not capture the same components with equal effectiveness. Some methods, by virtue of their reliance on monetary indicators, are better suited to capturing underground financial transactions; others, based on energy

proxies, may better reflect physical production activity across sectors; still others, such as the MIMIC model, attempt a synthetic representation of the NOE as a composite phenomenon driven by institutional, fiscal, and structural determinants.

Eurostat's tabular approach, adopted in 2005 and made obligatory for EU member states in 2016, provides a structured framework for identifying and adjusting for non-exhaustiveness (Eurostat, 2005).

The theoretical and practical importance of measurement accuracy extends beyond accounting consistency. Indicators that are calculated relative to GDP, including the public debt ratio, fiscal deficit, poverty, and various social and environmental indices, are directly affected by the accuracy of GDP estimates. An undercount of the NOE therefore implies a systematic overestimation of fiscal pressures and an underestimation of economic wellbeing, with concrete consequences for policy and international assessments.

3. CLASSIFICATION OF MEASUREMENT APPROACHES

Over the years, various methods have been developed to estimate the size and characteristics of the Non-Observed Economy (NOE). There is no single standard methodology that can be universally applied across countries, as the choice of method depends on the availability and quality of data, as well as on the specific characteristics of the economy under study. In practice, countries often employ a combination of methods to obtain more reliable and comprehensive estimates.

3.1 Statistical Methods

Statistical methods encompass both direct and indirect estimation techniques and rely primarily on statistical and administrative data sources.

3.1.1 Direct Methods

Direct methods aim to measure the Non-Observed Economy through the collection of additional information, usually by means of specially designed surveys. These surveys may focus on specific components of the NOE, such as the informal sector, underground economic activities, illegal production, or other activities that are not fully captured by official statistics.The main advantage of direct methods is their ability to provide detailed information on the nature, extent, and causes of non-observed activities. However, because such activities often involve sensitive issues, respondents may be reluctant to disclose accurate information, leading to underreporting or incomplete responses. Consequently, the reliability of these methods depends heavily on respondents' willingness to provide truthful information. (OECD, 2002)

3.1.2 Indirect Methods

Indirect methods, which constitute the focus of this paper, infer the existence and magnitude of the NOE from macroeconomic and financial data that are observable in official statistics. They proceed on the logic that the NOE, despite its concealed nature, leaves traces in legitimate economic variables: in energy consumption patterns, in monetary circulation, in labour force participation rates, or in discrepancies between income and expenditure aggregates. These traces can be identified, isolated, and scaled to produce estimates of the size of the hidden sector. The principal indirect methods include:

a) Source-Based Method

The source-based approach relies on information concerning the inputs used in the production process, such as labour, raw materials, land, and fixed capital. By applying technical relationships between inputs and outputs, estimates can be made of production and value added that may not be fully recorded in official statistics. A widely used variant of this approach is the Labour Input Method (LIM), which compares employment information obtained from labour force surveys with administrative employment records in order to identify informal or unregistered employment.

b) Demand-Based Method

The demand-based approach seeks to estimate production by relying on data indicators associated with the specific use of goods and services that provide a reliable representation of their production.

Examples include household final consumption expenditure on specific products (e.g., healthcare and personal services), the utilization of raw materials in agricultural processing, major export commodities, and administrative records reflecting demand for particular products and services, such as motor vehicle registrations and construction permits.

c) Income-Based Method

This method utilizes administrative information on income generated by individuals and businesses, including tax declarations, social security contributions, and other fiscal records. Discrepancies between reported income and observed economic activity may provide indications of production that is not fully captured by official statistics.

d) Commodity Flow Method

The commodity flow method involves balancing the total supply and use of individual products through accounting identities. By comparing the available supply of a product with its utilization within the economy, it is possible to identify discrepancies that may be associated with non-observed activities. One common application of this method is the estimation of retail trade output based on the supply of goods available in the market.

e) National Accounts Discrepancy Method

This method is based on the circular flow principle of the economy, according to which the expenditure of one economic unit constitutes income for another. In theory, GDP estimates derived from the production approach and the expenditure approach should be equal. Any discrepancy between the two estimates may indicate the existence of non-observed economic activities, although such differences may also arise from statistical errors, methodological limitations, or data deficiencies.

3.2 Model-based econometric approaches

Model-based econometric approaches, the MIMIC model, in particular, represents a methodologically sophisticated attempt to integrate multiple causes and indicators into a single estimation framework, treating the NOE as a latent variable in a structural equation system. This approach allows for a richer representation of the phenomenon but introduces its own assumptions and sensitivities. The results of econometric models can be highly sensitive to underlying assumptions, data transformations, measurement units, and sample selection.

The four methods examined here, the electricity consumption approach, the cash-to-deposit ratio, the monetary transactions approach, and the MIMIC model, represent the most widely applied indirect and model-based methods in the empirical literature, and together span a broad range of theoretical foundations, data requirements, and analytical assumptions.

4. THE PHYSICAL INPUT APPROACH: ELECTRICITY CONSUMPTION

4.1 Theoretical Foundations

The physical input approach rests on the premise that productive economic activity requires material inputs that leave observable traces in official data, even when the output of that activity is concealed. Among the various physical indicators that have been proposed, including freight volumes, raw material flows, and water consumption, electricity has attracted the most systematic attention in the measurement literature, primarily because of its pervasiveness across productive sectors and the availability of reliable administrative data.

The foundational insight, developed by Kaufmann and Kaliberda (1996), is that the elasticity of electricity consumption with respect to GDP tends toward unity over sufficiently long time horizons. This means that a one-percent increase in total economic activity, observed and unobserved, corresponds, on average, to a one-percent increase in electricity consumption. Consequently, if observed GDP growth diverges persistently from electricity consumption growth, the residual can be interpreted as an indicator of changing activity in the non-observed sector. When electricity consumption grows faster than official GDP, this signals an expansion of unregistered productive activity; when it grows more slowly, it may indicate formalisation.

The Lackó (1998, 2000) variant reorients the analysis from total electricity consumption to household electricity consumption specifically. The rationale is that significant portions of informal and underground activity take place in domestic settings, home-based production, informal service provision, small-scale family enterprises, and their energy demands are captured in residential electricity use. Lackó formalises this intuition in a two-equation system: a demand equation for household electricity that includes consumption, prices, heating needs, the share of alternative energy sources, and a term capturing hidden economy output; and a supply equation for hidden economy output driven by the tax burden, social expenditure, and dependency ratios. Estimation is conducted across countries,

using the United States, at an assumed NOE share of 10.5% of GDP, following Morris (1993), as the reference point for scaling country-level results.

4.2 Data Requirements and Implementation

The Kaufmann-Kaliberda approach requires two data series: annual electricity consumption and real GDP growth. Both are typically available from national statistical offices, energy regulatory authorities, and international databases maintained by the World Bank and the International Energy Agency, making this one of the least data-demanding methods. The Lackó approach requires a more complex cross-sectional dataset encompassing household electricity consumption per capita, electricity prices, heating degree days, alternative energy shares, tax-to-GDP ratios, and social expenditure data, necessitating access to harmonised international databases and cross-country comparisons.

4.3 Assumptions and Limitations

The core assumptions of the Kaufmann-Kaliberda method, stable long-run elasticity of electricity with respect to total GDP, and the use of official GDP as the baseline measure, are empirically contestable. The elasticity of unity is an approximation that varies across countries, sectors, and time periods. Energy-intensive industrial economies exhibit higher elasticities; service-dominated economies and those undergoing rapid technological change exhibit lower ones (Schneider & Buehn, 2013). The widespread adoption of energy-efficient technologies over recent decades has decoupled electricity consumption from output growth in many settings, introducing downward bias in NOE estimates derived from this method.

Furthermore, not all informal activities are electrically intensive. Labour-intensive informal services like: street vending, domestic work, cash-in-hand construction labour, etc, consume little electricity and therefore generate no signal in electricity data. The method is also blind to informal activities that substitute alternative energy sources (diesel generators, gas, solar) for grid electricity, which is particularly relevant in economies with unreliable electricity supply.

The Lackó variant addresses the sectoral scope problem partially by focusing on household-level consumption, but introduces a different set of assumptions. The use of the United States as a universal reference country has been criticised on the grounds that structural differences between economies, in climate, energy pricing policy, household size, and informality patterns, render such a benchmark methodologically questionable (Hassan & Schneider, 2016). The method also assumes that the relationship between household electricity and hidden economy output is structurally similar across very different national contexts, which is unlikely to hold universally.

5. THE MONETARY AGGREGATES APPROACH: CASH-TO-DEPOSIT RATIO

5.1 Theoretical Foundations

The monetary aggregates approach proceeds from the observation that underground and informal economic transactions are predominantly conducted in cash, since cash transactions are untraceable by tax authorities and leave no paper trail in the financial system. If this observation holds, then an expansion of the non-observed economy should produce an observable increase in the demand for currency relative to the deposits held in the banking system. Monitoring the ratio of currency outside banks to total deposits therefore provides an indirect signal of changing NOE activity.

Cagan (1958) was the first to formalise this intuition. His approach establishes a base-period ratio of currency to deposits, chosen as a point in time when the NOE is assumed to be negligible or at a historically low level and interprets subsequent increases in this ratio as evidence of growing underground activity. The excess currency demand over and above what would be required if the ratio remained at its base-period level is then converted into an NOE estimate by multiplying the estimated stock of shadow-economy money by the velocity of money assumed to be equal to the velocity in the formal economy.

Tanzi (1980, 1983) substantially refined Cagan's framework by introducing an econometric demand equation for currency. Rather than assuming a fixed base-period ratio, Tanzi models the demand for currency as a function of the burden of taxation, per capita income, the interest rate on deposits, and the share of wages in national income. The coefficient on the tax variable captures the marginal impact of fiscal pressure on currency demand beyond what can be explained by legitimate transaction motives. The NOE is then estimated as the shadow money supply the excess currency attributable to the tax variable multiplied by income velocity.

5.2 Data Requirements and Implementation

Both variants of the monetary aggregates approach rely primarily on data from central banks: currency in circulation outside the banking system, total deposits, interest rates, and, for the Tanzi variant, tax revenue and national income aggregates. These data are generally available from monetary statistics published by central banks and from IMF databases, making this approach comparatively accessible. Atanasijević et al. (2022), applying a variant of this method to Serbia, demonstrate its feasibility in transition economies where central bank data are consistently reported.

5.3 Assumptions and Limitations

The Cagan method rests on several assumptions that have attracted sustained critical discussion. The most fundamental is the choice of the base year: the method assumes that in the reference period, NOE activity was effectively zero, or at least negligibly small. In practice, this assumption is almost certainly violated. Informal and underground economies are not temporary aberrations that appeared at some identifiable point in history; they are structural features of all economies at all times (Feige, 1979). The choice of a 'clean' base year is therefore inherently arbitrary, and the resulting estimates are sensitive to this choice.

A second problematic assumption is that all NOE transactions are cash-mediated. The progressive digitalisation of informal transactions through mobile payments, cryptocurrency, and other non-cash instruments undermines this premise. As informal actors increasingly adopt digital transaction methods to take advantage of their convenience, the cash signal is attenuated, and the cash-to-deposit ratio becomes a less reliable indicator of NOE size (Medina & Schneider, 2021).

Third, the assumption that monetary velocity is identical in the formal and informal economies is maintained by necessity rather than by evidence. It is plausible that currency circulates more rapidly in the informal sector, where it cannot be deposited and must be recirculated quickly, but it is equally possible that hoarding and cash storage in high-inflationary or high-uncertainty environments depresses velocity in informal circuits relative to formal ones. This uncertainty introduces an unquantifiable source of bias.

The Tanzi refinement addresses some of these problems by replacing the base-year assumption with an econometric model, but it introduces its own vulnerability: the assumption that taxes are the only driver of excess currency demand. In practice, the ratio of currency to deposits is influenced by financial sector development, consumer preferences for cash, banking infrastructure access, and macroeconomic uncertainty none of which are related to informal activity (Isachsen & Strøm, 1985). Separating these factors from the actual effects of informality requires careful analysis and cannot be done perfectly.

6. THE MONETARY TRANSACTIONS APPROACH

6.1 Theoretical Foundations

Feige (1979) proposed a methodologically distinct approach that draws on the quantity theory of money as its theoretical backbone. The Fisher equation, $M \times V = P \times T$, relates the money supply (M) and its velocity of circulation (V) to the price level (P) and the total volume of transactions (T). Feige's critical insight is that total transactions encompassing all exchanges of goods and services, in both the formal and informal economies should bear a stable long-run relationship to total economic output, defined as observed plus unobserved GDP.

If this ratio of transactions to total output is assumed to be constant, and if the total volume of transactions can be estimated from monetary data (specifically, from currency and deposit turnover), then the gap between estimated total output and measured official GDP yields an estimate of the NOE. The method thus avoids the need to assume that any particular type of transaction medium (cash versus deposits) is the exclusive medium of informal exchange; instead, it works from the aggregate volume of all transactions.

6.2 Data Requirements and Implementation

The monetary transactions approach requires data on the total volume of transactions processed through the financial system not merely the stock of money but its rate of turnover. This demands data on currency circulation and the volume of bank debits or cheque clearances, which in many countries are either not systematically recorded or are available only in aggregate form that does not permit the necessary decomposition. The data demands of this method are therefore substantially more onerous than those of the cash-to-deposit ratio approach, and the method has proved difficult to implement

rigorously outside the United States and a handful of other economies with comprehensive monetary statistics.

6.3 Assumptions and Limitations

The fundamental challenge of the Feige approach lies in its reliance on the assumption of a stable long-run ratio between transactions and output. This ratio is not constant. It varies with the degree of financial intermediation, the complexity of production chains, the extent of financial market activity, and the payment technology in use at any given time. As economies become more financialised, the volume of transactions associated with a given level of GDP rises sharply — not because the real economy has grown, but because financial trading and intermediation generate their own transaction volumes. Disentangling productive economic transactions from purely financial ones is conceptually and empirically demanding.

A second limitation is the method's reliance on the Fisher equation, which presupposes a stable and identifiable velocity of money. Velocity is empirically unstable across countries and time periods, undermining the method's inferential logic. The assumption that informal transactions leave identical monetary traces to formal ones and that these traces can be separately identified adds further complexity. Feige (1979) himself acknowledged that the practical implementation of the method requires the identification of a base period during which the NOE is negligible, replicating the same fundamental problem encountered by the Cagan approach. The method is theoretically elegant but, as de Sousa Fernandes (2022) observes, has never been fully operationalised with the precision its theoretical framework demands.

7. THE MIMIC MODEL: A LATENT VARIABLE APPROACH

7.1 Theoretical Foundations

The Multiple Indicators Multiple Causes (MIMIC) model represents a fundamentally different analytical strategy. Rather than inferring the size of the NOE from a single proxy electricity consumption, a monetary ratio, or transaction volumes it treats the NOE as an unobserved latent variable that is simultaneously caused by a vector of structural determinants and manifested through a vector of observable indicators. This structural equation modelling framework was introduced to the NOE measurement literature by Frey and Weck-Hannemann (1984), who applied it to estimate hidden economy size across 17 OECD countries.

The model has two components. The structural equation specifies the determinants of the latent NOE variable typically including the overall tax burden, the regulatory burden on labour markets, the quality of governance, corruption indicators, unemployment, and macroeconomic stability measures. The intuition is that fiscal pressure and regulatory complexity raise the costs of operating within the formal economy, thereby incentivising migration toward informal arrangements; poor governance and corruption reduce the probability of detection and punishment; unemployment pushes workers toward informal labour markets. Each of these causal pathways corresponds to a coefficient in the structural equation.

The measurement equation links the unobservable NOE to its observable manifestations, or indicators. Commonly used indicators include the demand for currency, the labour force participation rate (which tends to fall when workers exit formal employment for informal arrangements), and statistical discrepancies between the income and expenditure sides of national accounts. The loading factors on these indicators capture the strength of the relationship between the latent NOE and each observable proxy.

7.2 Model Structure and Estimation

The MIMIC model is estimated using maximum likelihood methods within the structural equation modelling framework. Estimation requires a set of observable cause and indicator variables measured at regular intervals for the country or set of countries under study. The output of the estimation is not a direct measure of the level of the NOE but rather an index a time series of standardised scores representing the relative size of the NOE across periods or countries. To convert this index into a level estimate expressed as a percentage of GDP, an external reference value must be used, typically obtained from another method (such as the currency demand approach) for a specific benchmark period. This

calibration step introduces a significant dependency between the MIMIC estimate and the reliability of the reference method (Breusch, 2016).

Schneider and his collaborators have applied the MIMIC framework most extensively in the literature, producing estimates for large country panels spanning multiple decades (Medina & Schneider, 2021). Dell'Anno and Schneider (2009) provide a detailed methodological exposition of the approach and its application to Italian data. Hassan and Schneider (2016) apply it jointly with currency demand methods to Egypt, illustrating the calibration interdependency between the two methods.

7.3 Assumptions and Limitations

The MIMIC approach is analytically appealing precisely because it acknowledges what simpler methods ignore: that the NOE is a multi-causal phenomenon and that no single proxy captures it adequately. However, this breadth comes with significant vulnerabilities.

The model's results depend critically on the selection of cause and indicator variables. There is no theoretically mandated list of regressors; the choice is guided by theory and data availability, and different specifications yield substantially different results. Kirchgässner (2017) argues that this flexibility makes the MIMIC approach susceptible to specification search the inadvertent or deliberate selection of variable combinations that produce results consistent with prior expectations. Feld and Schneider (2017), in response, acknowledge the sensitivity but maintain that transparent reporting of specification choices mitigates this concern.

A further limitation noted by Soares and Afonso (2019) is that the MIMIC model does not establish whether the estimated causal relationships are statistically significant in the sense required for policy inference. The structural coefficients represent average relationships across the estimation sample, but they do not demonstrate that marginal changes in, say, tax pressure produce identifiable changes in informal activity in any specific country context. As Kirchgässner (2017) and Medina and Schneider (2021) both acknowledge, using MIMIC estimates to evaluate the effects of specific policy interventions on the NOE is therefore methodologically problematic without additional supporting evidence.

The calibration requirement also raises concerns. Since the MIMIC model produces an index rather than a level, converting this index to a share of GDP requires anchoring it to an externally obtained reference estimate. If that reference estimate is itself subject to bias as is the case with currency demand estimates, which are the most commonly used calibration benchmark the bias is imported into the final MIMIC estimate. This creates a form of methodological circularity in which the two most widely applied indirect methods are mutually dependent (Breusch, 2016).

8. COMPARATIVE ANALYSIS

8.1 Analytical Framework

The four methods reviewed in the preceding sections can be compared across six analytically meaningful dimensions: **(i)** theoretical foundation and the nature of the NOE component they primarily capture; **(ii)** data requirements and the feasibility of implementation across different country settings; **(iii)** core assumptions and their empirical plausibility; **(iv)** scope of the NOE that each method covers; **(v)** type of output produced; and **(vi)** specific strengths and limitations in the context of developing and transition economies.

Table 1 below provides a comparative summary of the four methods across these dimensions.

Table 1. Comparative Summary of Four NOE Estimation Methods

Criterion	**Electricity (K&K 1996) (Lackó 1998/2000)**	**Cash-to-Deposit (Cagan/Tanzi)**	**Feige Transactions**	**MIMIC Model**
Theoretical basis	- Physical input–output proportionality; elec.–GDP elasticity ≈ 1 - Household energy as proxy for home-based informality	Excess cash demand reflects unrecorded transactions	Quantity theory of money; stable transaction–output ratio	Structural equation modelling; latent variable theory

Primary data required	- Total electricity consumption; real GDP growth - Household electricity, prices, tax data (cross-country panel)	Currency in circulation, total deposits, tax revenue	Currency & deposit turnover; cheque clearances	Tax burden, governance indices, unemployment, currency demand, LFPR
Data availability (developing economies)	- Generally good - Moderate to difficult	Generally good	Poor to very poor	Variable; governance data often limited
Core assumption (most critical)	- Electricity–GDP elasticity stable at ≈ 1 - Household energy proxies home-based NOE; US benchmark valid	Base-year NOE ≈ 0; informal transactions are cash-only	Transactions/output ratio is stable; base-year NOE ≈ 0	Variable selection is theory-consistent; calibration reference is unbiased
Scope of NOE captured	- Primarily energy-intensive production-side activity - Home-based & informal service activity	Underground monetary transactions broadly	All informal monetary transactions (formal & informal)	Multi-dimensional: production, fiscal, labour market, institutional
Output type	- Change in NOE relative to base year (% deviation) - Level of NOE as % of GDP (via US reference)	Level in monetary units; % of GDP	Level in monetary units; % of GDP	Index (growth rates); calibrated to % of GDP
Susceptibility to technology change	- High, energy efficiency reduces signal - Moderate to high	Moderate, digitalisation erodes cash signal	Low to moderate	Low, multiple indicators buffer single-proxy failure
Cross-country comparability	- Limited, elasticity varies by economic structure - Moderate , common framework, questionable reference	Limited, cash preferences & banking infrastructure differ	Very limited, data inconsistency across countries	High, within consistent model specification
Applicability to transition economies	- Moderate, suited to industrial/post-socialist contexts - Moderate, requires harmonised cross-country data	Good, central bank data generally available	Poor, transaction data rarely compiled	Good in principle, depends on data and governance indicator quality

Source: Author's Compiliation

8.2 Theoretical Coherence and Internal Consistency

Among the four approaches, the MIMIC model exhibits the greatest theoretical coherence in the sense that it explicitly models the NOE as a multi-dimensional, causally structured phenomenon rather than

reducing it to a single-proxy inference. The electricity approach, in its Kaufmann-Kaliberda variant, offers a transparent and parsimonious theoretical logic but at the cost of scope: it captures only activities mediated through electricity consumption, which may be a declining share of informal activity as economies evolve. The monetary approaches occupy an intermediate position: the Tanzi variant of the cash-to-deposit ratio is theoretically more sophisticated than Cagan's original formulation, in that it models currency demand as a function of multiple determinants rather than assuming a fixed ratio, but it is still fundamentally reliant on a single transmission mechanism like the cash preference of informal actors.

The Feige approach is theoretically attractive in that it does not restrict itself to cash transactions alone but encompasses all transaction media. However, its practical implementation requires data on total transaction volumes that are rarely available in the necessary detail, particularly in developing and transition economies. The theoretical generality of the approach has thus not translated into widespread empirical application.

8.3 Data Requirements and Feasibility

The electricity consumption method in its Kaufmann-Kaliberda formulation is the most data-parsimonious of the four approaches, requiring only two consistently measured series. This makes it particularly viable in settings where other data are unreliable or absent. The Lackó variant raises the data bar considerably, requiring cross-country harmonised datasets and making single-country applications problematic.

Monetary aggregates data: currency outside banks, deposit volumes, interest rates are routinely published by central banks and are available in standardised form from IMF financial statistics, making the Cagan-Tanzi approach broadly applicable across both developed and developing economies. This is a significant practical advantage.

The Feige transactions approach fails this feasibility test for most developing and transition economies. Detailed data on the total volume of bank debits and cheque clearances are not systematically compiled in many countries, and where they exist, aggregation conventions differ, preventing meaningful cross-country comparison. The method has seen virtually no application in the economies of Southeast Europe or other transition regions.

The MIMIC model's data requirements are arguably the most complex, encompassing governance quality indicators, labour force participation rates, tax administration indices, and multiple financial variables. Many of these are available from international sources (World Bank Governance Indicators, IMF Fiscal Monitor), but their reliability in developing country contexts varies substantially. The model's sensitivity to variable availability means that specifications applied in high-income country contexts may not be directly transposable to data-constrained environments.

8.4 Core Assumptions and Empirical Plausibility

A candid comparative assessment must acknowledge that all four methods rest on assumptions that are empirically contestable and may be violated to varying degrees depending on context.

The unity elasticity assumption of the Kaufmann-Kaliberda approach has been empirically supported for post-socialist economies in the 1990s, which was the original application context, but has weakened considerably as energy efficiency programmes, structural economic shifts, and rising services shares have reduced the electricity intensity of GDP growth in many countries. In economies with a rapidly expanding service sector and active energy efficiency investments, the residual between electricity and GDP growth reflects these structural changes at least as much as it reflects changes in informal activity.

The zero-informality base-year assumption of both the Cagan and Feige approaches is, as argued above, empirically indefensible. It introduces a permanent and unquantifiable level bias into the resulting estimates. The Tanzi refinement partially addresses this by modelling currency demand econometrically, but the assumption that taxation is the primary driver of excess cash demand remains questionable in economies where cash is preferred for cultural, infrastructural, or macroeconomic stability reasons unrelated to informality.

The MIMIC model's calibration assumption that the reference estimate used to anchor the index is accurate imports the biases of the reference method into the final MIMIC result. Breusch (2016) subjects

this calibration procedure to rigorous scrutiny and concludes that MIMIC estimates are more sensitive to calibration choices than is generally acknowledged in the applied literature.

8.5 Scope Coverage: What Does Each Method Actually Measure?

A critical and often underemphasised dimension of the comparison is that the four methods do not measure the same thing. The Kaufmann-Kaliberda approach, because it is anchored in total electricity consumption, captures primarily the production-side NOE in sectors with significant energy intensity. It is relatively insensitive to informal services, agriculture, and home-based activities. The Lackó approach is specifically designed for home-based and household-level informal activity and therefore captures a distinct and complementary subset of the NOE.

The monetary approaches, whether in their cash-ratio or transactions variants, capture activities mediated through monetary exchange. Non-monetary exchanges barter, own-account production, informal care work fall outside their scope. This omission is particularly significant in rural economies and in sectors characterised by reciprocal non-monetary exchanges between households and communities.

The MIMIC model, by incorporating labour market indicators and national accounts discrepancies alongside monetary proxies, achieves broader coverage in principle. However, the coverage is determined by the indicator variables selected, and a MIMIC model using only monetary indicators will not be substantively broader than a single-method monetary approach.

This heterogeneity of scope has a crucial implication for empirical research: estimates generated by different methods are not directly comparable, even for the same country and time period. Observed differences between estimates obtained by different methods do not necessarily reflect inaccuracy in one or both approaches; they may instead reflect the genuinely different phenomena each method captures.

8.6 Comparative Performance in Developing and Transition Economies

Developing and transition economies present a specific set of methodological challenges: unstable macroeconomic conditions, weak institutional infrastructure, limited data availability, rapidly evolving financial and energy systems, and large structural shares of informal employment and production. These characteristics differentially affect the performance of the four methods.

The electricity approach performs relatively well in economies where industrial and manufacturing activity is a significant share of GDP, electricity infrastructure is reasonably developed, and alternative energy sources are not widely prevalent conditions that broadly characterised the post-socialist transition economies of Central and Eastern Europe in the 1990s, the context for which the Kaufmann-Kaliberda method was originally designed. Its applicability weakens as these economies develop and diversify.

The cash-to-deposit ratio approach performs well when banking system data are reliable and cash preferences are stable over time. In economies undergoing rapid financial deepening as is typical of transition countries the ratio of cash to deposits trends downward structurally, independent of any changes in informal activity. Failure to correct for this financial development trend risks interpreting formalisation-driven shifts in payment behaviour as changes in NOE size, introducing substantial bias.

The Feige approach is the least applicable in developing and transition economy contexts, given its demanding data requirements. Its theoretical elegance does not compensate for its practical infeasibility in data-constrained environments.

The MIMIC model, when properly specified and estimated, is arguably the most appropriate method for countries undergoing complex structural transitions, precisely because it can incorporate the multiple, simultaneous institutional and economic forces that drive informal activity in such settings. However, its dependence on good-quality governance and institutional data limits its practical utility when these inputs are themselves unreliable.

9. DISCUSSION

The comparative analysis above leads to several methodological implications that are relevant both for researchers studying the NOE and for national statistical offices seeking to improve the exhaustiveness of national accounts.

The most fundamental implication is that no single method should be treated as definitive. Each of the four approaches reviewed here captures a dimension of the NOE, operates under assumptions that will be more or less plausible in specific contexts, and produces estimates that are not directly comparable to those generated by alternative methods. Schneider and Buehn (2013) observe that different methods tend to produce estimates that are correlated across countries and time large NOEs are large regardless of the method used but differ substantially in their estimated levels. This suggests that while the methods converge on the ordering of countries by NOE size, they disagree on magnitudes in ways that matter for policy.

Methodological triangulation the use of multiple methods applied to the same country and time period, with a systematic effort to understand the sources of divergence between estimates offers the most robust analytical strategy. Where electricity-based estimates and monetary-aggregate-based estimates converge, confidence in the conclusion is higher than where they diverge. Where they diverge, the pattern of divergence may itself be informative: a case in which monetary estimates are high but electricity estimates are low might suggest that the NOE is concentrated in low-energy-intensity services and financial activities; the reverse pattern might indicate energy-intensive underground production.

For transition economies in particular, the temporal dynamics of estimation are important. Methods calibrated on base-year assumptions become increasingly unreliable as the economy evolves rapidly, making period-specific recalibration essential. The MIMIC model has an advantage here in its capacity to capture time-varying relationships, but requires longitudinal consistency in the underlying data series.

A further implication concerns the interaction between data quality and method choice. All four methods rely on official data that are themselves subject to measurement error. In a setting where national accounts, monetary statistics, and energy data are all imperfectly measured, the residuals from which NOE estimates are derived will be contaminated by statistical noise from multiple sources. Under these conditions, simpler methods with more transparent assumptions may be preferable to more complex approaches whose error propagation is harder to track. The parsimony of the Kaufmann-Kaliberda approach, despite its limitations, has methodological value in precisely this sense.

Finally, the policy use of NOE estimates must be aligned with the method through which they were produced. MIMIC-based estimates are appropriate for understanding the structural determinants of the NOE the relative contributions of fiscal pressure, labour regulation, and governance quality but, as Kirchgässner (2017) emphasises, should not be used to simulate the policy effects of marginal changes in these drivers without additional structural identification. Monetary aggregate estimates are appropriate for assessing the cash economy and for guiding tax administration efforts focused on cash-intensive sectors. Electricity-based estimates are useful for monitoring aggregate production activity in goods-producing sectors and identifying structural breaks associated with economic liberalisation or crisis events.

10. CONCLUSION

The Non-Observed Economy remains one of the most consequential and methodologically contested domains in empirical economics. The four methods examined in this paper the electricity consumption approach in its two principal variants, the monetary aggregates approach, the monetary transactions method, and the MIMIC latent variable model each contribute a distinct analytical perspective and together illustrate the breadth of strategies that researchers have developed in response to the fundamental challenge of measuring what is, by its nature, designed to be unmeasured.

The structured comparative analysis presented here demonstrates that the methods are not interchangeable. They differ in their theoretical foundations, data requirements, scope of coverage, and the nature of the assumptions they impose. The electricity approach offers operational simplicity and physical interpretability but is increasingly compromised by energy efficiency dynamics and the shift toward service-dominated economies. The monetary aggregate approach provides access through ubiquitous financial data but relies on empirically questionable assumptions about cash preference, monetary velocity, and the validity of a base-year counterfactual. The monetary transactions approach is theoretically comprehensive but practically infeasible in most country contexts due to data unavailability. The MIMIC model offers conceptual richness and multi-dimensional coverage but is sensitive to variable selection, depends on a calibration step that imports external biases, and cannot support structural policy inference without additional identification conditions being met.

Taken together, these observations point toward three conclusions that have practical import for the research community and for national statistical authorities engaged in the pursuit of exhaustive national accounts.

First, the selection of an estimation method should be driven by the specific question under investigation and by a clear-eyed assessment of the data environment, rather than by convention or disciplinary habit. Researchers and statistical offices working in transition economies with strong monetary data but unreliable energy statistics should favour monetary approaches; those with good energy data and limited financial sector development may find the electricity approach more reliable.

Second, whenever feasible, estimates from multiple methods should be produced and compared. The pattern of agreement and disagreement across methods is itself informative about the composition of the NOE and should be reported as part of the research output, not suppressed in the pursuit of a single headline figure.

Third, the NOE is not a static phenomenon. Its size, composition, and drivers evolve with economic structure, institutional development, technological change, and macroeconomic conditions. Any estimation strategy that treats the NOE as temporally stable through fixed elasticities, constant velocity assumptions, or unchanged model specifications will progressively accumulate bias. Regular methodological review and recalibration are essential components of a credible and durable measurement programme.

The pursuit of exhaustiveness in national accounts is ultimately a commitment to economic truth. That commitment is best served not by confidence in any single methodological approach, but by intellectual humility about the limits of each, and by sustained investment in the data quality and institutional infrastructure that make rigorous estimation possible.

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RECONCEPTUALIZING HERBAL KNOWLEDGE: INDIGENOUS PLANT-DERIVED REMEDIES FOR COVID-19 IN INDIA

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ABSTRACT
Traditional Indian medicine encompasses the practices of Ayurveda, Siddha, Unani, and Homeopathy, collectively providing a comprehensive understanding of medicinal plants and their various pharmacological properties. These encompass antiviral, immunomodulatory, anti-inflammatory, and antioxidant properties, rendering them attractive options for the management of COVID-19 and other respiratory infections, including SARS, Influenza, and Respiratory Syncytial Virus (RSV). This review examines current research and registered clinical studies on the application of traditional Indian herbal medicines in treating COVID-19. Ethnopharmacological research indicates that natural chemicals derived from these plants may assist in both prevention and treatment. Principal herbs under examination comprise Cinchona, Curcuma longa (turmeric), Nigella sativa (black seed), Azadirachta indica (neem), Tinospora cordifolia (giloy), Allium sativum (garlic), Oroxylum indicum, Punica granatum (pomegranate), Cocos nucifera (coconut), Mangifera indica (mango), Uvaria species, Artemisia annua, and Allium cepa (onion). This review facilitates the advancement of innovative natural herbal mixtures as alternative treatments. It underscores the potential of these formulations in the development of immunopotentiators, herbal or Ayurvedic antiviral medications, antibacterial and antiviral medicines, and their utilization in the prevention and treatment of COVID-19. This review advocates for the creation of novel herbal formulations as alternative therapies, emphasizing their promise as immunopotentiators and antiviral agents in the prevention and management of COVID-19.
Keywords: Artemisia annua, COVID-19, Immunopotentiators, Indigenous plants, Natural herbal mixtures, Ayurveda.

Introduction

The appearance of a new coronavirus in late 2019 triggered an outbreak of a serious pneumonia-like illness, which was subsequently named Coronavirus Disease 2019 (COVID-19). This illness rapidly developed into a global pandemic, profoundly affecting populations and healthcare systems across the globe (World Health Organization [WHO], 2020a). India, celebrated for its rich and varied heritage of traditional medicine, is home to well-established medical practices such as Ayurveda, Siddha, and Unani. Among these, Ayurveda is widely acknowledged as one of the oldest holistic healing systems in existence. It is acknowledged for its application of natural therapies and plant-based cures usually having low adverse effects (Sharma et al., 2015; Patwardhan et al., 2020). It also encourages a harmonic balance between the body, mind, and soul. By stressing the strengthening of immunity and thorough treatment, these conventional medical systems offer valuable viewpoints and possible therapeutic options, especially in regard to newly developing infectious disorders like COVID-19.

Comprising Ayurveda, Siddha, and Unani, the Indian Traditional System of Medicine is among the oldest holistic healing systems in the world, having amassed a great body of knowledge over millennia from the observation and use of medicinal plants. Plant-based remedies have long been used in these systems to strengthen immunity and cure a range of medical conditions, including infections. In light of the rise of viral diseases such as COVID-19, there has been a resurgence of interest in traditional medicine for its potential therapeutic benefits. (Patwardhan, 2005).

A variety of medicinal plants indigenous to India have shown antiviral and immunomodulatory properties. Notable examples include Tinospora cordifolia (Giloy), Glycyrrhiza glabra (Licorice), Azadirachta indica (Neem), Andrographis paniculata, Calotropis gigantea, Ocimum sanctum (Tulsi),

Curcuma longa (Turmeric), Withania somnifera (Ashwagandha), Zingiber officinale (Ginger), Allium sativum (Garlic), and Moringa oleifera (Drumstick tree), all of which are traditionally recognized for their immune-enhancing and antiviral effects.(Rastogi, 2020; Dhama, 2020; Ghosh, 2021)
Furthermore, additional botanicals such as Cinchona, Nigella sativa (Black seed), Oroxylum indicum, Punica granatum (Pomegranate), Cocos nucifera (Coconut), Mangifera indica (Mango), Uvaria species, Artemisia annua (Sweet wormwood), and Allium cepa (Onion) have been studied for their phytochemical compositions and biological activities, particularly in relation to viral infections. These plants are abundant in bioactive compounds, including alkaloids, flavonoids, terpenes, and essential oils, which play a significant role in their therapeutic effectiveness.(Shown in table-1)
This review emphasizes the significance of these herbs in relation to COVID-19 and other acute respiratory infections. By synthesizing findings from experimental research and documented clinical trials, it advocates for the creation of novel herbal formulations. Such formulations could function as immunopotentiators and alternative therapies, thus providing comprehensive approaches to pandemic readiness and public health initiatives.

Table-1: Scientific Categorization of Chosen Medicinal Flora

S.No.	Botanical Name	Family	Common Name	Part Used
1.	Tinospora cordifolia	Menispermaceae	Giloy	Stem, leaves
2.	Curcuma longa	Zingiberaceae	Turmeric	Rhizome
3.	Nigella sativa	Ranunculaceae	Black seed	Seeds
4.	Azadirachta indica	Meliaceae	Neem	Leaves, bark, seeds
5.	Allium sativum	Amaryllidaceae	Garlic	Bulb
6.	Allium cepa	Amaryllidaceae	Onion	Bulb
7.	Glycyrrhiza glabra	Fabaceae	Licorice	Root
8.	Ocimum sanctum	Lamiaceae	Tulsi (Holy Basil)	Leaves
9.	Zingiber officinale	Zingiberaceae	Ginger	Rhizome
10.	Withania somnifera	Solanaceae	Ashwagandha	Root
11.	Moringa oleifera	Moringaceae	Moringa	Leaves, seeds
12.	Punica granatum	Lythraceae	Pomegranate	Fruit rind, seeds
13.	Cocos nucifera	Arecaceae	Coconut	Kernel, oil
14.	Mangifera indica	Anacardiaceae	Mango	Bark, leaves
15.	Andrographis paniculata	Acanthaceae	Andrographis	Whole plant
16.	Calotropis gigantea	Apocynaceae	Calotropis	Latex, leaves
17.	Oroxylum indicum	Bignoniaceae	Oroxylum	Bark, fruit
18.	Cinchona spp.	Rubiaceae	Cinchona	Bark
19.	Artemisia annua	Asteraceae	Artemisia	Leaves
20.	Uvaria spp.	Annonaceae	Uvaria spp.	Leaves, fruits
21.	Botanical Name	Family	Common Name	Part Used
22.	Tinospora cordifolia	Menispermaceae	Giloy	Stem, leaves
23.	Curcuma longa	Zingiberaceae	Turmeric	Rhizome
24.	Nigella sativa	Ranunculaceae	Black seed	Seeds

The role of Tinospora cordifolia in the fight against SARS-CoV-2 and Other Pharmacological Impacts

Particularly in Ayurveda, Tinospora cordifolia also known as Giloy is a highly revered medicinal herb used in traditional Indian medicine. Often referred to as "Amrita," or "divine nectar," it is known for its revitalising properties and ability to strengthen the body's natural defences against disease. T. cordifolia drew much attention during the COVID-19 epidemic because of its possible ability to treat SARS-CoV-2 infections. Its varied phytochemical makeup highlights several pharmacological actions including antiviral, immunomodulating, anti-inflammatory, and antioxidant ones. Compounds such tinosporide, magnoflorine, and berberine have shown in silico studies to be able to block important viral proteins

including the major protease (Mpro) and the spike protein, therefore preventing viral multiplication and entry (Sagar et al., 2021; Krupanidhi et al., 2021). The potential of the plant to activate macrophages, natural killer (NK) cells, T-cells, and so promote balanced cytokine production—which helps prevent cytokine storms a major contributor to complications associated with COVID-19—showcases its immunomodulating properties (Singh et al., 2014; Siddiqui et al., 2021). Moreover, its anti-inflammatory action helps to lower pro-inflammatory cytokines including IL-6 and TNF-α, hence reducing lung inflammation and systemic immunological damage (More & Pai, 2011). While its antipyretic and antibacterial activities further help in giving symptomatic relief and avoiding subsequent infections, Giloy's antioxidant qualities help reduce oxidative stress, safeguarding tissues during infections, while their capabilities help protect tissues during infections. Especially in formulations like AYUSH-64, which are advised for mild to moderate instances, T. cordifolia has proven hepatoprotective and nephroprotective advantages, hence it is a useful supplement in the management of COVID-19.

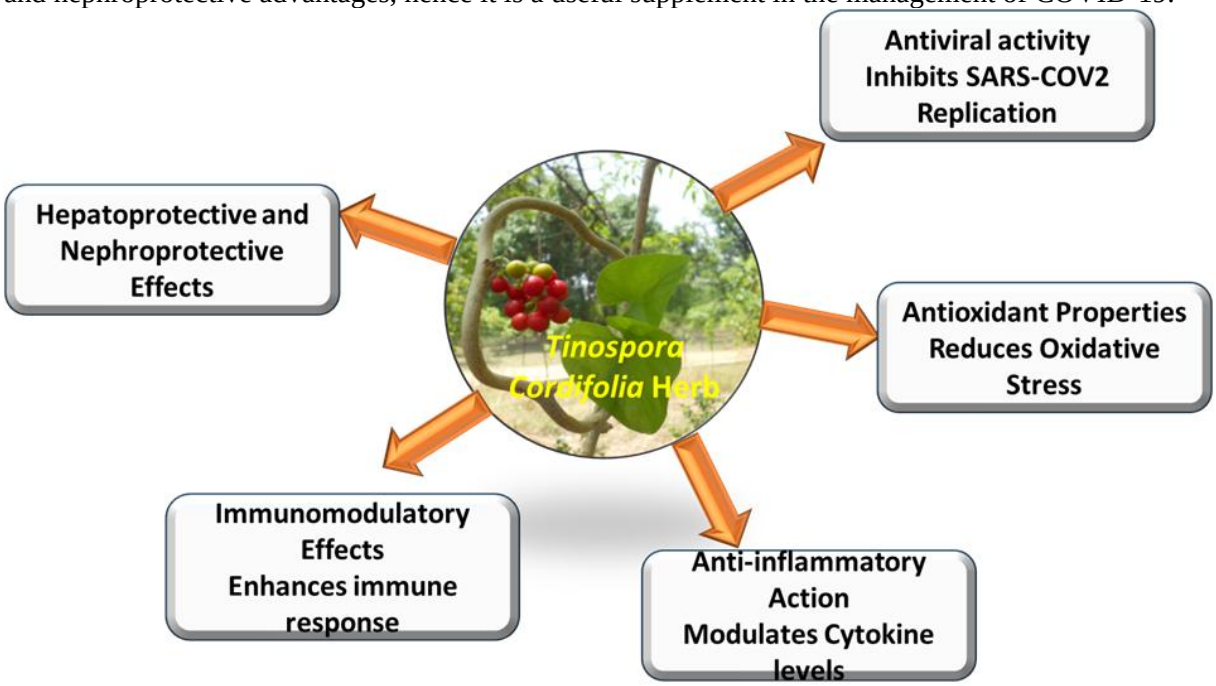

Figure-1: Illustrates that T. cordifolia, an essential herb in Ayurvedic medicine, serves multiple therapeutic functions. Notably, it plays a significant role in combating SARS-CoV-2 infections through its antiviral, immunomodulatory, anti-inflammatory, and antioxidant properties. Major phytochemicals such as tinosporide, berberine, as well as magnoflorine engage with viral proteins, regulate cytokine levels, enhance immune cell activity, and provide protection against oxidative stress and inflammation. These characteristics highlight its potential as an adjunctive treatment in strategies aimed at controlling COVID-19.

Licorice vs. COVID-19: Nature’s Antiviral Ally

Glycyrrhiza glabra, widely recognized as licorice, has garnered attention for its potential therapeutic benefits against SARS-CoV-2, primarily due to its active component, glycyrrhizin. This substance exhibits notable antiviral properties by hindering the virus's replication and modulating the host's immune response. Mechanistically, glycyrrhizin interferes with the virus's ability to penetrate and replicate within host cells by binding to the ACE2 receptor, which SARS-CoV-2 utilizes for cellular entry, thereby potentially blocking the virus's access. Furthermore, glycyrrhizin has been shown to inhibit the activity of the viral main protease (Mpro), an enzyme crucial for the virus's replication process. Beyond its antiviral capabilities, glycyrrhizin also possesses anti-inflammatory properties. It modulates the immune response by decreasing the production of pro-inflammatory cytokines such as IL-6 and TNF-α, which are often elevated in severe COVID-19 cases. This modulation can help mitigate the cytokine storm that may arise during the progression of the disease. Additionally, glycyrrhizin's antioxidant properties contribute to reducing oxidative stress, a factor linked to the onset of COVID-19. By neutralizing free radicals and enhancing the body's antioxidant defenses, it aids in protecting tissues

from oxidative damage. In summary, the multifaceted pharmacological effects of glycyrrhizin, which include antiviral, anti-inflammatory, and antioxidant actions, underscore the potential of Glycyrrhiza glabra as a complementary treatment option for COVID-19. However, clinical trials are essential to validate its efficacy and safety in this context. (Sun, 2019;Van de Sand, 2021)

Neem (Azadirachta indica): An Innate Antiviral Defence Against SARS-CoV-2

Azadirachta indica, widely recognized as neem, has been extensively studied for its antiviral properties, particularly concerning SARS-CoV-2. The bioactive compound nimbin, a triterpenoid found in neem, has demonstrated significant antiviral activity. Nimbin exhibits a strong affinity for the spike glycoprotein of SARS-CoV-2 and the ACE2 receptor, which the virus utilizes to penetrate host cells. This interaction may obstruct the virus's capacity to bind to and invade host cells, thereby preventing infection. Laboratory studies have shown that neem bark extract, which contains nimbin, can reduce the detrimental effects of SARS-CoV-2 on human lung cell models, underscoring its potential to avert infections in nasal and pulmonary tissues. Beyond its antiviral effects, neem also offers anti-inflammatory, immunomodulatory, and antioxidant properties. These attributes enhance its therapeutic potential in addressing COVID-19 by modulating the immune response and reducing inflammation associated with the disease. (Kumar, 2020)

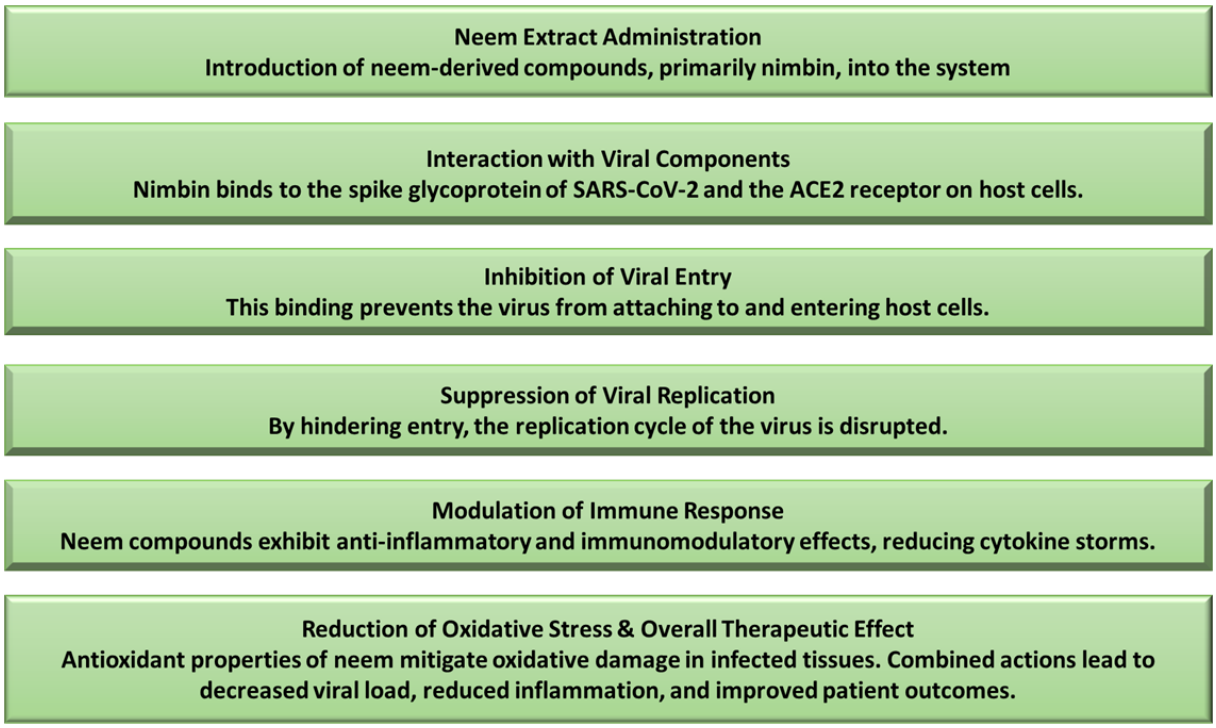

Figure-2:The Mode of Action of Azadirachta indica (Neem) in Combatting SARS-CoV-2

Andrographis paniculata, widely recognized as Kalmegh, contains a high concentration of the diterpenoid andrographolide, which has shown significant efficacy against SARS-CoV-2. In silico docking analyses indicate that andrographolide binds with strong affinity to the main protease (Mpro) of SARS-CoV-2, an essential enzyme involved in viral replication, thereby suggesting a potential mechanism for its direct antiviral effects. Complementary in vitro studies conducted with human lung epithelial Calu-3 cells demonstrated that both the extract of A. paniculata and the isolated andrographolide effectively lower infectious SARS-CoV-2 titers (IC_{50} = 0.036 µg/mL and 0.034 µM, respectively), while showing minimal cytotoxic effects across various organ-derived cell lines. In addition to its antiviral capabilities, andrographolide plays a role in modulating the host immune response by inhibiting NF-κB signaling and reducing pro-inflammatory cytokines (such as IL-6 and TNF-α), which may help alleviate the cytokine storm linked to severe cases of COVID-19. (Enmozhi,2020;Sa-ngiamsuntorn, 2021)

Immune-Boosting and Antiviral Properties of Prominent Indian Medicinal Plants in Relation to COVID-19

Traditional Indian medicinal plants such as Calotropis gigantea, Ocimum sanctum (Tulsi), Curcuma longa (Turmeric), Withania somnifera (Ashwagandha), Zingiber officinale (Ginger), Allium sativum (Garlic), and Moringa oleifera (Drumstick tree) are well-known for their abilities to enhance immunity and exhibit antiviral effects. Ocimum sanctum is rich in bioactive compounds like eugenol and ursolic acid, which enhance the activity of macrophages and lymphocytes while regulating cytokine production, thereby bolstering the body's defenses against viral infections. (Pandey, 2020) While the gingerols and shogaols contained in Zingiber officinale activate natural killer cells and boost mucosal immunity, Curcuma longa's curcumin boosts T-cell proliferation and improves macrophage functioning. Allicin from Allium sativum has been shown to enhance macrophage phagocytosis and dendritic cell maturation, therefore promoting both adaptive and innate immune responses. Rich in vitamins, minerals, and polyphenols, Moringa oleifera's nutrient-dense leaves also show notable immunostimulating action by raising antibody synthesis and lymphocyte count. In addition to their immune-modulating properties, these plants possess direct antiviral actions against SARS-CoV-2. Phytoconstituents from Calotropis gigantea, such as calotroposides, have a strong binding affinity for the viral main protease (Mpro), hindering viral replication. Withania somnifera's withanolides, particularly Withanoside V, have been found to interact with both Mpro and the spike protein, potentially obstructing viral entry and processing. Curcumin disrupts the integrity of the viral envelope and interferes with the binding of ACE2 to the spike protein, while allicin from garlic forms inhibitory hydrogen bonds with SARS-CoV-2 proteases. In silico analyses of flavonoids from Moringa oleifera, including luteolin and quercetin, have also identified them as potential Mpro inhibitors. Finally, the anti-inflammatory and antioxidant properties of these herbs help alleviate the cytokine storm and reduce oxidative tissue damage.(Choudhary,2021;Garg, 2020;Shrestha, 2021;Moyo, 2021)

Antiviral Characteristics and Promising Role of Essential Botanicals in Combatting SARS-CoV-2 and Various Viral Infections

Numerous botanicals have been examined for their phytochemical compositions and biological activities, especially concerning viral infections. Cinchona officinalis, known as the source of quinine, has a historical background in malaria treatment and is currently being explored for its potential antiviral effects against a range of viruses. Nigella sativa, commonly referred to as Black seed, contains thymoquinone, which has shown antiviral properties against various viruses, including influenza and hepatitis C. Oroxylum indicum has been utilized in traditional Ayurvedic medicine, with preliminary studies indicating its extracts may possess antiviral effects.(Arumugam, 2024; Khan, 2020; Shah, 2021) Punica granatum, or Pomegranate, is abundant in polyphenols, particularly ellagic acid, which has been identified as having antiviral properties against herpes simplex virus and human papillomavirus. Cocos nucifera, or Coconut oil, contains lauric acid, which has exhibited antiviral activity against enveloped viruses such as influenza and HIV. The leaves and seeds of Mangifera indica, or Mango, contain compounds like mangiferin that have demonstrated antiviral effects against dengue virus and herpes simplex virus. Uvaria species have been traditionally employed in various cultures, and while some studies indicate their potential antiviral properties, further investigation is warranted.(Asiri, 2023; Azrina, 2021; Mohanty, 2023)

Artemisia annua, known as Sweet wormwood, is the source of artemisinin, traditionally used for malaria treatment and currently under study for its potential antiviral properties against SARS-CoV-2.

Allium cepa, or Onion, contains quercetin and other flavonoids that have shown antiviral activity against influenza and rhinovirus. These botanicals, with their varied phytochemical profiles, present promising opportunities for the development of antiviral agents. Nonetheless, additional research and clinical trials are crucial to validate their efficacy and safety in the treatment of viral infections.(Irfan, 2024; Roy, 2024)

Way Forward: Research Recommendations

A comprehensive study approach is essential to fully harness the potential of traditional Indian medicinal herbs. Future research should prioritize the standardization of herbal extracts to ensure consistent quality and therapeutic effectiveness. The use of advanced phytochemical techniques, such as HPLC, LC-MS,

and NMR, is crucial for the identification and isolation of active compounds. To confirm their antiviral, immunomodulatory, and anti-inflammatory properties, these bioactive substances must be evaluated through both in vitro and in vivo studies. Additionally, in silico molecular docking studies are valuable for identifying promising pharmacological candidates targeting viral proteins, particularly those associated with SARS-CoV-2.Moreover, integrating traditional knowledge with modern scientific approaches necessitates collaboration across various disciplines, including botany, pharmacology, virology, and traditional medicine. There is an urgent need for ethically conducted clinical trials to evaluate these herbal treatments in human subjects, ensuring adherence to safety and regulatory standards. Future initiatives should also prioritize the conservation of medicinal plant biodiversity and promote sustainable harvesting practices. By merging contemporary scientific research with insights from Ayurveda and other traditional systems, we can develop effective, accessible, and nature-based therapeutic solutions for both existing and emerging viral diseases.

Conclusion

Especially because of the COVID-19 epidemic, the growing attention on traditional Indian medicinal plants emphasizes their great therapeutic power. Among the plants listed here are Tinospora cordifolia, Glycyrrhiza glabra, Azadirachta indica, and Andrographis paniculata, which show encouraging antiviral, immunomodulating, anti-inflammatory, and antioxidant activities. These centuries-old herbal therapies, which are progressively backed by modern scientific study and have been used for millennia, offer interesting paths for the development of creative, plant-based treatments for respiratory diseases including SARS-CoV-2. Combining conventional knowledge with contemporary biomedicine will help us to better handle present and future pandemics in a more all-encompassing and environmentally friendly way

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THE IMPACT OF SECURITY CHALLENGES ON EMERGING TECHNOLOGY IN MATHEMATICS, ENGINEERING, TECHNOLOGY, AND SCIENCE (METS) EDUCATION LECTURERS IN UNIVERSITIES

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ABSTRACT
This study investigates the impact of security challenges on the adoption and utilization of emerging technologies among Mathematics, Engineering, Technology, and Science (METS) education lecturers in universities. The increasing rate of insecurity, including terrorism, banditry, kidnapping, cybercrime, and infrastructural vandalism, has significantly disrupted academic activities in higher education institutions. The study adopted a descriptive survey research design involving 120 METS lecturers selected through stratified random sampling. Data were collected using a structured questionnaire and analyzed using mean and standard deviation. Findings revealed that insecurity significantly limits access to digital infrastructure, reduces lecturers' willingness to integrate emerging technologies, and negatively affects digital competency development. The study concludes that security challenges constitute a major barrier to technological advancement in higher education and recommends strategic interventions such as improved campus security, investment in digital infrastructure, and capacity-building programs.
Keywords: Security challenges, emerging technology, METS education, digital competency, university lecturers

Introduction
The integration of emerging technologies into higher education has transformed teaching, learning, and research processes globally. Technologies such as artificial intelligence (AI), virtual laboratories, augmented reality (AR), cloud computing, and learning management systems (LMS) are increasingly being adopted in Mathematics, Engineering, Technology, and Science (METS) education.
These technologies enhance instructional delivery, promote interactive learning, and equip students with skills required in the 21st-century workforce. However, the effective adoption of these technologies is highly dependent on a stable and secure learning environment.
In many developing countries, particularly Nigeria, the rising wave of insecurity—manifested in terrorism, banditry, kidnapping, and cyber threats—has created significant barriers to educational development. Universities, which are expected to serve as centers of innovation, are increasingly affected by these challenges.
Security challenges not only disrupt academic calendars but also hinder access to digital infrastructure, reduce funding for technological development, and create psychological stress among lecturers. As a result, the integration of emerging technologies in METS education is significantly compromised.

Statement of the Problem
Despite the global shift toward technology-driven education, many universities in Nigeria struggle to effectively integrate emerging technologies due to persistent security challenges.

Lecturers in METS disciplines face numerous difficulties, including:
Limited access to modern technological tools
Inadequate digital infrastructure
Disruptions in teaching and research activities
Fear and anxiety affecting productivity
These challenges have resulted in low levels of technology adoption, reduced teaching effectiveness, and inadequate preparation of students for modern industrial demands.
Therefore, this study seeks to examine how security challenges impact the adoption and utilization of emerging technologies among METS lecturers.

Objectives of the Study
The main objective of this study is to assess the impact of security challenges on emerging technology adoption among METS lecturers.
Specific objectives are to:
Examine the impact of security challenges on access to emerging technologies.
Determine the effect of insecurity on the utilization of digital tools in teaching.
Assess the influence of security challenges on digital competency development.
Identify strategies for improving technology adoption in insecure environments.

Research Questions
How do security challenges affect access to emerging technologies among METS lecturers?
What is the impact of insecurity on the utilization of digital tools in teaching?
To what extent does insecurity influence lecturers' digital competency?
What strategies can mitigate the effects of security challenges on technology adoption?

Hypotheses
H01: Security challenges have no significant impact on access to emerging technologies.
H02: Security challenges have no significant effect on the utilization of digital tools.
H03: Security challenges do not significantly influence digital competency development.

Literature Review
Concept of Emerging Technology in Education
Emerging technologies refer to innovative digital tools that enhance teaching and learning processes. According to recent studies (Oladipo, 2023; UNESCO, 2021), technologies such as AI, simulation tools, and virtual laboratories improve students' engagement and understanding, especially in METS disciplines.

Security Challenges in Higher Education
Security challenges include physical threats (terrorism, kidnapping, banditry) and cyber threats (hacking, data breaches). Recent studies (Ibrahim & Yusuf, 2022; Eze et al., 2019) indicate that insecurity disrupts academic activities and limits institutional development.
Impact of Security Challenges on Technology Adoption
Research shows that insecurity reduces access to infrastructure, discourages innovation, and affects lecturers' motivation (Ajayi, 2021; Okeke, 2020). Cyber insecurity also discourages the use of online platforms for teaching.

Theoretical Framework
This study is based on the Technology Acceptance Model (TAM) developed by Davis (1989), which explains that technology adoption is influenced by perceived usefulness and ease of use. Security challenges act as external barriers affecting these perceptions.
Additionally, the Diffusion of Innovation Theory supports the study by explaining how environmental factors influence technology adoption.

Methodology

Research Design

Descriptive survey design is use for study.

Area of Study

Universities offering METS-related programs in Nigeria.

Population

All METS lecturers in selected universities.

Sample and Sampling Technique

120 lecturers selected using stratified random sampling.

Instrument for Data Collection

A structured questionnaire titled: Security Challenges and Emerging Technology Questionnaire (SCETQ)

Validity and Reliability

Face and content validity by experts

Cronbach Alpha reliability coefficient: 0.84

Method of Data Analysis

Mean and standard deviation for research questions

t-test for hypotheses

Decision rule: Mean ≥ 2.50

Results

Table 1: Impact on Access to Technology

Item	Mean	Decision
Insecurity limits access to ICT tools	3.45	Agree
Poor infrastructure due to insecurity	3.30	Agree

Table 2: Utilization of Technology

Item	Mean	Decision
Reduced use of digital teaching tools	3.40	Agree
Cyber threats affect online teaching	3.35	Agree

Table 3: Digital Competency

Item	Mean	Decision
Insecurity affects training opportunities	3.38	Agree
Reduced participation in digital workshops	3.36	Agree

Discussion of Findings

The findings indicate that security challenges significantly affect the adoption of emerging technologies among METS lecturers. This aligns with recent studies emphasizing that unstable environments hinder technological advancement.

The results also show that insecurity reduces lecturers' confidence and willingness to integrate digital tools, thereby affecting teaching effectiveness.

Implications of the Study

Poor technology adoption affects students' learning outcomes
Limits innovation and research productivity
Reduces global competitiveness of universities

Conclusion

Security challenges remain a critical barrier to the integration of emerging technologies in METS education. Without addressing these issues, universities may fail to meet global educational standards.

Recommendations

Government should strengthen campus security systems.
Universities should invest in secure digital infrastructure.
Regular ICT training should be provided for lecturers.
Hybrid learning systems should be adopted.
Policies should support digital resilience in education.

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BEYOND GENETIC DETERMINISM: A GENOMIC AND DEVELOPMENTAL FRAMEWORK FOR AUTISM RISK ASSESSMENT

GENETİK DETERMİNİZMİN ÖTESİNDE: OTİZM RİSKİNİN DEĞERLENDİRİLMESİNE YÖNELİK GENOMİK VE GELİŞİMSEL BİR ÇERÇEVE

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ABSTRACT

Autism spectrum disorder (ASD) has a substantial genetic component; however, it cannot be deterministically predicted during the preconceptional, prenatal, or early postnatal periods. ASD represents a highly heterogeneous neurodevelopmental phenotype that cannot be explained by a single gene, genetic variant, biomarker, or neuroanatomical finding.

The aim of this review is to examine the factors that limit deterministic interpretations of autism risk and to propose a stepwise genomic-developmental risk assessment framework for clinical counseling. A narrative review approach was employed, drawing upon genomic, epigenetic, and developmental literature published since 2019.

Current evidence indicates that autism risk emerges through complex interactions among rare high-impact variants, copy number variations, de novo mutations, inherited variants, epigenetic mechanisms, and polygenic contributions. Nevertheless, the predictive value of these factors at the individual level remains limited because of variable expressivity, incomplete penetrance, pleiotropy, and marked phenotypic heterogeneity.

Based on these findings, a stepwise framework is proposed, including family history assessment, developmental phenotyping, genetic counseling, classification of genetic findings according to clinical significance, uncertainty communication, and postnatal developmental surveillance.

In conclusion, autism risk should not be conceptualized as a definitive prenatal or preconceptional diagnostic category. Rather, it should be understood as a probabilistic, developmental, and ethically sensitive domain that requires careful interpretation and longitudinal monitoring.

Keywords: Autism spectrum disorder; genomic risk; developmental phenotyping; genetic counseling; polygenic risk.

ÖZET

Otizm spektrum bozukluğu (OSB), güçlü bir genetik bileşene sahip olmasına rağmen prekonsepsiyonel, prenatal veya erken postnatal dönemlerde deterministik biçimde öngörülebilen bir durum değildir. Bunun temel nedeni, OSB'nin tek bir gen, genetik varyant, biyobelirteç veya nöroanatomik bulgu ile açıklanamayacak kadar heterojen bir nörogelişimsel fenotip olmasıdır.

Bu derlemenin amacı, otizm riskinin deterministik olarak yorumlanmasını sınırlayan faktörleri incelemek ve klinik danışmanlık süreçlerinde kullanılabilecek kademeli bir genomik-gelişimsel risk değerlendirme çerçevesi önermektir. Çalışma, 2019 yılı sonrasında yayımlanan genomik, epigenetik ve gelişimsel literatüre dayalı narratif derleme yaklaşımıyla hazırlanmıştır. Güncel bulgular, otizm riskinde nadir yüksek etkili DNA varyantları, kopya sayısı değişiklikleri, de novo mutasyonları, kalıtılmış varyantlar ile epigenetik mekanizmalar ve poligenik katkılar arasındaki karmaşık etkileşimlerden kaynaklandığını göstermektedir. Bununla birlikte, değişken ekspresivite, eksik penetrans, pleiotropi ve belirgin fenotipik heterojenlik nedeniyle bu faktörlerin bireysel düzeydeki öngörü gücü de sınırlı kalmaktadır. Bu bulgular doğrultusunda aile öyküsünün değerlendirilmesi, gelişimsel fenotipleme, genetik danışmanlık, genetik bulguların klinik anlam düzeylerine göre sınıflandırılması, belirsizliğin etkili biçimde paylaşılması ve doğum sonrası gelişimsel izlemi içeren kademeli bir değerlendirme çerçevesi önerilmektedir.

Sonuç olarak otizm riski, kesin prenatal veya prekonsepsiyonel bir tanı kategorisi olarak değerlendirilmemelidir. Bunun yerine, dikkatli yorumlama ve uzunlamasına izlem gerektiren olasılıksal, gelişimsel ve etik açıdan duyarlı bir danışmanlık alanı olarak ele alınmalıdır.
Anahtar Kelimeler: Otizm spektrum bozukluğu, genomik risk, gelişimsel fenotipleme, genetik danışmanlık, poligenik risk.

GİRİŞ

Otizm spektrum bozukluğu (OSB), DSM-5 tanı çerçevesinde sosyal iletişim ve sosyal etkileşim alanlarında kalıcı yetersizlikler ile sınırlı, tekrarlayıcı davranış, sınırlı ilgi ve etkinlik örüntülerinin birlikte bulunduğu bir nörogelişimsel durum olarak tanımlanır (American Psychiatric Association, 2013). Klinik görünüm yani fenotip, trizomi21 (down sendromu)'deki gibi tek tip değildir. Dil gelişimi, bilişsel profil, duyusal işlemleme, motor özellikler, regülasyon, adaptif işlevler, eşlik eden tıbbi durumlar ve destek gereksinimi bireyler arasında belirgin biçimde değişebilir. Bu nedenle OSB, yalnızca tanı kategorisi üzerinden değil, gelişimsel seyir ve fonksiyonel ihtiyaçlar üzerinden de değerlendirilmelidir.

Özellikle insan genom projesinden sonra OSB'nin güçlü bir genetik bileşene sahip olduğu tartışmalı değildir, diyebiliriz. Genom çapında ilişkilendirme çalışmaları yaygın varyantların küçük etkili fakat toplamda anlamlı katkısını göstermiş; büyük ölçekli ekzom dizileme çalışmaları ise nadir kodlayıcı varyantların, de novo mutasyonların ve kopya sayısı varyasyonlarının OSB riskinde rol oynadığını ortaya koymuştur (Grove ve ark., 2019; Satterstrom ve ark., 2020; Fu ve ark., 2022; Zhou ve ark., 2022). Antaki ve ark. (2022), nadir varyant yükü, poligenik risk ve biyolojik cinsiyetin birlikte OSB fenotip spektrumuna katkı sunduğunu göstermiştir. Warrier ve ark. (2022) ise genetik bulguların fenotipik heterojenlikle ilişkisini vurgulamıştır. Bu birikimler, genetik bilginin OSB biyolojisini anlamada oldukça önemli olduğunu göstermektedir.

Buna karşın genetik katkının güçlü olması, bireysel düzeyde kesin öngörü yapılabileceği anlamına gelmemektedir. Çünkü, OSB ile ilişkili varyantların önemli bir kısmı eksik penetrans ve değişken ekspresivite gösterir. Aynı genetik bulgu bazı bireylerde OSB, bazılarında entelektüel yetersizlik, dil gecikmesi, dikkat sorunları, epilepsi ya da daha hafif gelişimsel özelliklerle ilişkili olabilir. Bu durum pleiotropi ile de bağlantılıdır; bir genetik yol yalnızca OSB'ye özgü olmayabilir. Ayrıca OSB fenotipi gelişimsel olarak zaman içinde belirginleşir. Bazı çocuklarda erken sosyal iletişim farklılıkları öne çıkarken, bazılarında yoğun duyusal-motor-vokal stereotipiler görülebilmektedir. Ayrıca dil, motor koordinasyon, regülasyon ya da adaptif işlev örüntüleri daha belirleyici olabilir. Bu tartışmanın klinik önemi, ailelerin gebelik öncesi, gebelik dönemi veya erken çocuklukta karşılaştıkları genetik bilgiyi nasıl yorumlayacaklarıyla doğrudan ilişkilidir. Bir risk varyantının saptanması aile için açıklayıcı olabilir; ancak aynı bilgi bağlamından koparıldığında kaderci, damgalayıcı veya gereksiz kaygı ve korku yaratan bir dile dönüşebilir. Bu nedenle risk değerlendirmesinin amacı çocuğun geleceğini kesinleştirmek değil, izlem yoğunluğunu, tıbbi değerlendirme gereksinimini ve erken destek planını daha bilinçli biçimde düzenlemektir.

METODOLOJİ

Bu nedenle güncel klinik soru, 'OSB genetik midir?' sorusundan ziyade, 'Genetik bilgi bir çocuk ve aile için ne ölçüde güvenilir, yararlı ve etik biçimde yorumlanabilir?' sorusudur. Prenatal epigenetik imzalar, fetal görüntüleme bulguları ve poligenik risk skorları OSB'nin gelişimsel biyolojisine ilişkin değerli ipuçları sunabilir; ancak mevcut kanıtlar bu bulguların tek başına bireysel tanı, prenatal kesin öngörü ya da embriyo seçimi için kullanılmasını desteklememektedir (Capalbo et al., 2024; Lencz et al., 2022; de Wit et al., 2025). Bu çalışma, OSB riskinin genetik determinizme indirgenmesini bilimsel ve etik açıdan sınırlayan kanıtları tartışmakta ve genomik bilgiyi gelişimsel izlemle birleştiren danışmanlık odaklı bir model önermektedir.

Çalışma, sistematik derleme ya da meta-analiz olarak değil, yapılandırılmış anlatı derlemesi ve kavramsal sentez olarak tasarlanmıştır.

Bunun temel nedeni, ele alınan sorunun yalnızca nicel etki büyüklüklerinin karşılaştırılmasıyla yanıtlanamayacak kadar çok katmanlı olmasıdır. İncelenen literatür; OSB'nin genetik mimarisi, poligenik risk skorlarının klinik sınırları, prenatal ve prekonsepsiyonel biyobelirteç tartışmaları, ailevi

tekrar riski, postnatal genetik test ve genetik danışmanlık, erken gelişimsel izlem ve otizm genomikleri etiği olmak üzere altı ana başlık altında değerlendirilmiştir.
Kaynak seçimi 2019-2026 aralığında yayımlanmış hakemli çalışmalar ve ilgili mesleki rehber/pozisyon açıklamalarıyla sınırlandırılmıştır. Öncelik, büyük örneklemli genomik çalışmalar, Nature, Nature Genetics, Cell, Pediatrics, The Lancet Neurology, Human Reproduction Update, JAACAP Open, Genetics in Medicine, Journal of Genetic Counseling, European Journal of Medical Genetics, Communications Biology ve benzeri hakemli dergilerde yayımlanan makalelere verilmiştir. Ayrıca 2026 tarihli ASHG, NSGC ve ACMG ortak açıklaması, primer araştırma makalesi olarak değil, genetik danışmanlık ve klinik iletişim açısından güncel mesleki pozisyonu temsil eden resmi bir kaynak olarak ele alınmıştır.
Dahil etme ölçütleri şu şekilde belirlenmiştir: (1) OSB ile ilişkili yaygın varyantlar, nadir varyantlar, de novo ve kalıtılmış varyasyonlar, CNV, WES, WGS, poligenik risk skoru (PRS) veya epigenetik belirteçler hakkında doğrudan kanıt sunması; (2) bulguların OSB fenotipik heterojenliği, gelişimsel seyir veya klinik danışmanlıkla ilişkilendirilebilir olması; (3) prenatal, prekonsepsiyonel ya da postnatal risk değerlendirmesinin sınırlarına ilişkin bilimsel veya etik değerlendirme içermesi; (4) kaynakların DOI, PubMed, dergi sayfası ya da resmi kurum sayfası üzerinden doğrulanabilir olması önemli olmuştur. Dışlama ölçütleri ise OSB'ye özgü olmayan genel genetik yorumlar, doğrulanamayan popüler kaynaklar, nedensellik iddiasını desteklemeyen ancak klinik kesinlik gibi sunulan çalışmalar ve yalnızca spekülatif biyobelirteç iddialarıdır.
Metodolojik olarak kullanılan kavramsal sentez, özellikle farklı kanıt türlerinin aynı klinik düzlemde nasıl buluştuğunu göstermek için seçilmiştir. Genomik çalışmalar gen düzeyinde, PRS çalışmaları istatistiksel risk düzeyinde, prenatal biyobelirteç çalışmaları biyolojik mekanizma düzeyinde, gelişimsel izlem çalışmaları ise fenotipin zaman içindeki görünümü düzeyinde bilgi üretir. Bu düzeyler birbirinin yerine geçmez; ancak birlikte okunduğunda daha gerçekçi bir danışmanlık dili kurulabilir.
Bu metinde kullanılan yöntem, bir klinik uygulama rehberi üretme iddiası taşımaz. Amaç, mevcut kanıtları karar algoritması gibi sunmak değil, farklı kanıt türlerinin hangi noktada güçlü, hangi noktada sınırlı olduğunu görünür kılmaktır. Bu nedenle çalışmaların örneklem büyüklüğü, araştırma tasarımı ve yayın türü dikkate alınmış; ancak tek tek çalışmalar üzerinden kesin öneri üretmek yerine, literatürün ortak yönelimi kavramsal olarak sentezlenmiştir. Özellikle 2025 ve 2026 tarihli çalışmalar güncellik açısından değerli olmakla birlikte, klinik uygulamaya doğrudan aktarılmadan önce replikasyon, bağımsız doğrulama ve farklı popülasyonlarda geçerlilik gereksinimi açısından temkinli yorumlanmıştır.
Analiz sürecinde çalışmalar üç düzeyde kodlanmıştır: kanıt türü, klinik çıkarım ve deterministik yorum riski.
Kanıt türü; genomik mimari, poligenik risk, prenatal biyobelirteç, gelişimsel izlem ve etik danışmanlık olarak ayrılmıştır.
Klinik çıkarım, bulgunun tanı, risk sınıflaması, tıbbi izlem, aile danışmanlığı veya erken destek planlaması açısından ne sağlayabileceği üzerinden değerlendirilmiştir.
Deterministik yorum riski ise bir bulgunun 'kesin tanı', 'kaçınılmaz sonuç', 'tek genetik neden' ya da 'prenatal kesin öngörü' biçiminde yanlış kullanılma potansiyeli üzerinden tartışılmıştır.
Bu yaklaşım, literatürü yalnızca özetlemeyi değil, farklı kanıt düzeylerini klinik ve etik bir çerçevede birleştirmeyi amaçlamıştır.

BULGULAR

Literatürün ilk bulgusu, OSB'de genetik sinyalin güçlü ve aynı zamanda çok katmanlı olduğudur. Grove ve ark. (2019), yaygın varyantların OSB riskine katkısını genom çapında ilişkilendirme çalışmasıyla ortaya koymuştur. Satterstrom ve ark. (2020), 35.584 örnek ve 11.986 OSB olgusunu içeren büyük ölçekli ekzom dizileme çalışmasında 102 risk genini tanımlamıştır. Fu ve ark. (2022), 63.237 bireyden oluşan kohortta protein sonlandırıcı varyantlar, missense varyantlar ve CNV'leri birlikte değerlendirerek OSB ile güçlü ilişki gösteren 72 gen bildirmiştir. Zhou ve ark. (2022), de novo ve kalıtılmış varyantları birlikte inceleyerek yüksek ve orta risk genlerinin klinik etkilerinin aynı olmadığını göstermiştir.
Bu bulgular, OSB'nin genetik temelini güçlendirmekte olup özellikle de ailelerin ihtiyacı olan tek genli veya tek varyantlı bir cevap arayışının henüz mümkün olmadığını göstermektedir.

İkinci bulgu, genetik riskin fenotipik düzeyde doğrusal işlememesidir. Antaki ve ark. (2022), nadir DNA varyant yükü, poligenik risk ve cinsiyetin OSB fenotip spektrumuna birlikte katkı sunduğunu göstermiştir. Nadir ve yaygın DNA risk yükleri aynı bireylerde aynı biçimde birikmeyebilir; ayrıca kadınlarda daha yüksek genetik yük gözlenmesi, eşik modelleri açısından önemlidir. Warrier ve ark. (2022) genetik varyasyonların fenotipik heterojenlikle ilişkisini vurgularken, Litman ve ark. (2025) klinik alt grupların ortak, de novo ve kalıtılmış varyasyon programlarıyla ilişkilenebileceğini göstermiştir. Zhang ve ark. (2025) ise erken ve geç tanı alan OSB profillerinin farklı gelişimsel seyir ve poligenik yapılar gösterebileceğini bildirmiştir. Bu çalışmalar, OSB'nin tek bir gelişimsel yol değil, çoklu gelişimsel izlemler ve biyolojik programlar üzerinden anlaşılması gerektiğinin önemini göstermektedir.

Üçüncü bulgu, PRS/PGS gibi skorların araştırma düzeyinde anlamlı ancak klinik düzeyde sınırlı olduğudur. de Wit ve ark. (2025), otizm poligenik skoru ile fenotipik özellikler arasındaki ilişkileri sistematik derleme ve meta-analiz düzeyinde değerlendirmiştir. Bu tür skorlar grup düzeyinde istatistiksel ilişki kurabilir; ancak bireysel tanı, prenatal karar ya da embriyo seçimi için tek başına yeterli değildir. Capalbo ve ark. (2024) ve Lencz ve ark. (2022), poligenik embriyo taramasının özellikle psikiyatrik ve bilişsel özellikler söz konusu olduğunda klinik geçerlilik, genellenebilirlik, etik amaç ve yanlış güvenlik duygusu açısından ciddi sınırlılıklar taşıdığını belirtmektedir. Bu nedenle PRS, klinik danışmanlıkta deterministik bir öngörü aracı değil, araştırma bağlamında yorumlanması gereken olasılıksal bir gösterge olarak kullanılabilir.

Dördüncü bulgu, prenatal biyobelirteçlerin umut verici olmakla birlikte tanı aracı düzeyinde olmadığıdır. Stoccoro ve ark. (2023), OSB ile ilişkili DNA metilasyon (epigenetik) biyobelirteçlerine ilişkin çalışmaları sistematik olarak incelemiş ve alanın henüz klinik standardizasyon aşamasına ulaşmadığını göstermiştir. Williams ve ark. (2026), prenatal maternal plazma hücre-dışı DNA metilomu ile OSB ve maternal obezite arasındaki ilişkileri inceleyerek fetal ve plasental biyolojiye ilişkin önemli ipuçları sunmuştur. Ancak bu bulgular araştırma düzeyinde ilişki gösterir; bireysel prenatal OSB tanısı anlamına gelmez. Motta ve ark. (2026) fetal MRI biyobelirteçlerini prenatal nörogelişimsel kökenler açısından tartışsa da, görüntüleme bulgularının bugün için grup düzeyinde yorumlanması gerektiği anlaşılmalıdır.

Beşinci bulgu, genetik danışmanlık ve etik iletişimin teknik test bilgisinden ayrı düşünülemeyeceğidir. Manickam ve ark. (2021) ekzom ve genom dizilemenin bazı pediatrik klinik gruplarda yararlı olabileceğini gösteren kanıta dayalı bir rehber sunarken, Stafford ve Sanchez-Lara (2022) OSB bağlamında genetik/genomik testlerin etiyoloji, eşlik eden tıbbi durumlar ve aile bilgilendirmesi açısından değer taşıdığını tartışmaktadır. Buna karşın Natri ve ark. (2023), Klitzman ve ark. (2024) ve Gallion ve ark. (2025), genetik test ve genomik araştırmaların OSB'li bireylerin hakları, temsil edilmesi, damgalanma riski ve araştırma amaçlarının şeffaflığı açısından etik bir zemine yerleştirilmesi gerektiğini vurgulamaktadır. Bu bulgular, danışmanlığın yalnızca test sonucunu açıklamak değil, sonucun sosyal ve gelişimsel anlamını birlikte düşünme süreci olduğunu göstermektedir.

Altıncı bulgu ise, risk bilgisinin klinik anlamının gelişimsel izlemle oluştuğudur. Ozonoff ve ark. (2024), OSB'li büyük kardeşi olan 1.605 bebeği ilk üç yaşta izleyerek özellikle üç yaş değerlendirmesinde anlaşılmıştır ki; aile içinde yeniden görülme, tekrarlama oranını yüzde 20,2 oranındadır. Bu oran aile öyküsünün riski artırdığını gösterir; ancak yine de kesinlik sağlamaz. Dawson ve ark. (2023), bebeklerde otizm öngörüsünde ilerleme ve güçlükleri tartışarak erken göstergelerin ancak uzunlamasına, çok alanlı ve gelişimsel olarak duyarlı biçimde yorumlanabileceğini vurgulamıştır. Bu bulgular, genetik veya ailevi risk bilgisinin tek başına tanı yerine geçmediğini; sosyal iletişim, dil, motor gelişim, regülasyon ve adaptif becerilerin tekrarlı değerlendirmelerle izlenmesi gerektiğini göstermektedir.

Tablo 1'de, 2019–2026 yılları arasında yayımlanan temel genomik çalışmaların oluşturduğu kanıt alanlarını ve bu kanıtların klinik açıdan nasıl yorumlanması gerektiğini özetlemektedir. Tablo, yaygın ve nadir genetik varyantlardan poligenik risk skorlarına, fenotipik heterojenlikten gelişimsel farklılıklara kadar farklı düzeylerde üretilen kanıtların birbirinin yerine geçmediğini, aksine birbirini tamamladığını göstermektedir. Ortak sonuç, genetik bulguların OSB biyolojisini anlamada güçlü katkılar sağlamasına karşın, tek başına bireysel tanı, prenatal kesin öngörü veya klinik karar oluşturacak düzeyde olmadığıdır. Bu nedenle genomik verilerin aile öyküsü, gelişimsel değerlendirme ve klinik bağlam içerisinde bütüncül biçimde yorumlanması gerekmektedir.

Tablo 1. OSB genomik literatüründe kanıt alanları ve klinik yorum.

Kanıt alanı	Temel kaynaklar	Ana bulgu	Klinik yorum
Yaygın varyantlar	Grove ve ark, 2019	GWAS bulguları OSB ile ilişkili yaygın varyant sinyallerini göstermiştir.	Grup düzeyinde genetik katkı vardır; tek başına bireysel tanı sağlamaz.
Nadir kodlayıcı varyasyon	Satterstrom ve ark., 2020; Fu ve ark., 2022	Büyük örneklemli ekzom çalışmalarında çok sayıda risk geni tanımlanmıştır.	Genetik katkı güçlüdür; ancak çoklu gen ve yolaklar söz konusudur.
De novo ve kalıtılmış varyantlar	Zhou ve ark., 2022	Yüksek ve orta risk genleri farklı klinik etkiler gösterebilir.	Varyantın varlığı fenotipin şiddetini veya tipini kesinleştirmez.
PRS/PGS	Antaki ve ark., 2022; de Wit ve ark., 2025	Nadir, yaygın ve cinsiyetle ilişkili risk yükleri birlikte anlam kazanır.	PRS araştırma için değerlidir; prenatal karar veya bireysel tanı aracı değildir.
Fenotipik heterojenlik	Warrier ve ark., 2022; Litman ve ark., 2025; Zhang ve ark., 2025	Alt profiller ve tanı yaşı farklı gelişimsel/genetik örüntülerle ilişkilenebilir.	OSB tek bir gelişimsel yol olarak yorumlanmamalıdır.

Tablo 2'de, bu derlemede önerilen genomik-gelişimsel danışmanlık yaklaşımının temel basamaklarını özetlemektedir. Model, genomik bilginin tek başına tanısal bir araç olarak kullanılmasından ziyade, aile öyküsü, gelişimsel fenotipleme, uygun genetik test seçimi, varyantların klinik anlamının değerlendirilmesi, belirsizliğin etik biçimde paylaşılması ve uzunlamasına gelişimsel izlemin birlikte ele alınmasını önermektedir. Böylece genetik bilginin deterministik yorumlanmasının önüne geçilmesi ve klinik kararların çocuğun gelişimsel özellikleri ile tıbbi bağlamı dikkate alan bütüncül bir değerlendirme süreci içerisinde verilmesi amaçlanmaktadır.

Tablo 2. Önerilen genomik-gelişimsel danışmanlık çerçevesi

Danışmanlık basamağı	Klinik amaç	Dikkat edilmesi gereken sınır
Aile öyküsü ve klinik bağlam	Kardeş riski, gelişimsel örüntü ve tıbbi eşlik durumlarını değerlendirmek.	Aile öyküsü riski artırır; kesinlik sağlamaz.
Gelişimsel fenotipleme	Sosyal iletişim, dil, motor, regülasyon ve adaptif işlevleri izlemek.	Tek zamanlı gözlem gelişimsel seyri temsil etmeyebilir.
Genetik danışmanlık ve test seçimi	Uygun olgularda etiyolojik açıklama ve tıbbi izlem olasılığını değerlendirmek.	Genetik test OSB tanısının yerine geçmez.
Varyant anlam düzeyi	Patojenik, olası patojenik, VUS veya negatif sonucu klinik bağlama yerleştirmek.	VUS otomatik klinik karar üretmez; negatif sonuç genetik katkıyı dışlamaz.
Belirsizliği paylaşma	Aileye risk bilgisini anlaşılır ve etik bir dille aktarmak.	Deterministik, korkutucu veya öjenik dile kayılmamalıdır.
Uzunlamasına izlem	Risk bilgisini destek planı, yönlendirme ve takip yoğunluğu ile ilişkilendirmek.	Amaç etiketlemek değil, erken destek ve izlem planlamaktır.

TARTIŞMA VE SONUÇ

Bu derlemenin ortaya koyduğu temel sonuç, OSB riskinin genetik katkı ve gelişimsel fenotip arasındaki etkileşim içinde anlaşılması gerektiğidir. Genomik çalışmalar OSB'nin biyolojik temellerine ilişkin güçlü kanıtlar sunmuştur; ancak bu kanıtlar klinikte basit bir ‘ gen varsa OSB olur ' ya da ' prenatal dönemde kesin anlaşılır ' sonucuna götürmez. Eksik penetrans, değişken ekspresivite, pleiotropi ve fenotipik heterojenlik, deterministik öngörünün en önemli bilimsel sınırlılıklarıdır. Aynı DNA varyantı

farklı bireylerde farklı gelişimsel sonuçlarla ilişkili olabilir; aynı klinik fenotipe ise farklı genetik yollarla ulaşılabilir.

Bu çerçevede postnatal genetik testin yeri dikkatli tanımlanmalıdır. Genetik test OSB tanısını koymaz; tanı gelişimsel ve davranışsal değerlendirme ile konur. Bununla birlikte genetik test bazı çocuklarda altta yatan etiyolojiyi açıklayabilir, eşlik eden tıbbi risklerin izlenmesine katkı sağlayabilir ve aileye tekrar riski, belirsizlik ve destek planı konusunda daha yapılandırılmış danışmanlık verilmesine yardımcı olabilir. Manickam ve ark. (2021), ekzom ve genom dizilemenin özellikle konjenital anomaliler, gelişimsel gecikme ve entelektüel yetersizlikte klinik kullanımına ilişkin kanıta dayalı bir çerçeve sunmaktadır. Stafford ve Sanchez-Lara (2022) ise OSB bağlamında genetik testin tıbbi yönetim ve danışmanlık açısından önemini tartışmaktadır. Bu nedenle genetik test, tanının yerine geçen değil, tanı sonrası klinik anlamı genişletebilen bir araç olarak görülmelidir.

Genetik danışmanlık bu noktada merkezi hale gelir. 2026 ASHG-NSGC-ACMG ortak açıklaması, otizmde genetik bilginin klinik değerini vurgulamakla birlikte, bu değerin deterministik prenatal öngörü değil, tıbbi izlem, aile danışmanlığı, bilgilendirme ve destek planlaması bağlamında değerlendirilmesi gerektiğini ortaya koymaktadır. Genetik sonuçlar patojenik varyant, olası patojenik varyant, anlamı belirsiz varyant veya negatif sonuç gibi farklı kategoriler içerebilir. Negatif sonuç genetik katkı yoktur anlamına gelmez; anlamı belirsiz varyant ise otomatik klinik karar üretmez. Bu nedenle danışmanlık dilinde hem belirsizlik saklanmamalı hem de ailede gereksiz korku yaratılmamalıdır.

Etik açıdan en hassas alan, genomik bilginin neye hizmet ettiğidir. Natri ve ark. (2023), otizm genomik araştırmalarında otonomi, zarar vermeme, adalet ve OSB'li bireylerin araştırmaya katılımı gibi başlıkların önemini vurgulamaktadır. Klitzman ve ark. (2024) ve Gallion et al. (2025), OSB'li bireylerin genetik testlere yönelik görüşlerinin tek tip olmadığını, stigma, ayrımcılık, hizmete erişim ve temsil sorunlarının danışmanlık sürecinde dikkate alınması gerektiğini göstermektedir. Dolayısıyla genomik bilgi, 'ayıklama' ya da 'değer biçme' mantığına değil, sağlık, destek, yaşam kalitesi ve aileye doğru bilgi sağlama amacına bağlanmalıdır.

Bu çalışma kapsamında önerilen genomik-gelişimsel danışmanlık çerçevesi altı basamaktan oluşmaktadır: aile öyküsü ve klinik bağlamın değerlendirilmesi; sosyal iletişim, dil, motor, regülasyon ve adaptif işlevleri içeren gelişimsel fenotipleme; uygun olduğunda genetik danışmanlık ve test seçimi; varyantın klinik anlam düzeyinin açık biçimde paylaşılması; belirsizliğin aileyle etik ve anlaşılır bir dille konuşulması; doğum sonrası ve erken çocukluk döneminde uzunlamasına izlem planının oluşturulması (Tablo 2). Bu modelin amacı kesin prenatal tahmin üretmek değil, risk bilgisini klinik olarak yararlı, bilimsel olarak sınırlı ve etik olarak duyarlı biçimde kullanmaktır.

Bu çalışmanın sınırlılığı, literatürün yapılandırılmış anlatı derlemesi olarak ele alınmış olmasıdır; bu nedenle çalışmalar arasında nicel etki büyüklüğü karşılaştırması ya da PRISMA temelli sistematik kalite değerlendirmesi yapılmamıştır. Bununla birlikte metnin amacı, belirli bir biyobelirtecin tanısal performansını hesaplamak değil, genomik kanıtların klinik ve etik yorumundaki sınırları görünür kılmaktır. Gelecek çalışmaların, farklı genetik kökenlerden gelen örneklemleri içermesi, PRS bulgularının popülasyonlar arası taşınabilirliğini sınaması ve prenatal biyobelirteç iddialarını uzunlamasına gelişimsel sonuçlarla ilişkilendirmesi önemli olacaktır. Ayrıca klinik uygulamada ailelerin bilgi gereksinimi, belirsizliğe toleransı ve destek kaynaklarına erişimi de danışmanlık sürecinin ayrılmaz parçası olarak değerlendirilmelidir.

Bu çerçevenin kongre bağlamındaki katkısı, genomik kanıtı gelişimsel davranışsal değerlendirmeden ayırmadan ele almasıdır. Özellikle prekonsepsiyonel veya prenatal dönemde aileye verilen bilginin klinik karşılığı çoğu zaman 'kesin sonuç' değil, belirsizliğin yapılandırılmasıdır. Aile öyküsü, bilinen patojenik DNA varyantları, ultrason ya da fetal MRI gibi görüntüleme bulguları veya epigenetik araştırma sonuçları aynı düzeyde kanıt üretmez. Bu nedenle klinik iletişimde her bilgi türünün gücü ayrı belirtilmelidir. Örneğin ailevi tekrar riski yakın gelişimsel izlemi haklılaştırabilir; ancak tanı koymaz. Patojenik bir genetik varyant tıbbi izlemi yönlendirebilir; ancak fenotipin tüm ayrıntılarını belirlemez. PRS yüksekliği istatistiksel risk sinyali sağlayabilir; ancak çocuk için bireysel kader anlatısı oluşturmaz. Prenatal biyobelirteçler ise bugün için daha çok mekanizma ve erken biyoloji hakkında araştırma soruları üretir. Bu ayrımlar yapılmadığında aynı bilimsel veri hem abartılı umut hem de gereksiz korku kaynağına dönüşebilir.

Sonuç olarak; OSB'de genetik risk gerçektir; ancak bu risk deterministik bir tanı kategorisi değildir. Güncel literatür, genomik mimarinin çok katmanlı olduğunu, poligenik risk skorlarının bireysel klinik karar için sınırlı kaldığını, prenatal biyobelirteçlerin henüz araştırma düzeyinde olduğunu ve klinik anlamın gelişimsel izlemle güçlendiğini göstermektedir. En güvenilir yaklaşım, genomik bulguları gelişimsel seyir, fenotipik profil, aile öyküsü, tıbbi bağlam ve etik danışmanlıkla birlikte değerlendirmektir. Böyle bir yaklaşım, hem bilimsel aşırı yorumdan kaçınmayı hem de ailelere erken destek ve izlem açısından gerçekçi bir yol haritası sunmayı mümkün kılar.

EK-1. Kısaltmalar

ACMG (American College of Medical Genetics and Genomics): Amerikan Tıbbi Genetik ve Genomik Koleji.
ASHG (American Society of Human Genetics): Amerikan İnsan Genetiği Derneği.
Cell-free DNA (cfDNA): Anne kanında dolaşan hücre-dışı DNA parçacıkları.
CNV (Copy Number Variation): Kopya Sayısı Varyasyonu. DNA'nın belirli bölgelerinde kopya sayısının artması veya azalması.
De novo varyant: Anne veya babada bulunmayan, embriyo gelişimi sırasında yeni ortaya çıkan genetik varyant.
DSM-5 (Diagnostic and Statistical Manual of Mental Disorders, Fifth Edition): Amerikan Psikiyatri Birliği tarafından yayımlanan Ruhsal Bozuklukların Tanısal ve İstatistiksel El Kitabı'nın beşinci baskısı.
DNA (Deoxyribonucleic Acid): Deoksiribonükleik Asit.
Epigenetik: DNA dizisini değiştirmeden gen ekspresyonunu etkileyen biyolojik düzenleme mekanizmaları.
Ekzom (Exome): Protein kodlayan gen bölgelerinin tamamı.
Fenotip: Bir bireyin gözlenebilen klinik, davranışsal ve biyolojik özellikleri.
GWAS (Genome-Wide Association Study): Genom Çapında İlişkilendirme Çalışması. Yaygın genetik varyantların hastalıklarla ilişkisini araştıran yöntem.
NSGC (National Society of Genetic Counselors): Ulusal Genetik Danışmanlar Derneği.
OSB (Otizm Spektrum Bozukluğu): Sosyal iletişim ve sosyal etkileşim alanlarında güçlükler ile sınırlı ve tekrarlayıcı davranış örüntüleriyle karakterize nörogelişimsel durum.
PGS (Polygenic Score): Poligenik Skor. Çok sayıda yaygın genetik varyantın toplam etkisini gösteren istatistiksel skor.
Pleiotropi: Aynı genin veya genetik varyantın birden fazla fenotipik özelliği etkileyebilmesi.
PRS (Polygenic Risk Score): Poligenik Risk Skoru. Çok sayıda yaygın genetik varyantın belirli bir hastalık veya fenotipe ilişkin olasılıksal riskini hesaplayan istatistiksel skor.
PTV (Protein-Truncating Variant): Protein Sonlandırıcı Varyant. Protein sentezinin erken durmasına neden olabilen yüksek etkili genetik değişiklik.
Varyant: Referans genom dizisinden farklılık gösteren DNA değişikliği.
VUS (Variant of Uncertain Significance): Klinik Önemi Belirsiz Varyant. Hastalıkla ilişkisi mevcut bilgilerle kesin olarak yorumlanamayan genetik varyant.
WES (Whole Exome Sequencing): Tüm Ekzom Dizilemesi. Protein kodlayan bölgelerin tamamının dizilenmesi.
WGS (Whole Genome Sequencing): Tüm Genom Dizilemesi. Genomun tamamının dizilenmesi.

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HABERMAS'TA İLETİŞİMSEL AKIL VE HUKUKİ MEŞRUİYET SORUNU

COMMUNICATIVE RATIONALITY AND THE PROBLEM OF LEGAL LEGITIMACY IN HABERMAS

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ÖZET

Modern toplumların artan karmaşıklığı, toplumsal düzenin yalnızca geleneksel otorite biçimleri veya stratejik çıkar ilişkileri üzerinden açıklanmasını yetersiz kılmıştır. Jürgen Habermas, toplumsal bütünleşmenin temelini iletişimsel rasyonaliteye dayandıran kapsamlı bir kuramsal çerçeve geliştirmiştir. Habermas'ın iletişimsel eylem kuramı, bireylerin karşılıklı anlayışa ulaşma amacıyla yürüttükleri iletişim süreçlerinin toplumsal düzenin ve demokratik meşruiyetin temelini oluşturduğunu ileri sürmektedir. Bu yaklaşım, hukukun yalnızca devlet tarafından üretilen normlar bütünü olarak değil, kamusal tartışma ve uzlaşı süreçlerinin ürünü olan bir söylem alanı olarak değerlendirilmesine imkân tanımaktadır.

Bu çalışma, Habermas'ın iletişimsel eylem kuramı ile söylem kuramına dayalı hukuk anlayışı arasındaki ilişkiyi incelemeyi amaçlamaktadır. Çalışmada öncelikle iletişimsel eylem kavramı, iletişimsel rasyonalite ve yaşam dünyası kuramsal çerçevesi ele alınmakta; ardından hukuk normlarının meşruiyetinin hangi koşullarda sağlanabileceği tartışılmaktadır. Habermas'a göre modern hukuk sistemleri yalnızca pozitif hukuk kuralları aracılığıyla değil, aynı zamanda özgür ve eşit bireylerin katılımına açık söylemsel süreçler yoluyla meşruiyet kazanmaktadır. Zira hukukun geçerliliği, zorlayıcı gücünden çok kamusal akıl yürütme süreçleri içerisinde rasyonel olarak gerekçelendirilebilmesine bağlıdır.

Habermas, hukukun bir normlar sistemi olaması yanında, iletişimsel rasyonalite temelinde şekillenen ve demokratik söylem süreçleriyle meşruiyet kazanan toplumsal bir kurum olarak tanımlamaktadır. Bu yaklaşım, çağdaş hukuk sosyolojisi ve demokrasi teorisi açısından önemli bir kuramsal perspektif sunmaktadır.

Çalışmamızda hukukun, modern toplumlarda sistem ve yaşam dünyası arasında aracılık yapan normatif bir kurum olarak işlev gördüğü; demokratik meşruiyetin ise kamusal söylem süreçlerine dayandığı gösterilmek istenmiştir. Ayrıca hukukun söylemsel temellerinin zayıflaması durumunda, meşruiyet krizlerinin ortaya çıkabileceği ve demokratik katılımın fazlasıyla zarar görebileceği kolayca öngörülebilir.

Anahtar Kelimeler: Habermas, İletişimsel Eylem Kuramı, Söylem Kuramı, Hukuk Sosyolojisi, Meşruiyet, İletişimsel Rasyonalite, Demokrasi.

ABSTRCAT

asolely on traditional forms of authority or strategic interest relations insufficient. Jürgen Habermas developed a comprehensive theoretical framework that grounds social integration in communicative rationality. Habermas's Theory of Communicative Action argues that communicative processes aimed at achieving mutual understanding among individuals constitute the foundation of social order and democratic legitimacy. This approach makes it possible to conceptualize law not merely as a body of norms produced by the state, but also as a discursive sphere shaped through processes of public deliberation and consensus-building.

This study aims to examine the relationship between Habermas's Theory of Communicative Action and his discourse-theoretical conception of law. The analysis first addresses the concepts of communicative

action, communicative rationality, and the theoretical framework of the lifeworld. It then explores the conditions under which the legitimacy of legal norms can be established. According to Habermas, modern legal systems derive their legitimacy not only from positive legal rules but also from discursive processes that are open to the participation of free and equal individuals. The validity of law depends less on its coercive force than on its capacity to be rationally justified within processes of public reasoning and democratic deliberation.
Habermas defines law not only as a system of norms but also as a social institution shaped by communicative rationality and legitimized through democratic discourse. This perspective provides an important theoretical framework for contemporary legal sociology and democratic theory. By emphasizing the communicative foundations of legal legitimacy, Habermas highlights the indispensable role of participatory and deliberative processes in maintaining democratic governance.
This study argues that law functions as a normative institution mediating between the system and the lifeworld in modern societies, while democratic legitimacy is grounded in public discourse. Furthermore, it suggests that the weakening of the discursive foundations of law may lead to crises of legitimacy and significantly undermine democratic participation.
Keywords: Habermas, Theory of Communicative Action, Discourse Theory, Sociology of Law, Legitimacy, Communicative Rationality, Democracy.

1. Giriş

Modern hukuk devletinin temel sorunlarından biri, hukuk normlarının yalnızca geçerliliğinin değil, aynı zamanda meşruiyetinin de açıklanabilmesidir. Hukukun yürürlükte bulunması ile demokratik anlamda meşru olması aynı şeyi ifade etmemektedir. Bir hukuk normu yetkili organ tarafından anayasal usullere uygun biçimde kabul edilmiş ve devletin yaptırım gücüyle desteklenmiş olabilir; ancak bu özellikler tek başına normun muhatapları tarafından haklı ve meşru kabul edilmesini garanti etmez. Modern hukukun temel gerilimlerinden biri bu nedenle normların olgusal olarak uygulanabilirliği ile normatif olarak gerekçelendirilebilirliği arasındaki ilişkide ortaya çıkmaktadır (Habermas, 1996; Baxter, 2011). Habermas'ın hukuk teorisi, bu sorunu hukuki pozitivizm ile doğal hukuk arasında basit bir orta yol oluşturarak çözmeye çalışmaz. Bunun yerine hukukun meşruiyet sorununu demokratik irade ve kanaat oluşumunun iletişimsel koşulları üzerinden yeniden kurar. Bu bakımdan temel sorun yalnızca hangi normların hukuken geçerli veya maddi açıdan adil olduğu değildir. Daha temel soru, modern ve çoğulcu toplumlarda yurttaşların hangi koşullarda kendilerini tabi oldukları hukuk düzeninin aynı zamanda yazarları olarak görebilecekleridir (Habermas, 1996).
Bu yaklaşım Habermas'ın iletişimsel eylem kuramıyla doğrudan bağlantılıdır. İletişimsel eylem kuramı, toplumsal aktörleri yalnızca kendi amaçlarını gerçekleştirmeye çalışan stratejik bireyler olarak değil, dil aracılığıyla karşılıklı anlayış oluşturabilen ve ileri sürdükleri geçerlilik iddialarını gerekçelendirebilen özneler olarak ele almaktadır (Habermas, 1984; Baynes, 2015). Bu nedenle Habermas'ın hukuk teorisinde demokratik meşruiyetin kaynağı, önceden var olduğu kabul edilen homojen bir halk iradesinden ziyade, yurttaşların kamusal iletişim süreçleri içerisinde görüş oluşturabilme ve siyasal kararları etkileyebilme kapasitelerinde aranmalıdır.
Habermas'ın hukuk anlayışı özellikle *Between Facts and Norms* adlı eserinde sistematik biçimine ulaşmıştır. Burada hukuk, olgusallık ile geçerlilik arasındaki gerilimi bünyesinde taşıyan modern bir toplumsal kurum olarak ele alınmaktadır. Hukuk bir taraftan yaptırım gücüyle desteklenen pozitif normlardan oluşurken diğer taraftan muhatapları karşısında meşru kabul edilme iddiası taşımaktadır. Demokratik hukuk devletinin temel problemi, bu iki boyutun birbirinden kopmasını önleyebilecek iletişimsel ve kurumsal mekanizmaların oluşturulmasıdır (Habermas, 1996; Baxter, 2001, 2011).
Bu çalışma, Habermas'ın iletişimsel eylem teorisi ile söylem kuramına dayalı hukuk ve demokrasi anlayışı arasındaki ilişkiyi hukuki meşruiyet problemi üzerinden incelemektedir. Çalışmanın temel savı, Habermas'ın hukuk teorisinde demokratik meşruiyetin yalnızca hukuk normlarının biçimsel olarak doğru usullerle üretilmesinden değil, yurttaşların özgür ve eşit katılımına açık kamusal irade ve kanaat oluşturma süreçlerinin anayasal karar mekanizmalarıyla etkili biçimde bağlantı kurabilmesinden doğduğudur.

2. İletişimsel Eylem Kuramı: Sistem Ve Yaşam Dünyası

Habermas'ın hukuk teorisinin kavranabilmesi için iletişimsel eylem kuramında geliştirdiği toplumsal eylem ve rasyonalite anlayışının açıklanması gerekmektedir. İletişimsel eylem teorisi, özellikle araçsal ve stratejik rasyonalite anlayışlarının toplumsal bütünleşmeyi tek başına açıklayamayacağı düşüncesinden hareket etmektedir.

Araçsal eylem, aktörün belirli bir amacı en etkili araçlarla gerçekleştirmesine yönelirken stratejik eylem, diğer aktörlerin davranışlarını kendi başarı hesabı içerisinde dikkate almaktadır. İletişimsel eylemde ise aktörler eylem planlarını yalnızca bireysel başarı amacıyla değil, karşılıklı olarak kabul edilebilir bir durum tanımı üzerinde anlaşma amacıyla koordine etmektedirler (Habermas, 1984).

İletişimsel eylemin temelinde dilsel anlaşma bulunmaktadır. Ancak Habermas açısından anlaşma, eleştiriden uzak veya zorunlu bir görüş birliği anlamına gelmemektedir. İletişimsel rasyonalitenin ayırt edici özelliği, konuşmacıların ileri sürdükleri geçerlilik iddialarının gerektiğinde sorgulanabilir ve gerekçelendirilebilir olmasıdır. Bu nedenle iletişimsel eylem, iktidar ilişkilerinin fiilen ortadan kalktığı bir toplumsal durumu değil, geçerlilik iddialarının gerekçeler aracılığıyla eleştiriye açılabilmesini sağlayan normatif bir potansiyeli ifade etmektedir (Habermas, 1984, 1990).

Habermas'ın toplum teorisinde yaşam dünyası, iletişimsel eylemin arka planını oluşturmaktadır. Yaşam dünyası; kültürel bilginin, toplumsal dayanışmanın ve bireysel kimliklerin yeniden üretildiği sembolik alanı ifade etmektedir. Bu nedenle yaşam dünyası yalnızca ortak değerlerin pasif biçimde depolandığı bir alan değil, iletişimsel eylemin mümkün olmasını sağlayan kültürel ve normatif kaynakların sürekli yeniden üretildiği toplumsal bağlamdır (Habermas, 1987).

Modern toplumların farklılaşmasıyla birlikte ekonomi ve devlet yönetimi gibi bazı alanlar doğrudan iletişimsel anlaşmadan ziyade para ve idari güç gibi yönlendirme araçları üzerinden işlemeye başlamaktadır. Habermas bu alanları sistem kavramı aracılığıyla açıklamaktadır. Sistem ile yaşam dünyası arasındaki ayrım, iki tamamen bağımsız toplumsal gerçekliğin varlığı anlamına gelmemekte; modern toplumun farklı bütünleşme biçimlerini analitik olarak açıklamaktadır. Sorun, sistemik mekanizmaların kendi işlev alanlarını aşarak yaşam dünyasının iletişimsel olarak düzenlenmesi gereken alanlarına müdahale etmesiyle ortaya çıkmaktadır. Habermas bu süreci yaşam dünyasının sömürgeleştirilmesi olarak tanımlamaktadır (Habermas, 1987). Ekonomik ve bürokratik mekanizmaların toplumsal yaşamın giderek daha geniş alanlarını belirlemesi, bireylerin ortak meseleler üzerinde iletişimsel irade oluşturma kapasitelerini zayıflatabilir.

Hukukun bu noktadaki konumu özellikle önemlidir. Hukuk, doğrudan ve basit biçimde "iletişimsel aklın kurumsallaşmış görünümü" olarak tanımlanmamalıdır. Habermas'ın olgun dönem hukuk teorisinde hukuk, yaşam dünyasında iletişimsel olarak ortaya çıkan normatif beklentilerin siyasal sistem içerisinde bağlayıcı kararlara dönüştürülmesini sağlayabilen; aynı zamanda siyasal ve idari kararların toplumsal yaşam içerisinde hukuki biçim kazanmasına aracılık eden özgün bir toplumsal ortamdır (Habermas, 1996; Baxter, 2001, 2011).

Dolayısıyla hukuk, sistem ile yaşam dünyası arasındaki ilişkiyi yalnızca tek yönlü olarak aktaran bir araç değildir. İletişimsel olarak oluşan taleplerin siyasal ve idari dile çevrilmesine ve bağlayıcı kararların toplumsal yaşam içerisinde uygulanabilir hâle gelmesine aracılık etmektedir. Hukukun demokratik niteliği de büyük ölçüde bu aracılık işlevinin kamusal iletişim süreçlerine açık tutulmasına bağlıdır.

3. İletişimsel Rasyonalite, Söylem İlkesi Ve Demokrasi İlkesi

Habermas'ın iletişimsel rasyonalite anlayışında rasyonellik, yalnızca bireysel öznenin zihinsel kapasitesine indirgenemez. Bir iddianın rasyonelliği, onun gerekçelerle savunulabilmesine ve eleştiriye açık tutulabilmesine bağlıdır. Bu bakımdan iletişimsel rasyonalite özneler arası bir nitelik taşımaktadır (Habermas, 1984, 1990).

Habermas'a göre iletişimsel eylem sırasında konuşmacılar farklı geçerlilik iddialarında bulunurlar. Bunlar genel olarak önermesel doğruluk, normatif doğruluk ve öznel içtenlik iddialarıyla ilişkilidir. İletişimin rasyonel niteliği, bu iddiaların gerektiğinde problemleştirilebilmesine ve gerekçeler temelinde tartışılabilmesine bağlıdır. Dolayısıyla iletişimsel rasyonalite, her iletişimin fiilen eşit veya iktidardan bağımsız olduğu iddiasını değil, dilsel iletişimin eleştiri ve gerekçelendirmeye yönelik içkin potansiyelini ifade etmektedir (Habermas, 1984, 1990).

Burada söylem etiği ile hukuk söylemi arasında kavramsal bir ayrım yapılması gerekir. Söylem etiğinde ahlaki normların geçerliliği bütün ilgililerin çıkarlarının eşit biçimde dikkate alınmasıyla

ilişkilendirilirken, hukuk normlarının meşruiyeti yalnızca ahlaki doğruluk sorununa indirgenemez. Hukuki düzenlemeler ahlaki gerekçelerin yanında pragmatik amaçları, etik-politik tercihleri ve farklı çıkarlar arasında oluşturulan uzlaşmaları da içerebilir (Habermas, 1996).

Habermas'ın olgun dönem hukuk teorisinde genel söylem ilkesi ile hukuk alanına özgü demokrasi ilkesi arasında ayrım yapılmaktadır. Söylem ilkesi genel olarak, yalnızca ilgili herkesin rasyonel söylemlerin katılımcıları olarak kabul edebileceği eylem normlarının geçerlilik iddiasında bulunabileceğini ifade etmektedir. Demokrasi ilkesi ise söylem ilkesinin hukuki biçimde örgütlenmiş siyasal irade oluşumu içerisinde kurumsallaştırılmasıyla ilgilidir (Habermas, 1996; Baxter, 2011). Bu ayrım, Habermas'ın hukuk teorisinin usulcü niteliğinin doğru anlaşılması açısından önemlidir. Habermas'ın yaklaşımı, hukukun içeriğinin önemsiz olduğunu savunan salt biçimsel bir usulcülük değildir.

Demokratik usullerin kendileri eşit katılımı ve iletişimsel özgürlüğü mümkün kılan temel hakları gerektirmektedir. Dolayısıyla meşru hukuk üretimi yalnızca çoğunluğun karar vermesi anlamına gelmez; yurttaşların siyasal irade oluşumuna özgür ve eşit biçimde katılabilmelerini sağlayan hakların ve kurumların varlığını da gerektirir.

Demokratik meşruiyet bu nedenle soyut bir ideal konuşma durumuna indirgenemez. Temel haklar, demokratik yasama süreçleri, sivil toplum, kamusal alan ve anayasal kurumlar aracılığıyla gerçekleştirilen kurumsallaşmış söylem süreçlerine ihtiyaç vardır. Habermas'ın hukuk teorisi, iletişimsel rasyonalitenin normatif içeriğini modern toplumların kurumsal gerçekliğiyle bu noktada ilişkilendirmektedir.

4.Habermas'ın Hukuk Kuramı: Olgusallık, Geçerlilik Ve Özerklik

Habermas'ın hukuk teorisinin merkezinde olgusallık ile geçerlilik arasındaki gerilim bulunmaktadır. Pozitif hukuk, devlet tarafından uygulanabilir olması nedeniyle olgusal bir zorlayıcılığa sahiptir. Bununla birlikte modern hukuk aynı zamanda muhatapları tarafından meşru kabul edilme iddiası taşımaktadır. Hukukun bu çift yönlü yapısı, yurttaşların hukuk normlarına hem yaptırımdan kaçınmak gibi stratejik nedenlerle hem de normların haklı olduğuna inanarak uyabilmelerine imkân vermektedir (Habermas, 1996; Baxter, 2011).

Habermas bu gerilimi demokratik hukuk üretimi aracılığıyla açıklamaya çalışmaktadır. Buna göre demokratik meşruiyet iddiasında bulunabilecek hukuk normlarının, hukuken düzenlenmiş söylemsel irade ve kanaat oluşturma süreçlerinin ürünü olması gerekir. Burada meşruiyet, her yurttaşın her hukuk normunu fiilen kabul etmesi anlamına gelmemektedir. Belirleyici olan, normların özgür ve eşit yurttaşların katılımına açık demokratik süreçlerde gerekçelendirilebilir olmasıdır (Habermas, 1996).

Habermas'ın teorisinin özgün yönlerinden biri özel ve kamusal özerkliğin eş-kökenliliği tezidir. Liberal gelenek bireysel hakları demokratik halk egemenliğinin sınırı olarak görme eğilimindeyken, cumhuriyetçi gelenek siyasal öz-yönetime daha merkezi bir konum vermektedir. Habermas, yurttaşların özel özerkliklerini güvence altına alan bireysel haklarla kamusal özerkliklerini kullanmalarını sağlayan siyasal katılım haklarının birbirlerini karşılıklı olarak mümkün kıldığını savunmaktadır (Habermas, 1996, 2001).

Bu nedenle temel haklar demokratik sürecin dışarıdan belirlenmiş sınırları olarak değil, demokratik hukuk üretiminin kurucu koşulları olarak değerlendirilmelidir. Yurttaşlar ancak bireysel özgürlüklere ve iletişim haklarına sahip olduklarında kamusal özerkliklerini kullanabilirler. Aynı zamanda haklarının somut hukuki içeriğinin oluşumuna demokratik hukuk üretim süreçlerinin katılımcıları olarak katkıda bulunurlar. Hukuk düzeninin muhatapları ile yazarlarının aynı kişiler olabilmesi, özel ve kamusal özerkliğin bu karşılıklı ilişkisine bağlıdır.

Habermas'ın demokrasi teorisinde iletişimsel iktidar kavramı da merkezi öneme sahiptir. İletişimsel iktidar, kamusal iletişim süreçlerinde ortaklaşa oluşturulan siyasal kanaat ve iradenin etki kapasitesini ifade etmektedir. Ancak iletişimsel iktidar doğrudan idari iktidarla özdeş değildir. Kamusal alanda ortaya çıkan taleplerin bağlayıcı siyasal kararlara dönüşmesi, demokratik ve hukuki kurumların aracılığını gerektirmektedir (Habermas, 1996; Flynn, 2004).

Bu yaklaşım, Habermas'ın iki izli deliberatif demokrasi modelinin temelini oluşturmaktadır. Bir tarafta parlamentolar, mahkemeler ve kamu yönetimi gibi resmî kurumlar; diğer tarafta sivil toplum ve kamusal alan içerisinde gelişen gayriresmî iletişim ağları bulunmaktadır. Demokratik meşruiyet, bu alanlar arasındaki iletişim kanallarının işler durumda olmasına bağlıdır.

Kamusal alanda ortaya çıkan sorunların siyasal sisteme aktarılabilmesi ve siyasal sistemin bu taleplere duyarlı kalabilmesi demokratik hukuk devletinin temel koşullarındandır (Habermas, 1996; Flynn, 2004, 2014).

5. Hukuki Meşruiyet Sorunu

Habermas'ın hukuk kuramında meşruiyet, hukuk normlarının yalnızca usulüne uygun biçimde yürürlüğe konulmuş olmasıyla açıklanamaz. Demokratik meşruiyet, yurttaşların siyasal irade ve kanaat oluşumuna katılabilecekleri kurumsal ve iletişimsel koşulların varlığını gerektirmektedir. Bu nedenle demokratik hukuk devletinin meşruiyeti seçimlerden parlamentoya, sivil toplumdan özgür medyaya ve temel haklardan kamusal tartışmaya kadar uzanan karmaşık bir yapı içerisinde üretilmektedir (Habermas, 1996).

Habermas'ın meşruiyet anlayışında yurttaşların her somut hukuk normunu fiilen onaylamaları gerekli değildir. Modern toplumlarda böyle bir oydaşmanın gerçekleşmesi ne mümkün ne de zorunludur. Meşruiyet bakımından belirleyici olan, hukuk normlarının muhataplarının kendilerini demokratik hukuk üretiminin potansiyel katılımcıları olarak görebilmeleri ve normların kamusal gerekçelendirmeye açık olmasıdır. Habermasçı meşruiyet anlayışı bu nedenle fiilî uzlaşmadan ziyade gerekçelendirilebilirlik koşullarına dayanmaktadır.

Demokratik katılımın yalnızca seçimlere indirgenmemesi de bu nedenle önemlidir. Seçimler demokratik meşruiyetin vazgeçilmez unsurlarından biri olmakla birlikte siyasal irade oluşumu seçim dönemleri arasında da devam etmektedir. Sivil toplum örgütleri, toplumsal hareketler, medya ve farklı kamusal oluşumlar yeni sorunların siyasal gündeme taşınmasını sağlayarak demokratik irade oluşumuna katkıda bulunmaktadırlar.

Habermas'ın kamusal alan anlayışı bu noktada hukuk teorisiyle doğrudan bağlantılıdır. Kamusal alan, toplumsal sorunların algılandığı, yorumlandığı ve siyasal taleplere dönüştürüldüğü iletişim ağlarından oluşmaktadır. Bu süreçte oluşan kamuoyu doğrudan hukuki bağlayıcılık taşımasa da siyasal karar mekanizmaları üzerinde iletişimsel etki oluşturabilir. Demokratik hukuk devletinin meşruiyeti, siyasal sistemin bu iletişimsel akışlara tamamen kapanmamasına bağlıdır (Habermas, 1996).

Modern toplumlarda ortaya çıkan meşruiyet krizleri de bu çerçevede değerlendirilebilir. Habermas'ın erken dönem analizlerinde meşruiyet krizi, devletin artan müdahale alanı ile toplumsal beklentiler arasındaki gerilimler üzerinden ele alınmıştır (Habermas, 1975). Daha sonraki hukuk ve demokrasi teorisinde ise meşruiyet sorunu, kamusal iletişim kanalları ile siyasal karar alma sistemleri arasındaki ilişkinin niteliği üzerinden yeniden kurulmuştur.

Bu açıdan bir hukuk düzeninin meşruiyet krizi yaşaması yalnızca yurttaşların belirli yasalardan hoşnutsuz olması anlamına gelmez. Yurttaşların siyasal kararların oluşumunu etkileyebileceklerine ve kamusal tartışmaların karar alma mekanizmalarında karşılık bulabileceğine ilişkin inancının zayıflaması daha temel bir meşruiyet problemine işaret etmektedir.

Sonuç olarak Habermas açısından demokratik meşruiyet, hukukun yalnızca biçimsel geçerliliğine veya devletin yaptırım kapasitesine indirgenemeyen dinamik bir süreçtir. Meşru hukuk, demokratik usuller içerisinde üretilen, kamusal gerekçelendirmeye açık olan ve muhataplarının kendilerini potansiyel olarak hukuk düzeninin ortak yazarları şeklinde görebilmelerine imkân sağlayan hukuktur.

6.Habermas'ın Hukuki Meşruiyet Kuramının Eleştirel Değerlendirilmesi

Habermas'ın söylem kuramına dayalı hukuk anlayışı, modern demokratik toplumlarda hukuki meşruiyetin açıklanması bakımından güçlü bir normatif çerçeve ortaya koymaktadır.

Bu yaklaşımın en önemli katkılarından biri, hukukun meşruiyetini ne yalnızca devlet egemenliğine ne de demokratik süreçlerden bağımsız biçimde var olduğu varsayılan değişmez ahlaki doğrulara dayandırmasıdır. Habermas bunun yerine meşru hukuk ile demokratik öz-yönetim arasında içsel bir ilişki kurmaktadır (Habermas, 1996; Baxter, 2011).

Bununla birlikte söylemsel meşruiyet modeli, gerçek toplumsal koşullardaki güç eşitsizliklerinin demokratik iletişim üzerindeki etkisi bakımından eleştirilmiştir. İdeal bir demokratik tartışmanın katılımcıları biçimsel olarak eşit söz hakkına sahip olabilir; ancak ekonomik kaynaklara, eğitime, siyasal örgütlenme imkânlarına ve iletişim araçlarına erişimdeki eşitsizlikler kamusal tartışmanın fiilî koşullarını önemli ölçüde etkileyebilir.

Fraser'ın kamusal alan eleştirisi bu açıdan özel önem taşımaktadır. Fraser'a göre tek ve bütünleşmiş bir kamusal alan düşüncesi, toplumsal eşitsizliklerin demokratik iletişime nasıl yansıdığını yeterince açıklayamaz. Toplumsal açıdan dezavantajlı gruplar egemen kamusal söylem içerisinde eşit biçimde temsil edilemeyebilir ve kendi deneyimlerini ifade edebilmek için alternatif veya karşı-kamulara ihtiyaç duyabilirler (Fraser, 1990).

Young da demokratik iletişimin yalnızca soyut ve biçimsel argümantasyona indirgenemeyeceğini savunmaktadır. Anlatı, tanıklık, retorik ve kamusal protesto gibi iletişim biçimleri, özellikle siyasal olarak dışlanmış grupların deneyimlerinin görünür hâle gelmesinde önemli rol oynayabilir (Young, 2000). Bu açıdan Habermasçı söylem modelinin normatif çekirdeği korunmakla birlikte, meşru demokratik iletişimin daha çoğulcu iletişim biçimlerini kapsayacak biçimde değerlendirilmesi mümkündür.

Habermas'ın hukuk ve demokrasi teorisinde tartışılması gereken diğer bir konu, kamusal alanda oluşan iletişimsel iktidarın devletin idari iktidarıyla nasıl ilişki kurduğudur. İletişimsel iktidar doğrudan bağlayıcı karar alma yetkisine sahip değildir. Kamusal alanda ortaya çıkan taleplerin hukuken bağlayıcı kararlara dönüşebilmesi için anayasal ve siyasal kurumların aracılığından geçmesi gerekmektedir (Habermas, 1996; Flynn, 2004).

Bu durum Habermas'ın demokrasi teorisinin temel gerilimlerinden birini ortaya çıkarmaktadır. Bir taraftan demokratik meşruiyetin kaynağı yurttaşların iletişimsel özgürlüğünde aranmakta, diğer taraftan karmaşık modern toplumların yönetimi uzmanlaşmış bürokratik kurumlara ve idari mekanizmalara ihtiyaç duymaktadır. Dolayısıyla demokratik hukuk devletinin temel sorunu idari iktidarı ortadan kaldırmak değil, bu iktidarın kamusal iletişim süreçlerinde oluşan demokratik iradeye duyarlı kalmasını sağlamaktır (Flynn, 2004, 2014).

Habermas'ın özel ve kamusal özerklik arasında kurduğu eş-kökenlilik ilişkisi de hukuk kuramının hem en güçlü hem de tartışmaya açık unsurlarından biridir. Bireysel hakların demokratik halk egemenliğinden veya halk egemenliğinin bireysel haklardan mutlak biçimde öncelikli olduğu söylenemez. Yurttaşların özel özerkliklerini güvence altına alan temel haklar onların kamusal özerkliklerini kullanabilmelerinin koşuludur; aynı zamanda bu hakların somut hukuki biçimi demokratik hukuk üretim süreçleri içerisinde belirlenmektedir (Habermas, 1996, 2001).

Demokratik usuller her durumda adil sonuçların ortaya çıkmasını garanti etmemektedir. Çoğunluk iradesi azınlıkların veya siyasal açıdan güçsüz grupların haklarını ihlal edebilir. Bu nedenle Habermasçı yaklaşımda demokratik meşruiyet basit çoğunluk kararına indirgenemez. Temel hakların korunması, kamusal tartışmaya eşit katılım ve alınan kararların eleştiriye açık olması demokratik meşruiyetin kurucu koşullarıdır.

Habermas'ın yaklaşımına yöneltilebilecek başka bir eleştiri, uzlaşma kavramının siyasal çatışmanın kalıcı niteliğini yeterince açıklayıp açıklamadığıyla ilgilidir. Modern toplumlarda siyasal anlaşmazlıklar her zaman bilgi eksikliğinden veya iletişim yetersizliğinden kaynaklanmamaktadır. Farklı bireyler ve toplumsal gruplar, makul gerekçelere sahip olmalarına rağmen farklı değerleri ve çıkarları savunmaya devam edebilirler (Dryzek, 2000; Young, 2000).

Ancak bu eleştiri, Habermas'ın kuramının bütün siyasal anlaşmazlıkların ortadan kaldırılmasını öngördüğü anlamına gelmemektedir. Habermasçı anlamda demokratik söylemin temel amacı her konuda maddi bir görüş birliği oluşturmak değildir. Daha temel düzeyde amaç, siyasal kararların gerekçelendirilebilir, eleştirilebilir ve yeniden tartışılabilir olmasını sağlayan iletişimsel koşulların korunmasıdır.

Bu değerlendirmeler ışığında Habermas'ın hukuk kuramının en önemli katkısının, hukuki meşruiyeti tek bir maddi adalet anlayışına bağlamak yerine demokratik gerekçelendirme süreçleri üzerinden açıklaması olduğu söylenebilir. Bununla birlikte söylemsel meşruiyetin gerçek anlamda gerçekleşebilmesi yalnızca demokratik kurumların biçimsel olarak varlığına bağlı değildir. Kamusal iletişime erişimdeki eşitsizliklerin azaltılması, farklı toplumsal grupların seslerinin duyulabilmesi, medya çoğulculuğunun korunması ve iletişimsel iktidarın karar alma süreçlerini etkileyebileceği kurumsal kanalların işler durumda bulunması gerekmektedir.

7. Sonuç

Jürgen Habermas'ın hukuk kuramı, modern hukuk devletinde hukuki geçerlilik ile demokratik meşruiyet arasındaki ilişkinin yeniden düşünülmesine yönelik kapsamlı bir teorik çerçeve sunmaktadır.

Habermas'ın temel katkısı, hukukun bağlayıcılığını yalnızca devletin yaptırım gücüyle veya hukuk normlarının biçimsel geçerliliğiyle açıklamayı reddetmesidir. Modern hukuk, bir taraftan yaptırım gücüyle desteklenen pozitif normlardan oluşurken diğer taraftan muhatapları karşısında haklılık ve meşruiyet iddiasında bulunmaktadır.

Çalışmada ortaya konulduğu üzere Habermas'ın hukuk anlayışının teorik temelleri iletişimsel eylem kuramında bulunmaktadır. İletişimsel eylem teorisi, toplumsal bütünleşmenin yalnızca piyasa mekanizmaları, bürokratik yönetim veya stratejik çıkar ilişkileri aracılığıyla gerçekleşmediğini; karşılıklı anlayışa yönelik iletişim süreçlerinin de toplumsal düzenin yeniden üretiminde merkezi rol oynadığını göstermektedir.

Bununla birlikte Habermas'ın olgun dönem hukuk teorisinde hukuk, iletişimsel aklın basit veya doğrudan kurumsal karşılığı olarak değerlendirilmemelidir. Modern toplumların karmaşık yapısı içerisinde hukuk, yaşam dünyasında iletişimsel olarak ortaya çıkan talepler ile siyasal ve idari sistemlerin karar mekanizmaları arasında aracılık eden özgün bir işlev üstlenmektedir.

Habermas'ın söylem teorisine göre hukuk normlarının meşruiyeti, bütün yurttaşların somut normlar üzerinde fiilen uzlaşmasına değil, bu normların özgür ve eşit yurttaşların katılımına açık demokratik süreçlerde gerekçelendirilebilir olmasına bağlıdır. Bu nedenle demokratik meşruiyet yalnızca parlamenter karar alma süreçlerinin varlığına indirgenemez. İfade özgürlüğü, örgütlenme özgürlüğü, özgür ve çoğulcu kamusal iletişim, sivil toplum ve siyasal katılım hakları demokratik hukuk üretiminin kurucu koşullarını oluşturmaktadır.

Habermas'ın özel ve kamusal özerklik arasında kurduğu eş-kökenlilik ilişkisi de bu yaklaşımın önemli sonuçlarından biridir. Bireylerin temel hakları ile demokratik öz-yönetim birbirine rakip iki ilke değildir. Yurttaşların temel hakları olmadan siyasal irade oluşumuna özgür biçimde katılmaları mümkün değildir; demokratik katılım olmadan da tabi oldukları hukuk düzeninin oluşumuna ortak yazarlar olarak katılmaları mümkün olmayacaktır.

Bu çalışmanın ulaştığı temel sonuç, Habermas'ın hukuk teorisinde meşruiyetin devlet otoritesinden demokratik gerekçelendirme süreçlerine doğru yeniden konumlandırıldığıdır. Hukuk yalnızca yürürlükte olduğu için meşru değildir. Meşru hukuk, yurttaşların kamusal irade ve kanaat oluşumuna katılabilmelerini sağlayan iletişimsel ve anayasal koşullar altında üretilen ve kamusal eleştiriye açık tutulan hukuktur.

Bununla birlikte Habermas'ın teorisine yöneltilen eleştiriler, demokratik söylemin gerçekleştiği toplumsal koşulların ayrıca dikkate alınması gerektiğini göstermektedir. Toplumsal ve ekonomik eşitsizlikler farklı grupların kamusal iletişime eşit biçimde katılmasını engelleyebilir. Kamusal alanın biçimsel olarak açık olması tek başına siyasal etkinin eşit dağıldığını göstermemektedir. Bu nedenle Habermasçı meşruiyet modelinin güç ilişkileri, toplumsal dışlanma ve iletişim biçimlerinin çoğulluğu açısından eleştirel biçimde tamamlanması gerekmektedir.

Sonuç olarak Habermas'ın hukuk teorisinin güncelliği, demokratik meşruiyeti tamamlanmış ve değişmez bir özellik olarak değil, sürekli yeniden üretilmesi gereken iletişimsel ve kurumsal bir süreç olarak kavramasında yatmaktadır. Demokratik hukuk devletleri yalnızca anayasal kurumlara sahip oldukları için değil, yurttaşların siyasal kararları eleştirebildikleri, kamusal irade oluşumuna katılabildikleri ve siyasal sistem üzerinde etkili olabildikleri ölçüde meşruiyetlerini sürdürebilirler. Bu bakımdan Habermas'ın yaklaşımı, demokratik temsilin zayıflaması, kamusal alanın parçalanması, ekonomik ve bürokratik güçlerin siyasal süreçler üzerindeki etkisinin artması ve yurttaşların karar alma mekanizmalarına yabancılaşması gibi çağdaş sorunların değerlendirilmesi bakımından güçlü bir teorik çerçeve sunmaya devam etmektedir.

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KIBRIS'TA DENİZ EKOSİSTEMİNİN KORUNMASINDA ULUSLARARASI HUKUKUN ETKİSİNİN ANALİZİ

ANALYSIS OF THE IMPACT OF INTERNATIONAL LAW ON THE PROTECTION OF MARINE ECOSYSTEMS IN CYPRUS

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ÖZET

Bu çalışma, deniz kirliliği ile mücadele kapsamında uluslararası hukuk normlarının ve küresel çevresel rejimlerin, Kıbrıs hukuku üzerindeki etkilerini ve bu normların ulusal mevzuata entegrasyon süreçlerini değerlendirmeyi amaçlamaktadır. Araştırma, uluslararası yasal çerçevelerin, Kıbrıs'ın yerel hukuk sisteminde nasıl etkiler bıraktığını ve bu etkilerin somut çevre politikalarına dönüşme kapasitesini analitik bir yaklaşımla ele almaktadır. Çalışmanın temel ekseni; plastik kirliliğinin, özellikle de denizler üzerindeki yıkıcı etkileri bilinen tek kullanımlık plastiklerin denetimine yönelik uluslararası mevzuatın, yerel idari ve hukuki yapılar üzerindeki dönüştürücü gücünü vurgulamaktır.

Araştırmanın birincil hedefi, Barselona Sözleşmesi ve ek protokolleri başta olmak üzere, deniz çevresinin korunmasına ilişkin uluslararası konvansiyonların ve Avrupa Birliği hukukunun Kıbrıs ulusal politikaları üzerindeki belirleyici rolünü incelemektir. Bu yasal çerçevelerin tetkik edilmesiyle, yerel mevzuatın uluslararası standartlara uyum düzeyi ve bu standartların uygulanabilirliği hakkında kapsamlı ve karşılaştırmalı bir anlayış sağlanması hedeflenmektedir. Bu bağlamda, deniz ekosistemini tehdit eden atıkların hukuki statüsü ve bu atıkların yönetimine dair yasal boşluklar bilimsel bir süzgeçten geçirilmektedir.

Ayrıca bu araştırma, uluslararası hukuk kurallarının Kıbrıs iç hukukunda uygulanması aşamasında karşılaşılan yargısal zorlukları, siyasi statüden kaynaklanan engelleri ve uygulama kapasitesindeki noksanlıkları belirleyerek analiz etmektedir. Toplumun çevre hukukuna olan uyumunu artırmak ve yerel hukuk mekanizmalarını uluslararası standartlarla harmonize etmek adına çözüm önerileri sunulmaktadır.

Çalışmada, birincil veriler; yürürlükteki yasalar, tüzükler, uluslararası antlaşma metinleri ve yargı kararları aracılığıyla derlenerek doğrudan hukuki içgörüler sunacaktır. İkincil veriler ise; bilimsel makaleler ve kitapları kapsayacak olup, mevcut literatürdeki ve araştırma sorularına normatif yanıtlar üretmek amacıyla kullanılacaktır.

Anahtar Kelimeler: uluslararası çevre hukuku, Kıbrıs hukuku, deniz kirliliği mevzuatı, plastik kirliliği regülasyonları, hukuki uyumlaştırma, atık yönetimi politikaları.

ABSTRACT

This study aims to evaluate the influence of international legal norms and global environmental regimes on Cypriot law in the context of combating marine pollution, as well as the processes through which these norms are integrated into domestic legislation. The research adopts an analytical approach to examine how international legal frameworks shape the local legal system of Cyprus and the extent to which these influences are translated into concrete environmental policies. The central focus of the study is to emphasize the transformative role of international regulations governing plastic pollution—particularly single-use plastics, which are known to have devastating effects on marine ecosystems—on local administrative and legal structures.

The primary objective of the research is to investigate the decisive role of international conventions concerning the protection of the marine environment, particularly the Barcelona Convention and its supplementary protocols, as well as European Union environmental law, in shaping Cyprus's national environmental policies. Through an examination of these legal frameworks, the study seeks to provide a comprehensive and comparative understanding of the degree of harmonization between domestic legislation and international standards, as well as the practical applicability of such standards. In this context, the legal status of waste threatening marine ecosystems and the existing regulatory gaps concerning waste management are critically assessed.
Furthermore, the study analyzes the judicial challenges encountered during the implementation of international environmental law within the domestic legal framework of Cyprus, including obstacles arising from the island's political status and deficiencies in institutional enforcement capacity. It also proposes legal and policy recommendations aimed at enhancing public compliance with environmental law and harmonizing local legal mechanisms with international environmental standards.
The study relies on primary legal sources, including legislation, regulations, international treaty texts, and judicial decisions, to provide direct legal insights. Secondary sources consist of academic articles and scholarly books, which are utilized to evaluate existing literature and develop normative responses to the research questions.
Keywords: International Environmental Law, Cypriot Law, Marine Pollution Legislation, Plastic Pollution Regulations, Legal Harmonization, Waste Management Policies.

GİRİŞ

Akdeniz; güneşli kıyıları, biyolojik çeşitlilik zenginliği ve tarihi birikimi itibarıyla uygarlık tarihinin en köklü coğrafyası olma özelliğini sürdürmektedir. Ne var ki bu havza aynı zamanda küresel ölçekteki plastik atık birikiminin en yoğun yaşandığı alanlardan biri konumuna gelmiştir. Yıllık yüz binlerce tonu bulan plastik yükü deniz ortamına karışmakta; bu olgu deniz ekosistemlerini, kıyı biyoçeşitliliğini ve uzun vadede insan sağlığını tehdit eden yapısal bir soruna dönüşmektedir (UNEP/MAP, 2022, s. 12-15). Kıbrıs adası bu sorunun en savunmasız coğrafyaları arasında yer almaktadır; dahası, salt konumu nedeniyle değil, eşsiz (sui generis) hukuki ve siyasi yapısı itibarıyla da uluslararası çevre hukukunun uygulanabilirlik sınırlarını en belirgin biçimde gözler önüne seren olağandışı bir örnek teşkil etmektedir. Ada fiilen iki ayrı yönetim alanına bölünmüş durumdadır: Güneyde AB hukuku çerçevesinde egemenlik kullanan Kıbrıs Cumhuriyeti, kuzeyde ise uluslararası toplumda yalnızca Türkiye tarafından tanınan Kuzey Kıbrıs Türk Cumhuriyeti (KKTC). Bu bölünmüşlük, uluslararası çevre normlarının ada genelinde tutarlı biçimde hayata geçirilmesini yapısal olarak engellemektedir.
Araştırma, birbirini tamamlayan iki temel soruyu sorgulamaktadır: Uluslararası hukuk, deniz ekosistemlerinin korunması için normatif olarak yeterli bir zemin sunabilmekte midir? Ve daha da belirleyici olan: Bu zemin, Kıbrıs adasının özgün siyasi ve hukuki koşulları altında işlevselliğini koruyabilmekte midir? Bu sorulardan hareketle çalışma; uluslararası hukuki düzenlemelerin Kıbrıs Cumhuriyeti mevzuatı üzerindeki etkisini, AB çevre hukukunun yönlendirici rolünü ve uygulamadaki yapısal engelleri, adanın siyasi statüsünün yarattığı hukuki bütünleşme açıklarını ve bu açıkları kapatmaya yönelik politika seçeneklerini bütüncül bir yaklaşımla ele almaktadır.
Çalışma; yürürlükteki yasal düzenlemeler, çok taraflı antlaşma belgeleri ve mahkeme içtihadından oluşan birincil hukuki kaynaklara; akademik çalışmalar ise ikincil kaynaklar olarak araştırmanın temel dayanağını oluşturmaktadır. Uluslararası, Avrupa Birliği ve ulusal hukuk katmanları arasındaki normatif etkileşimi gün yüzüne çıkarmak amacıyla karşılaştırmalı hukuk yöntemi benimsenmiştir.

ULUSLARARASI HUKUKİ ÇERÇEVE

Londra Sözleşmesi (1972) ve 1996 Protokolü

Uluslararası hukukun deniz kirliliğiyle mücadele konusundaki birikimi elli yılı geride bırakmış durumdadır. Bu sürecin başlangıç noktasını 1972 tarihli Londra Sözleşmesi oluşturmaktadır; söz konusu belge, gemi, uçak ve deniz tesislerinden kaynaklanan atıkların denize dökülmesini yasaklamaya yönelik tarihsel açıdan ilk kapsamlı küresel girişimi temsil etmektedir. 1996 yılında imzalanan Londra Protokolü bu çerçeveyi köklü biçimde dönüştürmüş; "açıkça izin verilenler hariç her şeyin yasak olduğu" ihtiyatlılık ilkesini benimseyerek tek kullanımlık plastiklerin denize dökülmesini açıkça yasaklamıştır. Bununla birlikte her iki düzenleme de yalnızca deniz kaynaklı atık dökümünü kapsamakta; kara üretimi

olan ve akarsu yollarıyla ya da rüzgar aracılığıyla denize ulaşan plastik yükü bu sözleşmelerin uygulama alanı dışında kalmaktadır.

MARPOL Sözleşmesi

Gemi kaynaklı deniz kirliliğine karşı uluslararası alanda en kapsamlı normları öngören düzenleme, 1973/1978 tarihli MARPOL Sözleşmesi'dir. Sözleşmeye ek V no'lu Ek, plastik ve katı nitelikteki gemi atıklarının denize boşaltılmasını yasaklamakta; Kıbrıs Cumhuriyeti de dahil olmak üzere sözleşmeye taraf tüm devletleri bu yükümlülükle bağlamaktadır. Ne var ki MARPOL da Londra Sözleşmesi gibi kara menşeli kirlilik kaynaklarını kapsam dışında bırakmaktadır. Oysa mevcut araştırma bulguları, Akdeniz'deki plastik yükünün büyük bölümünün kara kökenli olduğunu ve bu atıkların nehir sistemleri ile atmosferik taşınım yoluyla denize ulaştığını açıkça ortaya koymaktadır (UNEP/MAP, 2022). Bu yapısal boşluk, uluslararası deniz hukukunun plastik kirliliğiyle mücadelede hâlâ aşılamayan en kritik sorunu olmaya devam etmektedir.

Barselona Sözleşmesi ve Akdeniz Özel Çerçevesi

Akdeniz havzasına özgü olarak tasarlanmış en geniş kapsamlı çevre koruma sistemi; 1976 tarihli Barselona Sözleşmesi ve bu sözleşmeye bağlı protokollerden oluşmaktadır. Barselona Sözleşmesi, kıyı devletlerini deniz kirliliğinin bertarafı, azaltılması ve bölgesel düzeyde işbirliği mekanizmalarının güçlendirilmesi hususlarında bağlayıcı yükümlülükler altına sokmaktadır. Sözleşmeye ek Kara Kaynaklı Kirlilik Protokolü, karasal kökenli plastik atıkların deniz ortamı üzerindeki etkisini düzenleyen ve coğrafi bakımdan Akdeniz özelinde geçerli olan önemli bir normatif araç işlevi görmektedir.

Barselona Sözleşmesi, normatif yapısı itibarıyla güçlü bir başlangıç noktası oluşturmaktadır. Kuzey Afrika'dan Güney Avrupa'ya ve Ortadoğu'dan Balkan yarımadasına uzanan geniş bir kıyı devletler topluluğunu kapsayan bu sözleşme, Akdeniz'i bütünleşik bir yönetim alanı olarak konumlandırabilmektedir. Ancak sözleşmenin uygulamadaki etkinliği kaçınılmaz biçimde taraf devletlerin ulusal aktarım kapasitesi ve siyasi taahhüt düzeyiyle orantılı seyretmektedir. Kıbrıs adası özelinde bu kapasiteyi en derinden etkileyen değişken, adanın kendine özgü siyasi bölünmüşlük tablosudur.

BM Deniz Hukuku Sözleşmesi ve Diğer Belgeler

Uluslararası deniz hukukunun omurgasını oluşturan BM Deniz Hukuku Sözleşmesi (UNCLOS, 1982), deniz çevresinin korunmasına ilişkin sistematik ve kapsamlı bir normlar bütünü sunmaktadır. Kıbrıs Cumhuriyeti bu sözleşmeye 1988 yılında taraf olmuştur. UNCLOS'un XII. Bölümü, kıyı devletlerini deniz kirliliğini önleme ve denetim altına alma konusunda pozitif eylem yükümlülükleriyle donatmakta; kirlilik kaynaklarını (gemi, kara, hava kökenli vb.) ayrı ayrı ele alan farklılaştırılmış bir hukuki yapı benimsemektedir. Tehlikeli atıkların ülkeler arasında taşınmasını düzenleyen Basel Sözleşmesi de Kıbrıs Cumhuriyeti'nin taraf olduğu diğer uluslararası belgeler arasında sayılabilir. Kıbrıs Cumhuriyeti'nin söz konusu antlaşmalar çerçevesindeki taahhüt profili göreli olarak güçlüdür; esas sorun bu taahhütlerin ulusal mevzuata aktarılması ve sahada etkin biçimde uygulanması aşamalarında kendini göstermektedir.

AVRUPA BİRLİĞİ HUKUKU VE KIBRIS'A ETKİSİ

Deniz Stratejisi Çerçeve Direktifi

Avrupa Birliği'ne üye bir ada devleti sıfatıyla Kıbrıs Cumhuriyeti, Birlik çevre hukuku düzeninin bütünüyle bağlıdır. Deniz kirliliği alanında bu düzenin en temel aracı olan 2008/56/EC sayılı Deniz Stratejisi Çerçeve Direktifi (DSÇD), AB üyesi kıyı devletlerinin deniz sularında 2020 yılına dek "İyi Çevresel Durum"a (Good Environmental Status) ulaşmasını zorunlu kılmaktadır. Kıbrıs Cumhuriyeti'nin bu direktif kapsamında hazırladığı Ulusal Deniz Stratejisi; kıyı atıklarının sınırlandırılmasını, deniz biyolojik çeşitliliğinin korunmasını ve özellikle Caretta caretta denizkaplumbağalarına ait yuvalama habitatlarının güvence altına alınmasını öncelikli politika hedefleri olarak belirlemiştir.

Atık Çerçeve Direktifi

2008/98/EC sayılı Atık Çerçeve Direktifi, atık yönetiminde bir öncelik hiyerarşisi benimser: önleme, yeniden kullanım, geri dönüşüm, geri kazanım ve nihayetinde bertaraf.

Bu aşamalı model Kıbrıs Cumhuriyeti iç hukukuna aktarılmış olmakla birlikte, uygulamanın gerçek anlamda etkin olup olmadığı hâlâ tartışma konusudur. Kıbrıs Cumhuriyeti kontrolündeki bölgede direktif çerçevesindeki denetim ve izleme mekanizmaları fiilen işletilmekte; ancak fiziksel altyapı yetersizlikleri ve kurumsal kapasite açıkları bu mekanizmaların etki gücünü kısıtlamaktadır.

Tek Kullanımlık Plastikler Direktifi

2019/904 sayılı Tek Kullanımlık Plastikler Direktifi, Avrupa Birliği'nin plastik kirliliğiyle mücadele araçlarının en güncel ve kapsamlı örneğini oluşturmaktadır. Direktif; plastik pipet, tek kullanımlık çatal-bıçak takımı ve pamuklu çubuk gibi belirli ürünlerin piyasaya erişimini yasaklamakta ve 2030 yılına kadar ambalaj atıklarında yüzde yetmiş geri dönüşüm oranına ulaşılmasını zorunlu kılmaktadır.

Direktif Kıbrıs Cumhuriyeti iç hukukuna entegre edilmiş olsa da, başta KKTC'nin yönetimindeki kuzey bölgede belirgin olan denetim ve uygulama eksiklikleri nedeniyle tek kullanımlık plastik tüketimi çevresel kirlilik yaratmaya devam etmektedir.

Bu noktada altı çizilmesi gereken yapısal bir olgu bulunmaktadır: Söz konusu AB direktiflerinin tamamının etki alanı yalnızca Kıbrıs Cumhuriyeti egemenliğindeki güney bölgeyle sınırlıdır. KKTC, AB müktesebatının uygulama kapsamı dışında kalmaktadır; bu nedenle AB çevre direktiflerinin ada genelinde bütüncül biçimde uygulanması hukuken ve fiilen mümkün değildir.

KIBRIS'IN SİYASİ STATÜSÜ VE UYGULAMA SORUNU

Kıbrıs Cumhuriyeti 2004 yılında Avrupa Birliği'ne katılmış; ancak AB müktesebatının yürürlük alanı Kıbrıs Cumhuriyeti yönetimindeki güney bölgeyle kısıtlı kalmıştır. KKTC, uluslararası toplumda yalnızca Türkiye tarafından tanınmakta; bu fiili durum AB çevre direktiflerinin ve ilgili uluslararası mekanizmaların adanın kuzeyinde uygulanmasını hukuken olanaksız kılmaktadır. Ortaya çıkan sonuç, tek bir ada üzerinde çift başlı bir hukuk düzenidir: adanın kıyı şeridi siyasi sınırları tanımayan bütünleşik bir coğrafi yapı oluştururken, çevre hukuku bu şerit boyunca fiilen ikiye bölünmüş durumdadır.

Söz konusu hukuki ikiliğin çevresel yansımaları son derece ağırdır. Başta plastik olmak üzere KKTC topraklarında yeterince yönetilemeyen atıklar aynı deniz ortamına karışmakta ve adanın tamamını çevresinde dolaşan tek bir su kütlesini kirletmektedir. Ekosistemler hukuki sınırlarla sınırlı olmaksızın işlev gördüğünden, Caretta caretta denizkaplumbağaları, Akdeniz fokları ve kıyı biyoçeşitlilik türleri siyasi bölünmüşlüğün yarattığı koruma boşluklarını ne hissedebilmekte ne de bu boşluklardan kaçınabilmektedir.

Bu tablonun uluslararası hukuk kuramı açısından kritik bir sonucu bulunmaktadır: Siyasi statü belirsizliğinden doğan normatif boşluklar, çevresel etkileri itibarıyla ada topraklarının tamamını olumsuz etkileyen kronik bir soruna dönüşmektedir. Bu nedenle Kıbrıs, uluslararası çevre hukukunun bölünmüş egemenlik yapılarındaki sınırlılıklarını hem somutlaştıran hem de uyarıcı bir örnek olarak değerlendirilebilir.

UYGULAMA GÜÇLÜKLERİ VE YAPISAL KISITLAR

Çalışmanın ortaya koyduğu başlıca uygulama engelleri üç temel boyutta değerlendirilebilir. Birincisi kurumsal kapasite sorunudur. KKTC'de atık altyapısı AB düzenleyici standartlarının oldukça gerisinde seyretmektedir: Geri dönüşüm oranları düşük, belediye atık toplama kapasitesi ise mevcut ihtiyacın altında kalmaktadır. Bu tablonun doğrudan yansıması, plastik atıkların yetersiz denetim koşullarında çevre ortamına yayılmaya devam etmesidir.

İkincisi mevzuat uyumlaştırması ve denetim yetersizliğidir. Uluslararası sözleşmelerin KKTC topraklarında fiilen uygulanamaması, iki yönetim bölgesi arasındaki normatif harmonizasyonu yapısal olarak imkânsız kılmaktadır. Bu hukuki boşluk, deniz suyu kalitesine ilişkin izleme verilerinin yetersizliğiyle birleştiğinde kirliliğin gerçek ölçeğinin tespitini de güçleştirmektedir. Sivil toplum örgütlerinin bu konudaki kaygıları kayda değerdir: Bağımsız çevre gözlem mekanizmaları kurumsal destek olmaksızın varlığını sürdüremediği sürece kirlilik takibinin sistematik bir zemine oturtulması olanaklı görünmemektedir.

Üçüncüsü yaptırım boşluğudur. Adanın her iki yönetim bölgesinde de çevresel denetim mekanizmaları gereksinimi karşılamaktan uzak kalmaktadır. Toplumsal farkındalığın yükseldiği ve sivil toplum aktörlerinin sahada görece etkin rol üstlendiği gözlemlenmektedir; sosyal medya kampanyaları, kıyı temizlikleri ve okul tabanlı çevre programları bu çabaların somut yansımalarıdır. Ancak bu toplumsal dinamiklerin kalıcı etkiye dönüşebilmesi için hukuki altyapının güçlendirilmesi ve etkin yaptırım mekanizmalarıyla desteklenmesi gerekmektedir.

Sayılan bu güçlüklere ek olarak iklim değişikliği bağlamsal bir baskı katmanı daha eklemektedir. Yükselen deniz suyu sıcaklıkları ve artan aşırı hava olayları hem deniz ekosistemlerini doğrudan zedelemekte hem de mevcut atık ve kirlilik yönetim kapasitesi üzerindeki yükü katlamaktadır (Kiss ve Shelton, 2007, s. 215-218).

ÇÖZÜM ÖNERİLERİ VE POLİTİKA TASARIM ÇERÇEVESİ

Bu bulgulardan hareketle çalışmanın önerdiği politika yolları dört temel eksen üzerinde biçimlendirilmiştir. Birinci politika ekseni, teknik işbirliği protokollerinin oluşturulmasıdır. Kıbrıs Cumhuriyeti ile KKTC arasında her iki tarafın siyasi statüsüne ilişkin herhangi bir tanıma talebi içermeyen teknik düzeyli koordinasyon mekanizmaları hayata geçirilebilir.

Çevre yönetimi, atık izleme, deniz suyu kalite denetimi ve acil müdahale gibi alanlarda kurulacak teknik iletişim kanalları, toplulukları siyasi statü müzakerelerinden bağımsız işlevsel bir zemine taşıyabilir. Benzer çerçeveler dünyanın pek çok çatışmalı ya da bölünmüş toprak yapısında denenmiş ve çevresel alanda ölçülebilir kazanımlar üretmiştir (Birnie vd., 2009, s. 648-652).

İkinci eksen, uluslararası kuruluşların arabulucu ve teknik destek rolünün güçlendirilmesidir. Barselona Sözleşmesi'nin sekretarya işlevini üstlenen UNEP/MAP, adanın her iki tarafını kapsayan teknik yardım programları yürütme kapasitesine yapısal olarak sahiptir. Bu tür çerçeveler siyasi tanıma koşulu aramaksızın çevresel zorunluluk zemininde işleyebilmektedir. Aynı model, UNEP Küresel Çevre Fonu (GEF) finansmanı ve UNDP teknik altyapısıyla pekiştirilerek uygulamaya alınabilir.

Üçüncü eksen, sivil toplum kapasitesinin hukuki ve kurumsal mekanizmalarla sistematik olarak desteklenmesidir. Kıbrıs'ta her iki toplumda da çevresel alanda faaliyet gösteren sivil toplum kuruluşları fiili olarak köprü işlevi görmekte ve toplumlar arası bütünleşmede önemli bir rol üstlenmektedir. Bu potansiyelin finansman güvenceleri, yasal koruma ve kurumsal kapasite geliştirme programlarıyla desteklenmesi, kısa vadede somut çevresel kazanımlar üretecek en erişilebilir politika seçeneğini oluşturmaktadır. AB'nin Uyum Fonu ve LIFE+ finansman araçlarından yararlanılarak izleme ve yaptırım kapasitesinin sistematik biçimde artırılması da değerlendirilmeye değer bir tercih olarak öne çıkmaktadır.

Dördüncü eksen, uluslararası normatif çerçevenin yenilenmesine etkin katkı sunmaktır.

Kara kaynaklı plastik kirliliğini doğrudan hedefleyen bağlayıcı küresel bir antlaşmanın müzakere süreçlerine Kıbrıs Cumhuriyeti'nin etkin katılımı; hem ulusal farkındalığı güçlendirecek hem de ada deneyiminin küresel norm yapıcılığına yansımasını sağlayacaktır (Sands vd., 2018, s. 298-300).

DEĞERLENDİRME: ULUSLARARASI HUKUKUN ETKİNLİK SINIRI

Uluslararası çevre hukuku sisteminin bütüncül bir değerlendirmesi, normatif kapsam alanının sürekli genişlemesine rağmen uygulamadaki etkinliğin görece kısıtlı kaldığını gözler önüne sermektedir. Bu etkinlik sınırlılığının temelinde birbirini besleyen üç yapısal etken bulunmaktadır.

Birinci etken, uluslararası hukukun sistemik zayıflığıdır. Uluslararası hukuk düzeni ağırlıklı olarak devlet egemenliğine saygı ilkesi temelinde şekillenmiştir. Bu kurucu ilke, uluslararası çevre normlarının ulusal hukuka aktarımını ve fiilî uygulamasını neredeyse tümüyle devletlerin takdir yetkisine terk etmektedir. Bağımsız doğrulama ve yaptırım mekanizmalarının zayıf yapısı, uluslararası taahhütlerin somut politikalara ve ölçülebilir eylemlere dönüştürülmesini münhasıran ulusal iradeyle orantılı hale getirmektedir.

İkinci etken, Kıbrıs adasına özgü siyasi bölünmüşlüğün yarattığı yapısal kısıttır. Doğal ekosistemler siyasi sınır çizgilerine tabi değildir; oysa uluslararası hukukun fiilî uygulama kapasitesi bu sınırlar tarafından dolaylı biçimde belirlenmektedir. Ortaya çıkan boşluk; Kıbrıs Cumhuriyeti ile KKTC arasındaki siyasi statüye ilişkin köklü bir çözüme ulaşılmadan yalnızca hukuki tedbirlerle aşılması son derece güç olan, yapısal nitelikte bir çevre sorununa evrilmektedir.

Üçüncü etken, küresel plastik kirliliğiyle mücadelede mevcut normatif araçların yetersiz kalmasıdır. 2024 yılı itibarıyla müzakere süreci devam eden küresel plastik antlaşması girişimi, kara kaynaklı plastik akışlarını doğrudan hedef alan bağlayıcı bir uluslararası belgenin hâlâ mevcut olmadığını açıkça ortaya koymaktadır. Halihazırdaki hukuki çerçeve plastik kirliliğinin yalnızca deniz kaynaklı boyutuyla ilgilenmekte; kirliliğin birincil kaynağını oluşturan kara menşeli akışlar bu çerçevenin kapsamı dışında kalmaktadır. Bu temel boşluğun giderilmesi, uluslararası çevre hukukunun en acil gündem konuları arasındaki yerini korumaktadır (Wolfrum ve Matz, 2003, s. 42-45).

Bu değerlendirmeler bir bütün olarak ele alındığında Kıbrıs vakasının yalnızca bir ada devletinin iç hukuk uyum sorununu değil, aynı zamanda uluslararası çevre hukukunun bölünmüş ya da tartışmalı egemenlik yapılarında nasıl işlev görebileceği—ya da işlev göremeyeceği—sorusunu da temsil ettiği görülmektedir. Bu niteliğiyle Kıbrıs, uluslararası çevre hukuku kuramcıları ve politika uygulayıcıları için derin ve çok katmanlı analitik bir referans alanı sunmaktadır.

SONUÇ

Bu araştırma, uluslararası çevre hukukunun Kıbrıs adasındaki deniz ekosistemini korumaya yönelik kapasitesini birbiriyle bağlantılı üç düzlemde ele almıştır: normatif çerçevenin içsel yeterliliği, AB çevre hukukunun yönlendirici rolü ve adanın siyasi bölünmüşlüğünden doğan yapısal kısıtlar.

Araştırmanın temel bulguları şu şekilde özetlenebilir: Uluslararası hukuk, deniz ekosistemlerinin korunması amacıyla teorik bakımdan bütünlüklü ve kapsamlı bir normatif mimari sunmaktadır. Londra Sözleşmesi'nden Barselona Sözleşmesi'ne, UNCLOS'tan AB Tek Kullanımlık Plastikler Direktifi'ne uzanan bu normatif yapı, uygun koşullarda etkin bir çevresel koruma işlevi görebilecek niteliktedir. Ne var ki bu çerçevenin hayata geçirilmesi, siyasi gerçekliklerle doğrudan bir hesaplaşmayı zorunlu kılmaktadır.

Kıbrıs adası bu gerçekliği en açık biçimde somutlaştıran özgün örnek olma niteliğini korumaktadır. KKTC'nin yönetimindeki bölgede uluslararası çevre hukukunun etkin biçimde uygulanamaması salt bir siyasi sorun değil; aynı zamanda Caretta caretta kaplumbağaları, Akdeniz fokları ve kıyı biyolojik çeşitliliği açısından son derece somut bir ekosistem kaybıdır. Bu nedenle Kıbrıs örneği, uluslararası çevre hukuku yazınında çevresel normların siyasi ve kurumsal boyutlarından ayrı ele alınamayacağını kanıtlayan kritik bir referans noktası olmayı sürdürmektedir.

Uluslararası hukuk, deniz ortamını koruma altına almak için gerekli normatif araç setini zaten sunmaktadır. Ancak bu araçların gerçek anlamda işlevsellik kazanabilmesi için siyasi irade, kurumsal kapasite ve geniş tabanlı toplumsal sahiplenmenin eş zamanlı olarak sağlanması gerekmektedir. Kıbrıs özeli ve küresel ölçek bir arada değerlendirildiğinde, bu üç unsurun bütünleşik biçimde harekete geçirilmesi uluslararası çevre hukukunun etkinliğini gerçek kılmanın vazgeçilmez koşuludur.

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İKLİM DEĞİŞİKLİĞİNİN HİDRO-METEOROLOJİK PARAMETRELER ÜZERİNDEKİ ETKİSİ (KLASİK TESTLER İLE ITA VE IPTA YÖNTEMLERİNİN ENTEGRASYONU)

THE IMPACT OF CLIMATE CHANGE ON HYDRO-METEOROLOGİCAL PARAMETERS: INTEGRATİON OF CLASSICAL TESTS WİTH ITA AND IPTA METHODS

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ÖZET
İklim değişikliğinin, günümüzde hidro-meteorolojik süreçlerin yeniden şekillenmesine neden olarak su kaynakları yönetimi ve tarımsal sürdürülebilirlik üzerinde büyük bir etkisi vardır. Bu çalışma, 1965-2025 yıllarını kapsayan, Doğu Anadolu Bölgesi'ni temsil eden sekiz stratejik meteoroloji istasyonuna (Ağrı, Iğdır, Van, Doğubeyazıt, Erciş, Muradiye, Özalp, Başkale) ait Yıllık Toplam Yağış (YTY) ve Aylık Ortalama Sıcaklık (AOS) verilerini analiz etmektedir. Çalışmanın temel amacı, klasik istatistiksel yöntemler ile yenilikçi grafiksel yaklaşımları entegre ederek, iklimsel parametrelerdeki değişimleri ve olası iklimsel kaymaları karakterize etmektir. Araştırmanın metodolojik altyapısını, trendin varlığını ve anlamlılığını test eden Mann-Kendall (MK) ve Spearman's Rho (SRHO) testleri ile Yenilikçi Trend Analizi (ITA) ve aylık geçiş dinamiklerini dairesel poligonlarla görselleştiren Yenilikçi Poligon Trend Analizi (IPTA) oluşturmaktadır. Klasik testlerin aksine ITA yöntemi, herhangi bir dağılım şartı aramaksızın uç değerlerdeki (ekstrem sıcaklıklar veya kurak dönemler) gizli eğilimleri saptarken; IPTA yöntemi, ardışık aylar arasındaki geçişleri poligonlar üzerinden tanımlayarak mevsimsel döngüdeki sapmaları ve iklimsel kaymaları görsel olarak ortaya koymaktadır. Analiz sonuçları, sıcaklık parametresinde (AOS) tüm lokasyonlarda istatistiksel olarak yüksek derecede anlamlı bir artış olduğunu kanıtlamaktadır. Aylık bazdaki incelemeler, bu termal artışın özellikle Haziran, Temmuz ve Ağustos aylarında zirveye ulaştığını ve bölgede belirgin bir iklimsel rejim değişikliğine işaret ettiğini göstermektedir. Sonuç olarak, klasik testlerin genel trendleri belirlemedeki gücü ile yenilikçi yöntemlerin (ITA/IPTA) verinin alt kategorilerindeki hassasiyeti, bölgedeki iklimsel değişimin şiddetini ve mevsimsel geçişlerdeki düzensizleşmeyi net bir şekilde ortaya koymuştur. Bu çok boyutlu yaklaşım, bölgedeki su kaynakları yönetimi ve iklim değişikliğine uyum stratejileri için kritik bulgular sunmaktadır.
Anahtar Kelimeler: İklim Değişikliği, Yenilikçi Trend, Mann-Kendall, Doğu Anadolu

ABSTRACT
Climate change is currently causing a reshaping of hydro-meteorological processes, placing vital pressure on water resource management and agricultural sustainability. This study analyzes Annual Total Precipitation (ATP) and Monthly Average Temperature (MAT) data from eight strategic meteorological stations (Ağrı, Iğdır, Van, Doğubeyazıt, Erciş, Muradiye, Özalp, Başkale) representing the Eastern Anatolia Region, covering the years 1965-2025. The main objective of the study is to characterize changes in climatic parameters and potential climatic shifts by integrating classical statistical methods with innovative graphical approaches. The methodological framework of the research consists of Mann-Kendall (MK) and Spearman's Rho (SRHO) tests, which test the existence and significance of trends, Innovative Trend Analysis (ITA), and Innovative Polygon Trend Analysis (IPTA), which visualizes monthly transition dynamics with circular polygons.
Unlike classical tests, the ITA method detects latent trends in extreme values (extreme temperatures or dry periods) without seeking any distribution conditions; while the IPTA method visually reveals deviations in the seasonal cycle and climatic shifts by defining transitions between consecutive months

through polygons. The analysis results prove a statistically highly significant increase in the temperature parameter (AOS) in all locations. Monthly analyses show that this thermal increase peaks particularly in June, July, and August, indicating a significant climatic regime change in the region. In conclusion, the power of classical tests in determining general trends and the sensitivity of innovative methods (ITA/IPTA) in subcategories of data clearly reveal the severity of climatic change and the irregularity in seasonal transitions in the region. This multi-dimensional approach provides critical findings for water resource management and climate change adaptation strategies in the region.
Keywords: Climate Change, Innovative Trend, Mann-Kendall, Eastern Anatolia

GİRİŞ

Küresel iklim değişikliği, hidro-meteorolojik süreçlerin döngüsel yapısını bozarak su kaynakları yönetimi, ekolojik denge ve tarımsal sürdürülebilirlik üzerinde geri dönüştürülmesi güç olumsuzluklar oluşturmaktadır. Bu düzensizleşmenin en çarpıcı ve yıkıcı sonuçlarından biri olan kuraklık; belirli bir bölgede nem ve yağış miktarlarının uzun yıllar ortalamasının altına düşmesiyle tetiklenen, zamansal ve mekânsal olarak geniş alanlara yayılan hidro-meteorolojik bir afettir. Artan sera gazı emisyonlarına bağlı olarak küresel sıcaklıklarda yaşanan belirgin yükselişler, buharlaşma-terleme (evapotranspirasyon) oranlarını artırarak kuraklık süreçlerinin hem şiddetini hem de frekansını doğrudan tırmandırmaktadır. Özellikle topoğrafik ve iklimsel açıdan hassas dengelere sahip olan yarı kurak ve dağlık havzalarda, hidro-meteorolojik parametrelerdeki en küçük sapmalar bile su arzı güvenliğini tehdit eden ciddi kuraklık risklerini beraberinde getirmektedir.

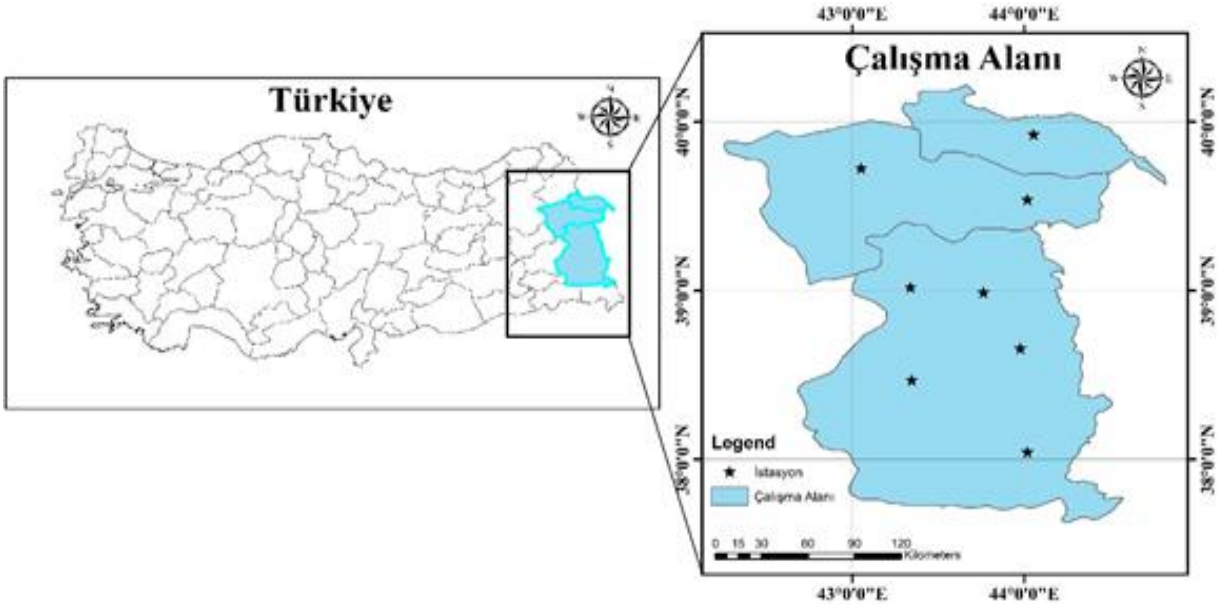
Hidro-meteorolojik zaman serilerinde meydana gelen bu değişimlerin ve eğilimlerin doğru analiz edilmesi, bölgesel planlamalar ve risk yönetimi açısından büyük önem taşımaktadır. Bu doğrultuda literatürde, veri serisindeki eğilimlerin varlığını ve istatistiksel anlamlılığını test etmek amacıyla parametrik olmayan Mann-Kendall (MK) ve Spearman's Rho (SRHO) gibi klasik istatistiksel testler yaygın bir biçimde kullanılmaktadır. Ancak, bu geleneksel testler verinin normal dağılım göstermesi ya da serisel bağımlılıktan arındırılmış olması gibi ön şartlara ihtiyaç duyabildiği gibi, verinin alt kategorilerindeki (örneğin uç kurak dönemler veya ekstrem yüksek sıcaklıklar) gizli eğilimleri saptamada yetersiz kalabilmektedir. Bu kısıtlamaları aşmak adına geliştirilen Yenilikçi Trend Analizi (ITA) yöntemi, herhangi bir dağılım şartı aramaksızın veriyi düşük, orta ve yüksek değer gruplarına ayırarak grafiksel olarak incelenmesine olanak tanır. Sürecin mevsimsel ve aylık geçiş dinamiklerini dairesel poligonlar üzerinden tanımlayan Yenilikçi Poligon Trend Analizi (IPTA) yöntemi ise ardışık aylar arasındaki ardışıl döngüsel sapmaları ve iklimsel kaymaları görselleştirerek daha dinamik ve mikro ölçekli bir yaklaşım sunmaktadır.

Konuyla ilgili literatürler incelendiğinde, iklim değişikliği ve kuraklık ekseninde sıcaklık ve yağış trendlerinin belirlenmesi üzerine bazı çalışmalar yapıldığı görülmektedir. Geleneksel yaklaşımlar genellikle Mann-Kendall ve Spearman's Rho testleriyle havzaların genel eğilim haritasını çıkarmaya odaklanmıştır. Son yıllarda ise Şen (2012) tarafından literatüre kazandırılan Yenilikçi Trend Analizi (ITA) ve bu yaklaşımın mevsimsel/aylık döngüleri dairesel poligonlarla modelleyen bir üst aşaması olarak geliştirilen Yenilikçi Poligon Trend Analizi (IPTA) yöntemleri (Şen ve ark., 2019), hidro-meteorolojik parametrelerin incelenmesinde yeni bir dönem başlatmıştır. Türkiye'deki hidro-meteorolojik parametrelerin (yağış, sıcaklık vb.) trend eğilimlerini belirlemek amacıyla yürütülen çalışmalarda, bu yenilikçi grafiksel yöntemlerin klasik testlere kıyasla aylık ve yıllık değişimleri yakalamadaki hassasiyeti ve esnek yapısı açıkça ortaya konmuştur; nitekim Esit (2023) tarafından Ankara bölgesi için yapılan benzer bir çalışmada, anlamlılık testli ITA ve IPTA yöntemlerinin klasik Mann-Kendall testine göre hidro-meteorolojik değişkenlerdeki gizli trend eğilimlerini çok daha yüksek bir hassasiyet ve yüzdeyle yakaladığı belirlenmiştir. Ancak, klasik istatistiksel yöntemlerin genel makro eğilimleri ortaya koymadaki gücü ile yenilikçi grafiksel yaklaşımların (ITA/IPTA) mikro ölçekli alt veri kategorilerindeki (düşük, orta, yüksek değerler) duyarlılığını bütüncül bir yaklaşımla entegre eden çalışmaların sayısı literatürde halen sınırlıdır.

Bu çalışma, 1965-2025 yıllarını kapsayan 60 yıllık uzun vadeli homojen bir veri setini temel alarak Doğu Anadolu Bölgesi'ni temsil eden sekiz stratejik meteoroloji istasyonuna (17099, 17100, 17172, 17720, 17784, 17786, 17812, 17880) ait Yıllık Toplam Yağış (YTY) ve Aylık Ortalama Sıcaklık (AOS) verilerini kapsamlı bir entegrasyonla ele almaktadır. Elde edilen bulgular doğrultusunda yapılacak bir değerlendirmeyle; klasik testlerin sunduğu makro ölçekli istatistiksel çıktılar ile ITA ve IPTA

yöntemlerinin sağladığı görsel ve hassas alt veri analizlerinin bir arada kullanılmasının, Doğu Anadolu gibi hidrolojik açıdan kritik bir bölgede iklimsel rejim değişikliklerini anlamlandırmada önemli bir katkı sunduğu görülmektedir. Özellikle sıcaklık parametresinde (AOS) tüm istasyonlarda gözlenen yüksek derecede anlamlı artış trendlerinin yaz aylarında zirve yapması, bölgede buharlaşma baskısıyla tetiklenecek bir hidrolojik kuraklık riskinin kapıda olduğunu ve tarımsal sürdürülebilirlik açısından acil eylem planlarının geliştirilmesi gerektiğini açıkça ortaya koymaktadır.

YÖNTEM



Şekil 1. Çalışma Alanı

Doğu Anadolu Bölgesi'ndeki iklimsel ve hidrolojik trendlerin analiz edilmesi amacıyla, bölgede faaliyet gösteren 17099, 17100, 17112, 17720, 17784, 17786, 17812 ve 17880 numaralı 8 adet Meteoroloji Genel Müdürlüğü (MGM) gözlem istasyonuna (Ağrı, Iğdır, Van, Doğubeyazıt, Erciş, Muradiye, Özalp, Başkale) ait veriler incelenmiştir.

Çalışma alanının coğrafi konumu ile analizlerde kullanılan bu istasyon ağının alansal dağılımı Şekil 1'de ayrıntılı olarak sunulmuştur.

Tablo 1.Yıllık Sıcaklık ve Yağış Değerleri

İstasyon İsmi	Veri	Enlem	Boylam	İlk-son Kayıt tarihi	Ortalama	Min	Max	Standart Sapma
Ağrı	ATY (mm)	39,7253	43,0522	1965-2025	5214656	329.6	779.6	0,966389485
	AOS (°C)			1965-2025	6411749	3416667	9566667	1,047657673
Iğdır	ATY (mm)	39,925912	44,05372	1965-2025	2602492	114.5	374.9	0,375485517
	AOS (°C)			1965-2025	1239071	9641667	1510833	0,632348574
Van	ATY (mm)	38,4693	43,346	1965-2025	3895885	234	542.6	0,436852222
	AOS (°C)			1965-2025	9592623	6916667	12175	0,827919336
Doğubeyazıt	ATY (mm)	39,5396	44,018	1965-2025	3217033	188.5	649.9	1,398917082
	AOS (°C)			1965-2025	9149727	6725	1164167	0,593425234
Erciş	ATY (mm)	39,0198	43,3386	1965-2025	4218393	193.8	751.1	1,404667785
	AOS (°C)			1965-2025	8288388	5183333	1116667	0,776539021

Muradiye	ATY (mm)	38,989833	43,763	1965-2025	5300311	232.1	970.8	1,531726615
	AOS (°C)			1965-2025	8891257	6225	27699	0,894510348
Özalp	ATY (mm)	38,657333	43,976667	1965-2025	4403115	167	1039.5	0,897426009
	AOS (°C)			1965-2025	6080874	46056	8841667	0,890550138
Başkale	ATY (mm)	38,0435	44,0173	1965-2025	4267098	251.9	664.7	0,396265295
	AOS (°C)			1965-2025	638306	3933333	8783333	0,649274362

Çalışma kapsamında Doğu Anadolu Bölgesi'nde belirlediğimiz 8 farklı meteorolojik istasyona ait 1965-2025 dönemini kapsayan verilerin tanımlayıcı istatistikleri tabloda sunulmuştur. Bu istatistikler, ilgili istasyonların coğrafi koordinatları ile birlikte, bölgedeki hidro-klimatik değişimlerin analizinde temel teşkil eden Yıllık Toplam Yağış (ATY) ve Ortalama Yıllık Sıcaklık (AOS) değerlerini içermektedir. Tabloda yer alan istatistiksel veriler istasyonların ait iklimsel değişkenliğin kapsamlı bir özetini sunmaktadır. Ortalama, minimum (min) ve maksimum (max) değerler, bölgenin uç değerler (ekstrem olaylar) konusundaki hassasiyetini ve iklimsel karakteristiğini yansıtmaktadır. Ayrıca, hesaplanan standart sapma (SS) değerleri, istasyon bazlı verilerin zamansal dağılımdaki dalgalanma düzeyini ve istikrarını ortaya koymaktadır.
Bu veriler, çalışmanın ilerleyen bölümlerinde kullanılan Trend Analizi (IPTA, ITA, MK, SRHO vb.) yöntemleri için gerekli temel değişkenleri oluşturmakta olup, 1965-2025 periyodunda gözlemlenen iklimsel kaymaların ve yağış-sıcaklık ilişkisinin daha derinlemesine yorumlanmasına imkan sunmaktadır.

Mann-Kendall (MK) ve Spearman's Rho (SRHO) Testleri
Hidrometeorolojik zaman serilerinin analizinde trendin varlığını, yönünü ve istatistiksel anlamlılığını belirlemek amacıyla literatürde parametrik olmayan (non-parametric) testler yaygın olarak tercih edilmektedir. Bu testlerin başında Mann (1945) ve Kendall (1975) tarafından geliştirilen Mann-Kendall (MK) testi ile Spearman (1904) tarafından önerilen Spearman's Rho (SRHO) katsayısı gelmektedir. Parametrik testlerin aksine, bu yöntemler verilerin normal dağılıma uygunluk göstermesini şart koşmaz ve serideki uç (ekstrem) değerlere karşı oldukça dirençlidir (Yue vd., 2002).
MK testinde, zaman serisindeki veriler ardışık olarak birbiriyle kıyaslanarak S test istatistiği hesaplanır ve veri sayısının yeterli olduğu durumlarda bu istatistik standart normal dağılım gösteren bir Z skoruna dönüştürülür. Benzer şekilde SRHO testi de verilerin kronolojik sıralaması ile değerlerin kendi içindeki rütbe sıralaması arasındaki doğrusal ilişkiyi ρ (rho) katsayısı üzerinden derecelendirir. Bu çalışmada, her iki testten elde edilen Z ve ρ test istatistikleri, çift yönlü bir trend analizinde %95 güven düzeyini temsil eden kritik $\alpha = 0.05$ anlamlılık seviyesine ($|Z| > 1.96$) göre test edilmiştir. Elde edilen değerlerin pozitif olması artış (artan trend), negatif olması ise azalış (azalan trend) eğilimini doğrulamaktadır.

Sen'in Eğim Tahmini (Sen's Slope)
Mann-Kendall ve Spearman's Rho testleri trendin varlığı ve yönü hakkında doğrusal bir bilgi sunarken, bu eğilimin birim zamandaki (yıllık) değişim miktarını veya büyüklüğünü (magnitude) hesaplayamazlar. Zaman serisindeki bu zamansal değişim oranının doğrusal yönünü ve miktarını belirlemek amacıyla Sen (1968) tarafından geliştirilen parametrik olmayan "Sen'in Eğim Tahmini" (Sen's Slope Estimator) yöntemi kullanılmıştır. Bu yöntem, serideki tüm olası veri çiftleri arasındaki eğimlerin (değişim oranlarının) hesaplanmasına ve bu eğim dizisinin medyan (ortanca) değerinin seçilmesine dayanır. Medyan değerinin kullanılması, zaman serisi içerisindeki ani sıçramalardan, eksik verilerden veya ekstrem iklimsel anomalilerden kaynaklanabilecek sapmaların eğim üzerindeki yanıltıcı etkisini ortadan kaldırır (Drapela ve Drapelova, 2011).
Bu çalışmada hesaplanan yıllık Sen eğim değerleri, Akdeniz Bölgesi'ndeki sıcaklık artış hızları ile yağış düşüş miktarlarının kantitatif (niceliksel) olarak ortaya konulmasını sağlamıştır.

Yenilikçi Trend Analizi (ITA) ve Yenilikçi Poligon Trend Analizi (IPTA)

Geleneksel parametrik olmayan testler (Mann-Kendall ve Spearman's Rho gibi), veri setinde seri korelorasyon bulunmaması, verilerin normal dağılım gösterme zorunluluğu olmasa dahi doğrusal varyasyon varsayımı ve verinin bağımsızlığı gibi katı ön kabullere dayanmaktadır. Ayrıca bu yöntemler, trendin zaman serisi içerisindeki düşük, orta ve yüksek (ekstrem) değerlerdeki dağılımı hakkında detaylı grafiksel bilgi sunamamaktadır. Bu kısıtlılıkları aşmak amacıyla Şen (2012) tarafından Yenilikçi Trend Analizi (Innovative Trend Analysis - ITA) yöntemi geliştirilmiştir. ITA metodolojisinde, incelenen hidrometeorolojik zaman serisi eşit uzunlukta iki alt döneme (n/2) ayrılmakta ve her iki alt seri kendi içinde küçükten büyüğe doğru sıralanmaktadır. Sıralanan ilk alt seri yatay eksene (Xi), ikinci alt seri ise dikey eksene (Yi) yerleştirilerek iki boyutlu bir kartezyen koordinat sisteminde kartezyen grafik elde edilmektedir. Grafikte yer alan 1:1 (45°) doğrusu trendin olmadığı (no-trend) referans durumunu temsil etmektedir. Veri noktalarının bu referans doğrusunun üzerinde yer aması zaman serisinde bir artış (pozitif trend) eğilimine, altında kalması ise bir azalış (negatif trend) eğilimine işaret etmektedir. Verilerin saçılımı; az, orta ve yüksek değerler alt sınıflarında ayrı ayrı yorumlanarak, parametrenin ekstrem davranışlarındaki saklı eğilimlerin belirlenmesini sağlamaktadır.

Yenilikçi Trend Analizi yöntemi serideki genel eğilimleri saklı yapılarıyla ortaya koymada oldukça başarılı olmasına karşın, iklim parametrelerinin ardışık zaman dilimleri (aylar veya mevsimler) arasındaki geçiş dinamiklerini ve döngüsel varyasyonlarını zamansal bütünlük içinde göstermede yetersiz kalmaktadır. Bu eksikliği gidermek adına Şen ve ark. (2019) tarafından Yenilikçi Poligon Trend Analizi (Innovative Polygon Trend Analysis - IPTA) yöntemi literatüre kazandırılmıştır. IPTA yönteminde, her bir aya veya döneme ait uzun dönemli aritmetik ortalama değerleri hesaplanarak ardışık zaman serisi dizileri elde edilir. Tıpkı ITA yönteminde olduğu gibi veri seti iki eşit alt döneme ayrılır; ancak veriler bu kez küçükten büyüğe sıralanmadan, kronolojik sıralaması korunarak kartezyen koordinat sistemine yerleştirilir. Yatay eksen birinci alt dönemin kronolojik ortalamalarını, dikey eksen ise ikinci alt dönemin kronolojik ortalamalarını temsil eder. Koordinat düzleminde her bir aya karşılık gelen noktalar belirlendikten sonra, bu noktalar kronolojik sıra takip edilerek (Ocak'tan Şubat'a, Şubat'tan Mart'a vb.) düz çizgilerle birbirine bağlanır ve kapalı bir poligon geometrisi oluşturulur. Elde edilen poligonun 45° referans doğrusuna göre konumu, büyüklüğü, doğrultusu ve yönü; iklim parametresinin dönemler arasındaki geçiş hızını, anomalilerini ve döngüsel trend varyasyonlarını makroskopik olarak analiz etmeye olanak tanır.

İstatistiksel Trend Yöntemleri

Tablo 2. Yıllık Trend

İstasyon İsmi	Veri	MK Z	SRHO Z	Trend (%95)	
Ağrı	ATY (mm)	-0.60986	-0.08151879	↓	↓
	AOS (°C)	4.7918	0.5796745	↑	↑
Iğdır	ATY (mm)	0.63475	0.09164584	↑	↑
	AOS (°C)	6.1171	0.7111052	↑	↑
Van	ATY (mm)	0.51029	0.05486588	↑	↑
	AOS (°C)	7.032	0.812438	↑	↑
Doğubeyazıt	ATY (mm)	-0.03111	-0.02728715	↓	↓
	AOS (°C)	4.4124	0.5333175	↑	↑
Erciş	ATY (mm)	-3.3417	-0.4171867	↓	↓
	AOS (°C)	3.398	0.4370348	↑	↑
Muradiye	ATY (mm)	-2.1532	-0.2557675	↓	↓
	AOS (°C)	6.0745	0.7085873	↑	↑
Özalp	ATY (mm)	-0.98324	-0.1147821	↓	↓
	AOS (°C)	4.742	-0.9197403	↑	↑
Başkale	ATY (mm)	-1.6242	-0.2277631	↓	↓
	AOS (°C)	6.012	0.7229457	↑	↑

Çalışma alanındaki istasyonlara ait Yıllık Toplam Yağış (ATY) ve Ortalama Yıllık Sıcaklık (AOS) parametrelerinin 1965-2025 dönemini kapsayan trend analizi sonuçları verilmiştir. %95 güven düzeyinde (α=0.05) yürütülen analizlerde, MK ve SRHO analizleri arasında yönsel bir uyum olduğu tespit edilmiştir. Tüm istasyonlarda sıcaklık değerlerinde istatistiksel olarak anlamlı (z> 1.96) ve güçlü bir artış eğilimi (yukarı yönlü mavi oklar) belirlenmiştir. Özellikle 17172 ($Z_{MK} = 7.032$) ve 17100 ($Z_{MK} = 6.1171$) istasyonlarındaki yüksek Z değerleri, bölge genelindeki ısınma trendinin mekansal olarak sistematik ve kararlı olduğunu göstermektedir. Yağış verilerinde ise istasyonlar arasında mekansal bir çeşitlilik görülmekle birlikte, genel olarak bir azalma (kırmızı oklar) eğilimi hakimdir. İnceleme alanındaki 8 istasyonun 6'sında yağışlarda düşüş kaydedilmiş; bu düşüş trendi 17784 ($Z_{MK} = -3.3417$) ve 17786 ($Z_{MK} = -2.1532$) istasyonlarında istatistiksel olarak anlamlı (Z < -1.96)

bulunmuştur. 17100 ve 17172 istasyonlarında ise anlamsız hafif bir artış gözlenmiştir. Sonuç olarak; bölge genelinde sıcaklıkların istisnasız yükselmesi ve yağışların büyük oranda azalması, çalışma alanının belirgin bir hidro-klimatik değişim ve kuraklaşma eğilimi altında olduğunu ortaya koymaktadır.

Tablo 3. Aylık Trend MK-SRHO

İstasyon İsmi	Veri	Test	Ocak	Şubat	Mart	Nisan	Mayıs	Haziran	Temmuz	Ağustos	Eylül	Ekim	Kasım	Aralık
Ağrı	ATY	MK	0,837	0,064	0,284	0,44	0,886	0,29	0,242	0,751	0,538	0,789	0,232	0,344
	(mm)	SRHO	-0,027	-0,297	0,167	0,178	-0,042	-0,207	0,129	0,017	0,069	0,063	-0,26	-0,15
	AOS	MK	0,078	0,023	0,001	0,001	0,006	2E-06	0,003	4E-06	1E-04	0,001	0,089	0,152
	(°C)	SRHO	0,05	0,064	0,085	0,054	0,023	0,048	0,03	0,049	0,04	0,031	0,028	0,04
Iğdır	ATY	MK	0,37	0,067	0,227	0,123	0,206	0,152	0,542	0,58	0,756	0,779	0,408	0,505
	(mm)	SRHO	-0,059	-0,13	0,12	0,182	0,163	-0,171	0,042	0,017	0,014	0,036	0,061	0,031
	AOS	MK	0,062	7E-05	3E-04	0,006	1E-03	8E-09	3E-07	5E-08	8E-07	8E-05	0,043	0,357
	(°C)	SRHO	0,05	0,106	0,062	0,036	0,03	0,066	0,046	0,062	0,053	0,04	0,027	0,019
Van	ATY	MK	0,26	0,632	0,232	0,867	0,837	0,167	0,798	0,651	0,356	0,623	0,513	0,672
	(mm)	SRHO	0,157	-0,06	0,186	0,016	0,044	-0,119	0	0	0,009	-0,107	-0,147	0,081
	AOS	MK	8E-05	3E-05	7E-05	1E-05	9E-05	4E-09	9E-08	2E-09	2E-07	1E-06	9E-04	0,004
	(°C)	SRHO	0,071	0,083	0,062	0,053	0,039	0,058	0,044	0,059	0,048	0,043	0,04	0,05
Doğubeyazıt	ATY	MK	0,659	0,057	0,522	0,232	0,47	0,354	0,588	0,799	0,98	0,891	0,61	0,681
	(mm)	SRHO	-0,04	-0,147	0,074	0,197	-0,176	-0,165	0,063	0,018	0	0,03	0,039	0,028
	AOS	MK	0,118	0,021	0,007	0,036	0,058	6E-04	0,022	3E-04	0,049	0,042	0,567	0,154
	(°C)	SRHO	0,035	0,055	0,048	0,029	0,021	0,043	0,021	0,042	0,022	0,023	0,007	0,028
Erciş	ATY	MK	0,444	0,018	0,597	0,202	0,206	0,005	0,955	0,676	0,398	0,046	0,072	0,147
	(mm)	SRHO	-0,119	-0,3	0,109	-0,295	-0,263	-0,364	0	0	-0,008	-0,435	-0,412	-0,266
	AOS	MK	0,036	0,026	0,011	0,007	0,121	1E-04	0,016	7E-04	0,004	0,012	0,185	0,255
	(°C)	SRHO	0,039	0,047	0,05	0,04	0,014	0,038	0,024	0,035	0,028	0,024	0,018	0,021
Muradiye	ATY	MK	0,645	0,165	0,332	0,209	0,584	0,49	0,737	0,368	0,98	0,123	0,127	0,584
	(mm)	SRHO	-0,077	-0,275	0,174	-0,321	-0,127	-0,097	-0,013	0,01	0	-0,425	-0,297	-0,095
	AOS	MK	0,004	8E-04	0,002	0,002	0,015	6E-07	1E-04	5E-06	0,001	5E-04	0,015	0,003
	(°C)	SRHO	0,047	0,052	0,066	0,045	0,026	0,056	0,037	0,05	0,029	0,035	0,029	0,05
Özalp	ATY	MK	0,709	0,08	0,575	0,344	0,429	0,509	0,677	0,366	0,871	0,332	0,357	0,397
	(mm)	SRHO	-0,063	-0,319	-0,114	-0,165	0,226	-0,106	0,054	0,023	0	-0,205	-0,148	-0,1
	AOS	MK	0,051	0,012	0,002	0,004	0,01	1E-05	8E-04	2E-05	0,004	0,016	0,278	0,247
	(°C)	SRHO	0,038	0,059	0,068	0,038	0,024	0,042	0,029	0,037	0,024	0,024	0,016	0,024

Başkale	ATY	MK	0,204	0,042	0,704	0,94	0,99	0,411	0,147	0,965	0,736	0,057	0,813	0,147
	(mm)	SRHO	-0,199	-0,238	-0,0737	-0,0223	-0,0147	-0,09	0,096	0	0	-0,33	-0,039	-0,243
	AOS	MK	0,004	0,008	7E-04	3E-04	7E-04	8E-06	0,003	2E-05	5E-04	0,002	0,036	0,014
	(°C)	SRHO	0,043	0,044	0,057	0,052	0,032	0,05	0,03	0,042	0,033	0,03	0,029	0,042

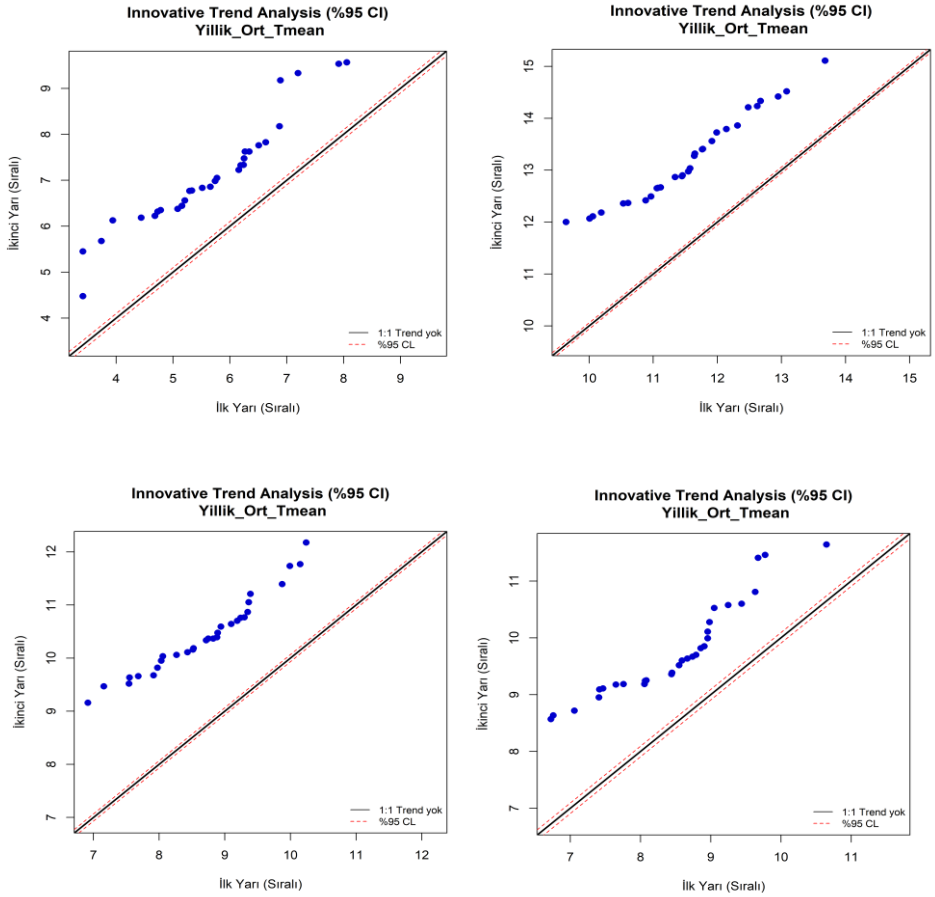
İstasyonların Yıllık Toplam Yağış (ATY) ve Ortalama Yıllık Sıcaklık (AOS) parametrelerine ait aylık trend analizlerinin p-anlamlılık düzeyleri tabloda sunulmuştur. Veriler, iklimsel değişimin yıl içindeki dağılımını ve dönemsel hassasiyetleri ortaya koymaktadır.

Sıcaklık verilerine ait MK ve SRHO p-değerleri incelendiğinde, neredeyse tüm istasyonlarda özellikle Mart, Nisan, Mayıs, Haziran, Temmuz ve Ağustos aylarında trendlerin istatistiksel olarak son derece anlamlı ($p < 0.05$) olduğu görülmektedir. Bu durum, bölgedeki ısınma eğiliminin özellikle ilkbahar ve yaz aylarında çok daha agresif ve sistematik bir şekilde gerçekleştiğini kanıtlamaktadır. Kış aylarında (Kasım, Aralık, Ocak) ise bazı istasyonlarda anlamlılık düzeyinin düştüğü gözlenmiştir.

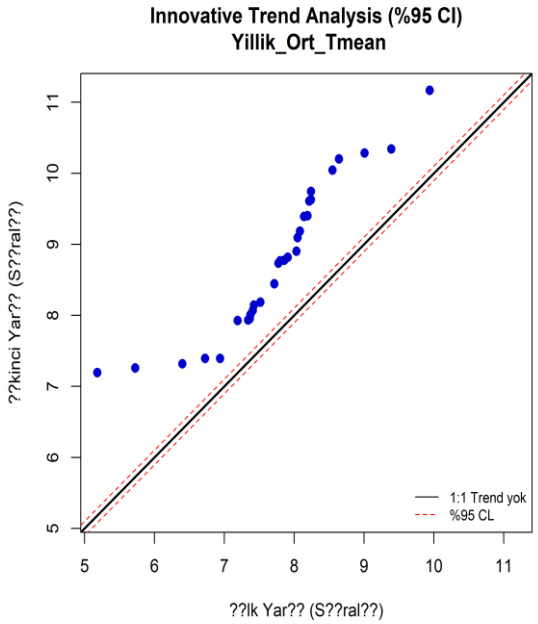
Aylık yağış trendleri genel olarak istatistiksel açıdan anlamsız ($p > 0.05$) kalma eğiliminde olsada, kritik mevsimsel sinyaller mevcuttur. Özellikle 17784 istasyonunda Şubat ve Haziran aylarında, 17880 istasyonunda ise Şubat ayında yaşanan yağış değişimleri %95 güven düzeyinde anlamlı bulunmuştur. Yağışlardaki bu aylık istikrarsızlık, bölgedeki hidrolojik rejimin düzensizleştiğine işaret etmektedir.

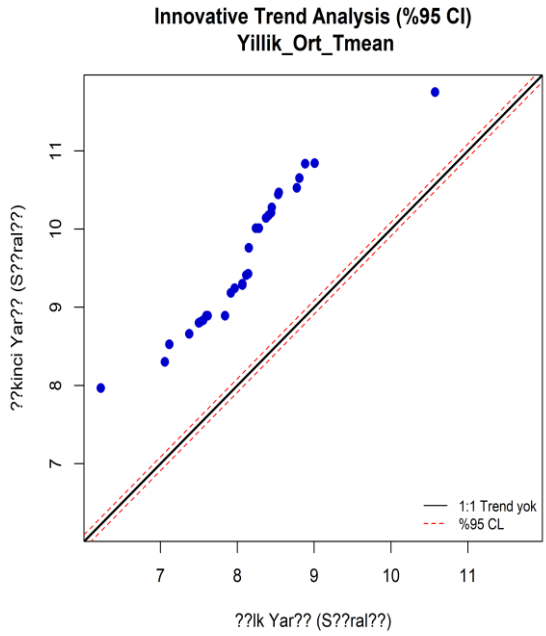
Özetle, aylık analiz sonuçları çalışma alanındaki iklim değişikliği baskısının homojen olmadığını; ilkbahar-yaz dönemi sıcaklık artışları ile belirli aylardaki değişiklik gösteren yağış kaymalarının hidro-klimatik dönüşümü tetikleyen ana unsurlar olduğunu göstermektedir.

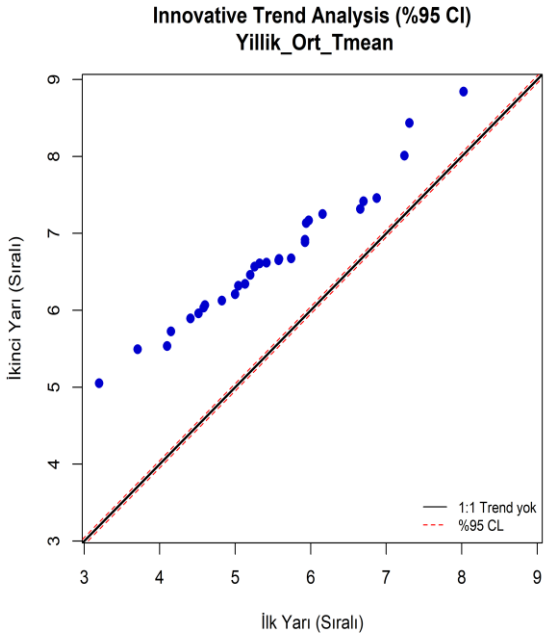
BULGULAR VE TARTIŞMA

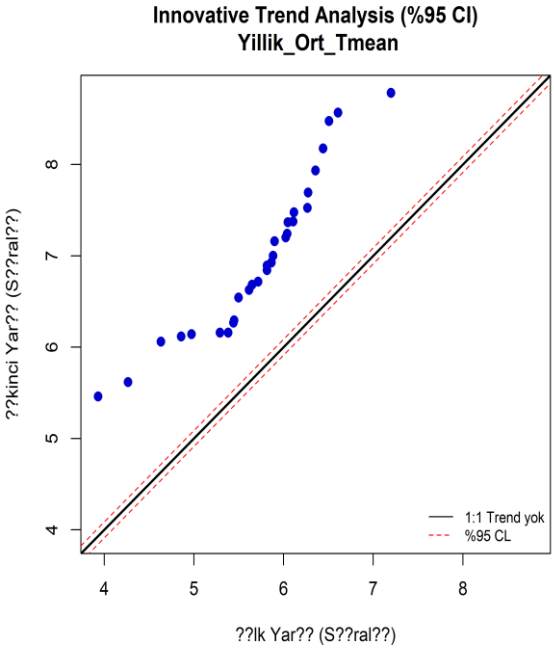


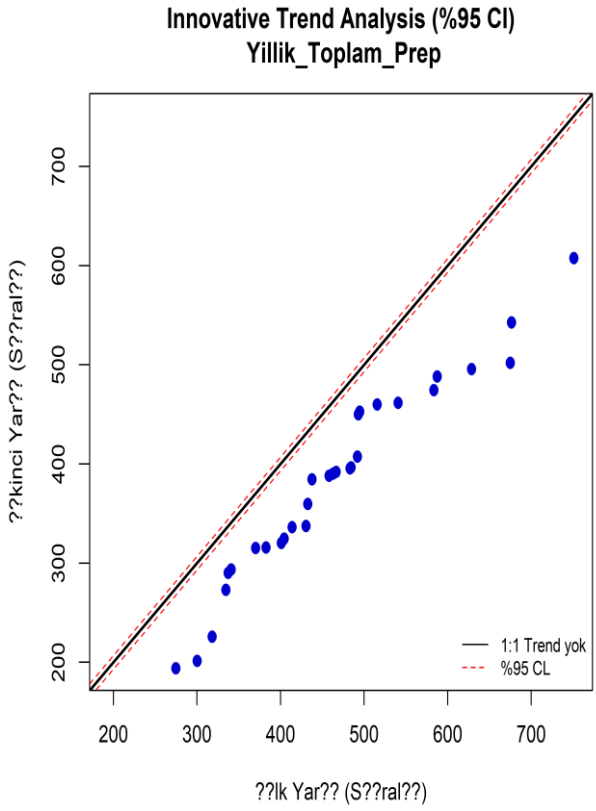
Sıcaklık, Yağış Parametreleri Trend Sonuçları







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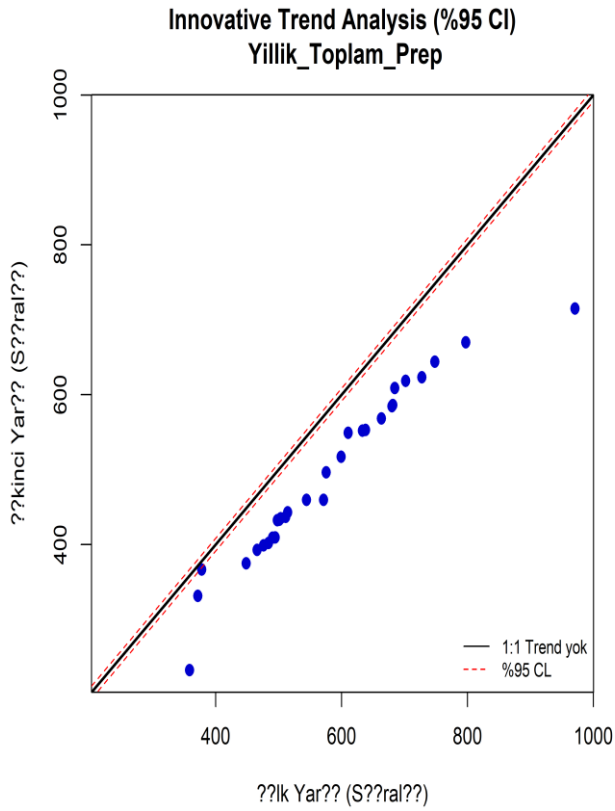
%95 CL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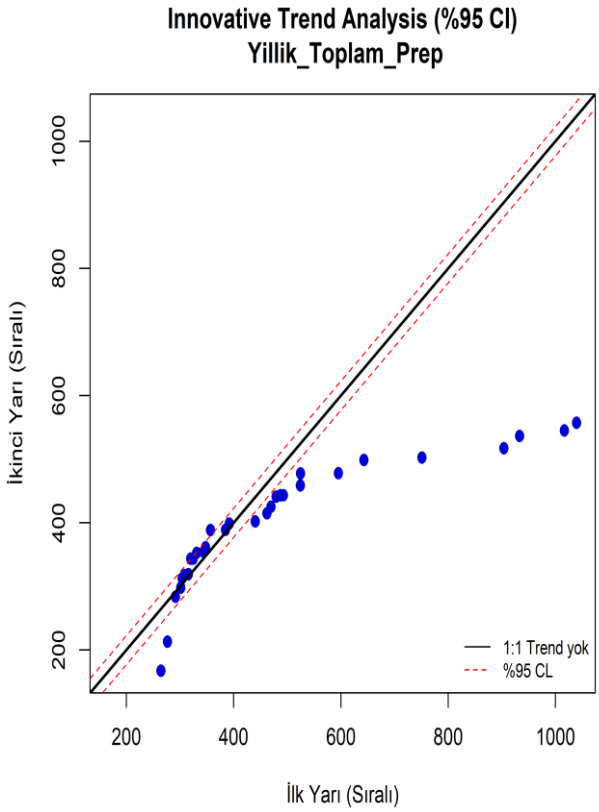
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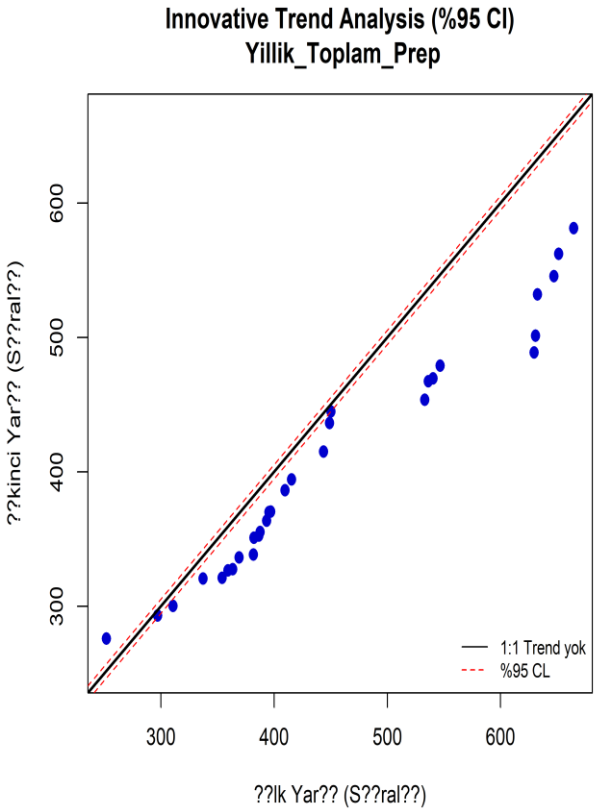
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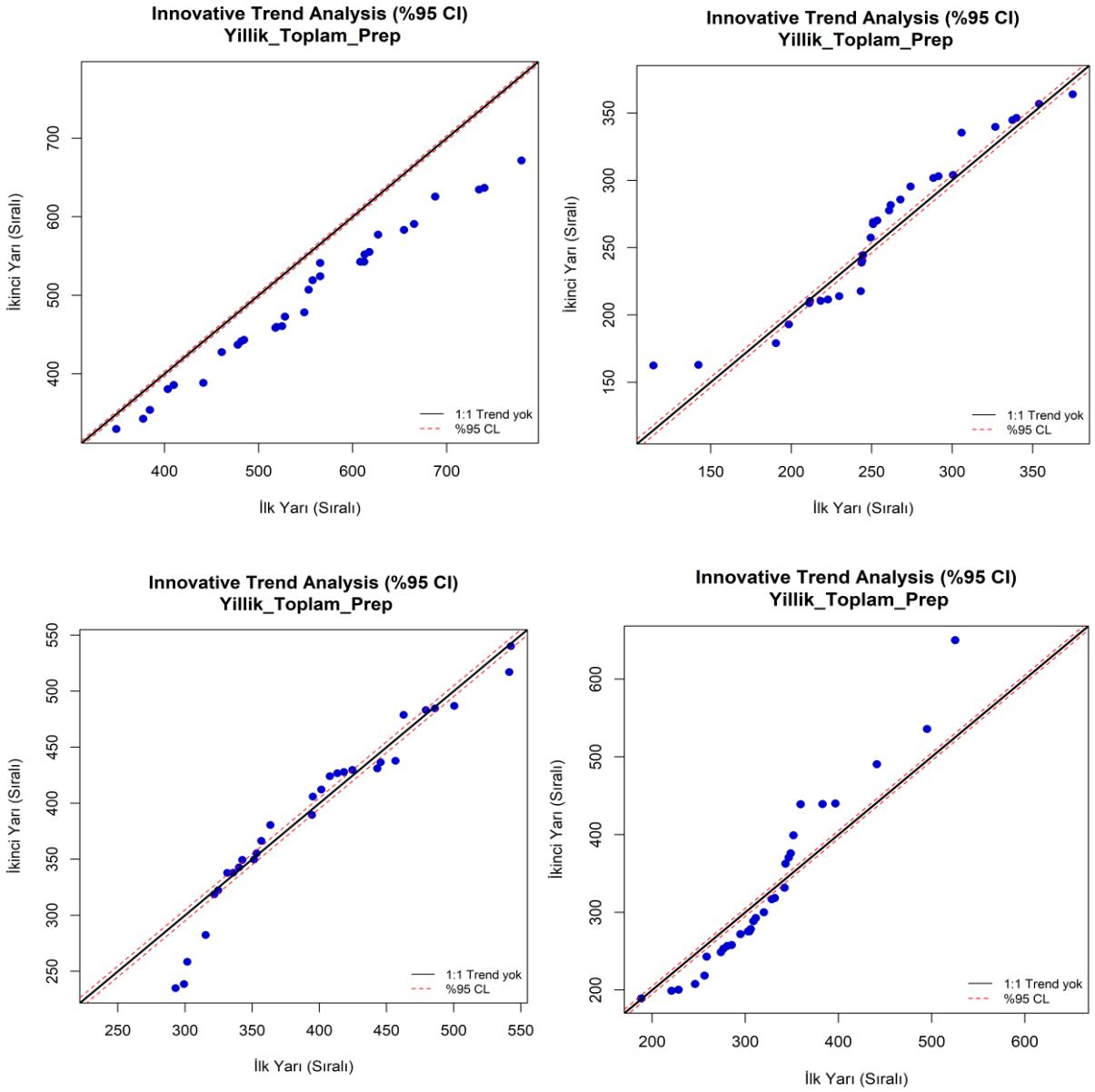
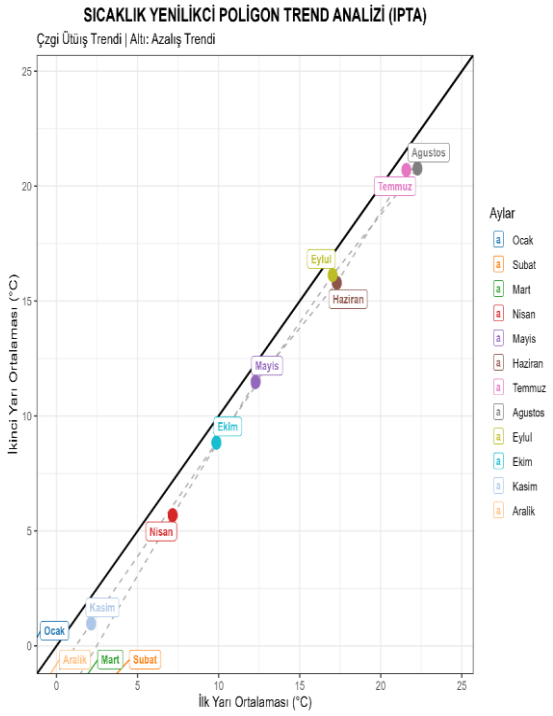


Şekil 2. ITA Yıllık Yağış Grafikleri

Tüm istasyonlara ait grafiklerde veri noktalarının neredeyse tamamı, "trend yok" anlamına gelen 1:1 (köşegen) doğrusunun ve %95 güven sınırlarının (kırmızı kesikli çizgiler) üst bölgesinde yer almaktadır. Bu durum, incelenen tüm merkezlerde yıllık ortalama sıcaklıklarda istatistiksel olarak anlamlı bir artış eğilimi olduğunu göstermektedir.

Zaman serisinin ilk yarısı ile ikinci yarısı karşılaştırıldığında; sadece ortalama sıcaklıklarda değil, düşük (soğuk dönemler) ve yüksek (sıcak dönemler) uç değerlerde de paralel bir artış gözlenmektedir. Grafiklerdeki saçılımın doğrusal eğilimden belirgin şekilde yukarı sapması, özellikle son yıllarda ısınma trendinin ivme kazandığına işaret etmektedir.

Yağış verilerinde istasyon bazlı yapısal farklılıklar ve belirgin bir azalış eğilimi dikkat çekmektedir: Grafiklerin büyük bir bölümünde veri noktaları 1:1 ideal doğrusunun ve %95$güven sınırlarının alt bölgesinde kümelenmiştir. Bu durum, zaman serisinin ikinci yarısında yıllık toplam yağış miktarlarının ilk yarıya kıyasla istatistiksel olarak anlamlı derecede azaldığını ortaya koymaktadır.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Çzgi Ütüş Trendi | Altı: Azalış Trendi
İkinci Yarı Ortalaması (°C)
İlk Yarı Ortalaması (°C)
Aylar
Ocak
Subat
Mart
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Haziran
Temmuz
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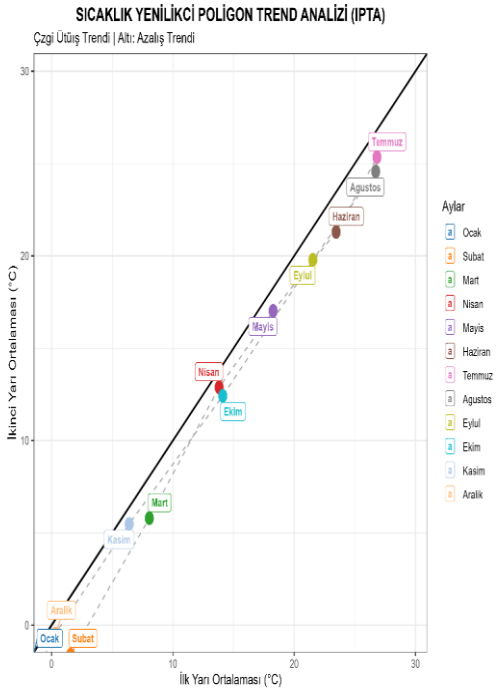
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Çzgi Ütüş Trendi | Altı: Azalış Trendi
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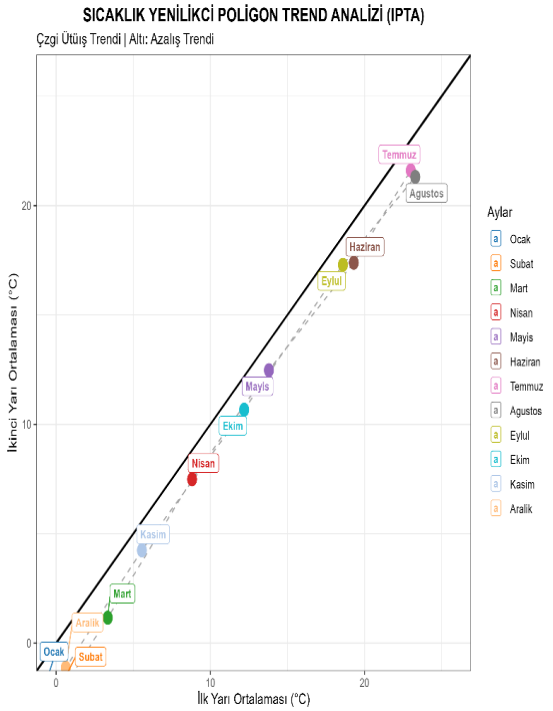
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Çzgi Ütüş Trendi | Altı: Azalış Trendi
İkinci Yarı Ortalaması (°C)
İlk Yarı Ortalaması (°C)
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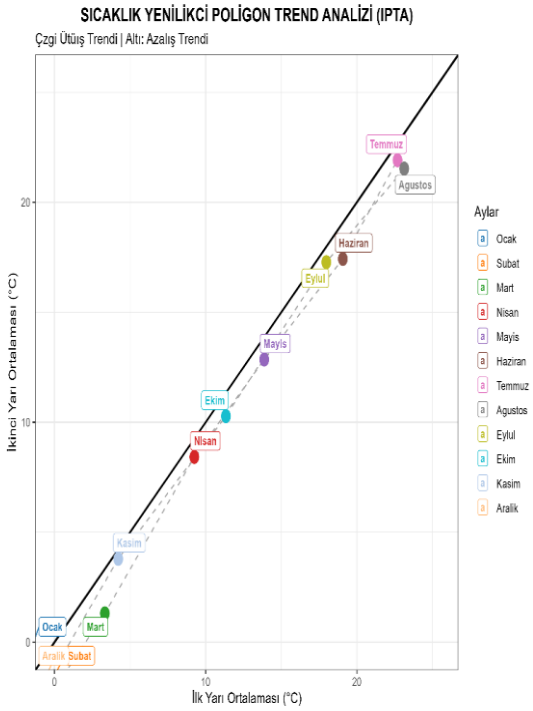
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Çzgi Ütüş Trendi | Altı: Azalış Trendi
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İlk Yarı Ortalaması (°C)
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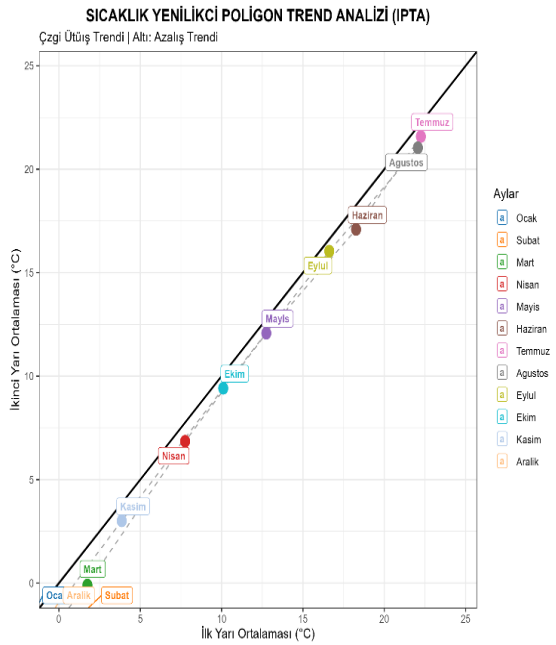
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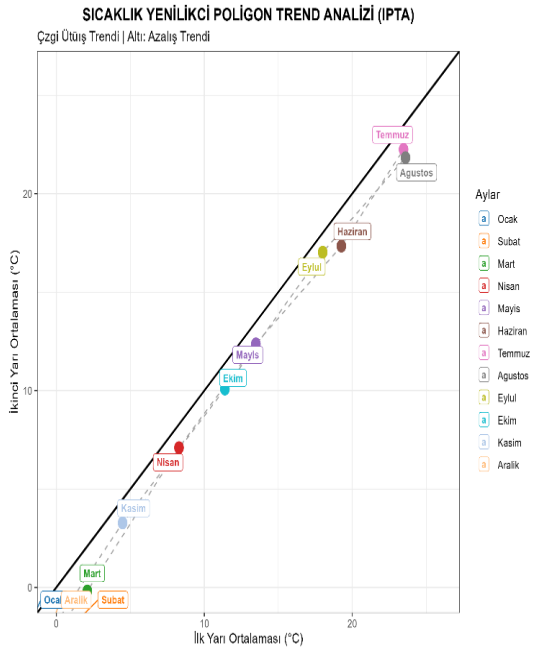
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Çzgi Ütüş Trendi | Altı: Azalış Trendi
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İlk Yarı Ortalaması (°C)
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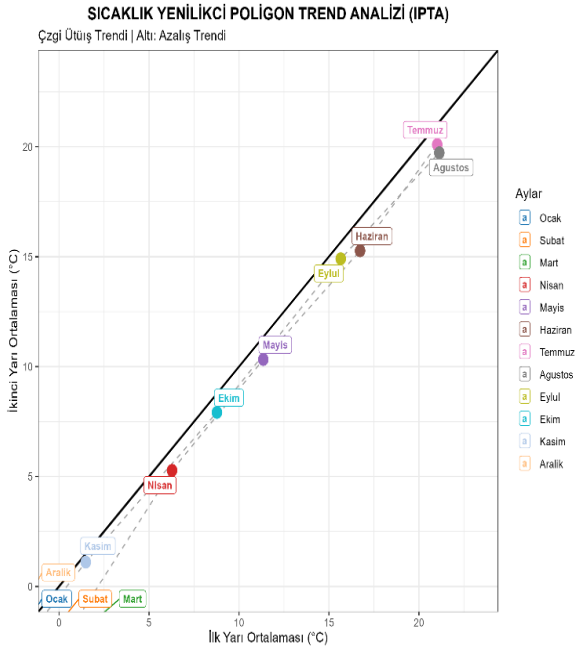
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Çzgi Ütüş Trendi | Altı: Azalış Trendi
İkinci Yarı Ortalaması (°C)
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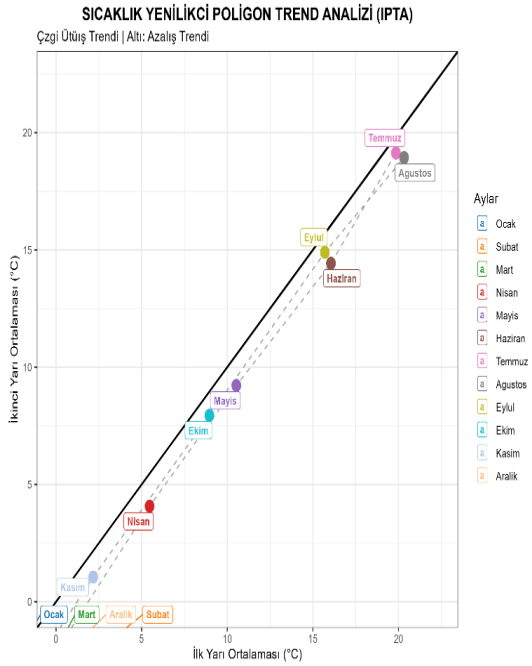
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Çzgi Ütüş Trendi | Altı: Azalış Trendi
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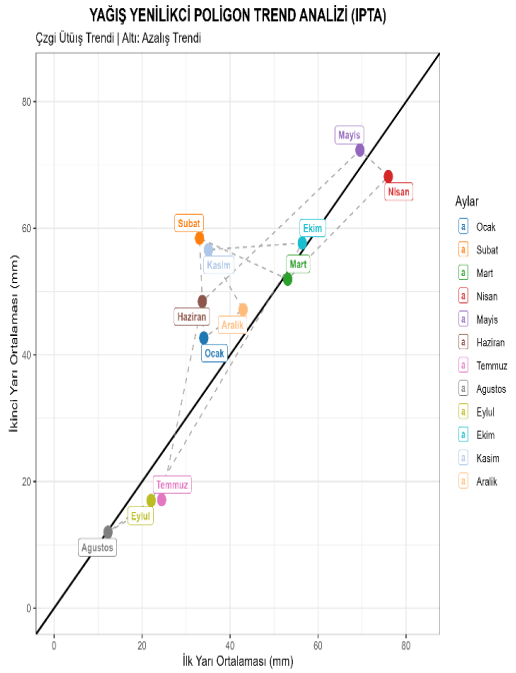
YAĞIŞ YENİLİKCİ POLİGON TREND ANALİZİ (IPTA)
Çzgi Ütüş Trendi | Altı: Azalış Trendi
İkinci Yarı Ortalaması (mm)
İlk Yarı Ortalaması (mm)
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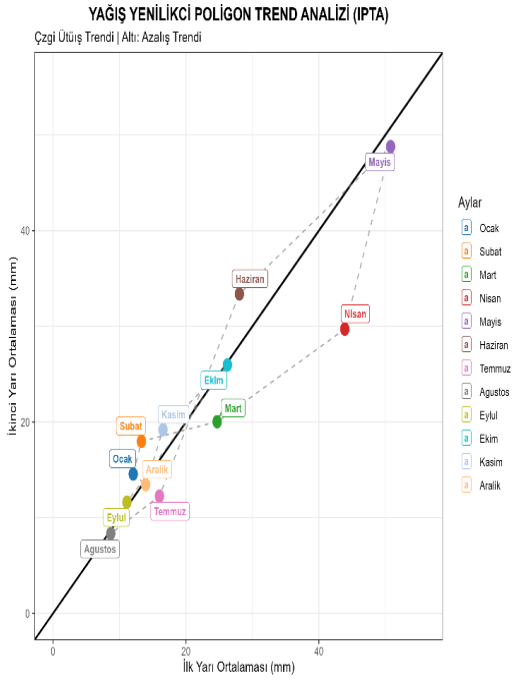
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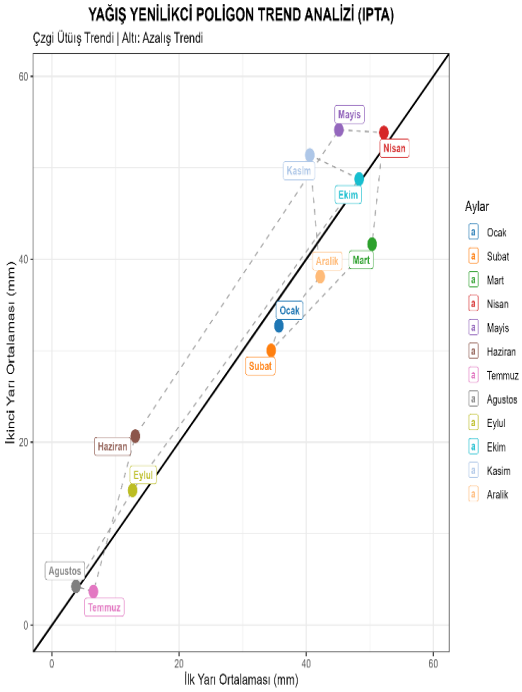
YAĞIŞ YENİLİKCİ POLİGON TREND ANALİZİ (IPTA)
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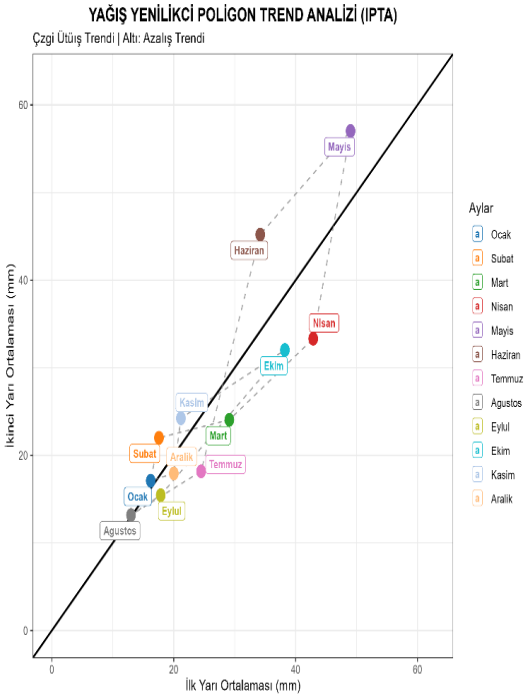
YAĞIŞ YENİLİKCİ POLİGON TREND ANALİZİ (IPTA)
Çzgi Ütüş Trendi | Altı: Azalış Trendi
İkinci Yarı Ortalaması (mm)
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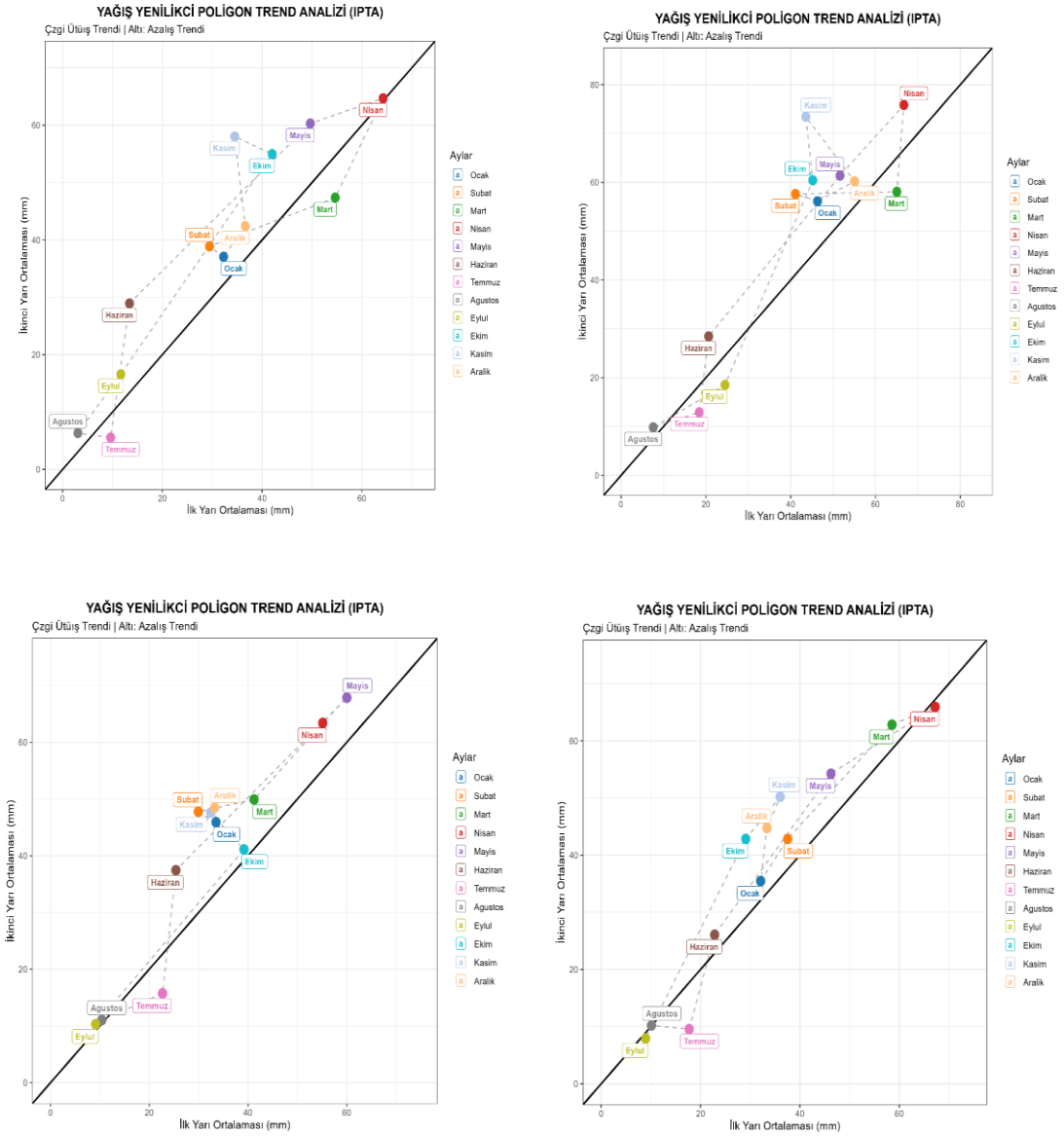
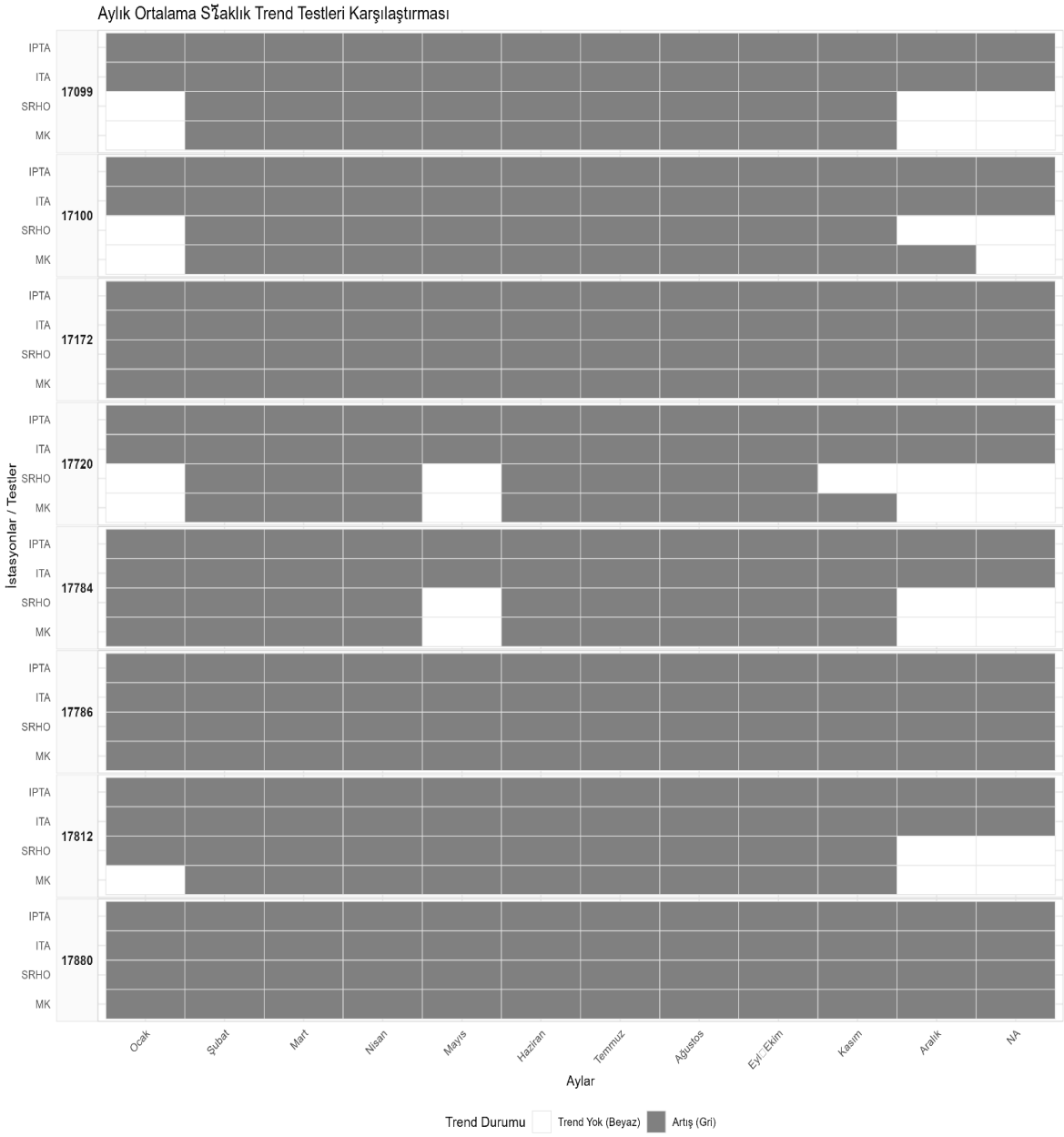


Şekil 3. IPTA Sıcaklık Grafikleri

Analiz edilen tüm lokasyonlarda poligonların genel morfolojisi, yönelimleri ve ayların dağılım örüntüleri yüksek oranda benzerlik sergilemektedir. Bu kararlı benzerlik, havza veya bölge genelinde aylık sıcaklık rejimlerini yönlendiren makro-ölçekli atmosferik mekanizmaların homojen bir etkiye sahip olduğunu kanıtlamaktadır. İstasyonlar arasında poligonların tepe noktaları ve yönelimleri (özellikle sonbahar ve kış aylarında) mikro düzeyde yapısal farklılıklar sergilemektedir. Bu durum, topoğrafik unsurların veya yerel dinamiklerin aylık toplam yağış paternleri üzerinde belirleyici bir rol oynadığını kanıtlamaktadır.

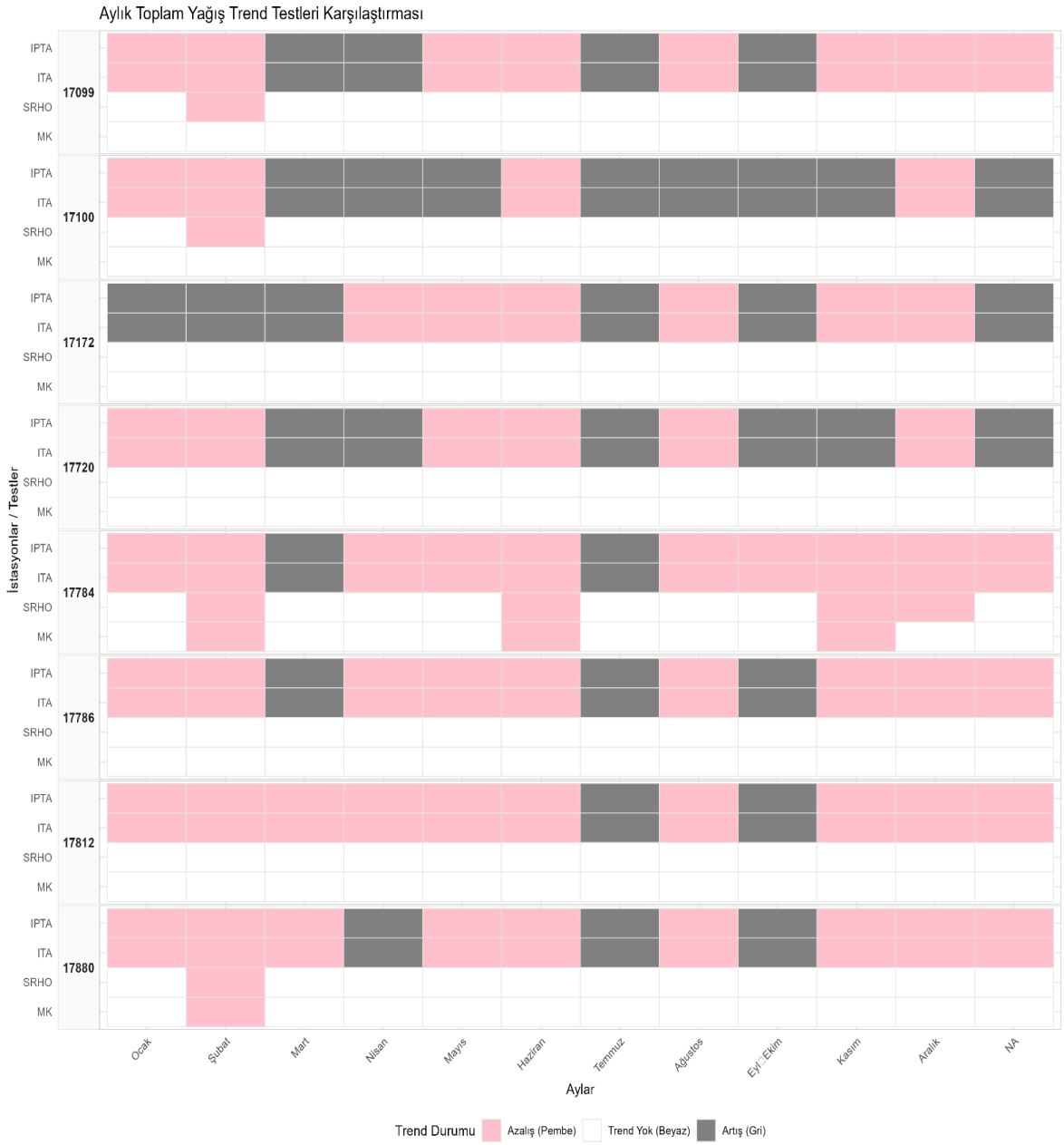
17099-Ağrı, 17100-Iğdır, 17112-Van, 17720-Doğubeyazıt, 17784-Erciş, 17786-Muradiye, 17812-Özalp, 17880-Başkale.



Şekil 4. Sıcaklık Karşılaştırması

Geleneksel testlerin (özellikle Spearman's Rho) kış ortası (Ocak, Aralık) ve geçiş dönemi (Mayıs, Kasım) gibi yağış/bulutluluk dinamiklerinin değiştiği aylarda trendi anlamsız bulma (beyaz kalma) eğilimi daha yüksektir. Bu durum, klasik testlerin verinin doğrusal yapısına veya serideki varyansa olan hassasiyetinden kaynaklanmaktadır.

17099-Ağrı, 17100-Iğdır, 17112-Van, 17720-Doğubeyazıt, 17784-Erciş, 17786-Muradiye, 17812-Özalp, 17880-Başkale.



Şekil 5. Yağış Karşılaştırması

İncelenen istasyonlara ait aylık toplam yağış verileri; Yenilikçi Poligon Trend Analizi (IPTA), Yenilikçi Trend Analizi (ITA), Spearman's Rho (SRHO) ve Mann-Kendall (MK) yöntemleri kullanılarak karşılaştırmalı olarak analiz edilmiştir. Matris grafiğinde pembe alanlar azalış trendini, gri alanlar artış trendini, beyaz alanlar ise trendin istatistiksel olarak anlamsız olduğunu (trend yok) göstermektedir.

SONUÇ

Elde edilen bulgular doğrultusunda öne çıkan ana sonuçlar şunlardır:

Yaygın Kuraklaşma ve Azalış Trendi, grafikte pembe renkli alanların en yoğun olması, bölge genelinde yıllık hidrolojik döngünün yapı taşını oluşturan aylık yağışlarda kronik ve geniş ölçekli bir azalış eğilimi olduğunu net bir şekilde ortaya koymaktadır. Özellikle Ocak, Şubat, Haziran, Ağustos ve Kasım ayları, istasyonların neredeyse tamamında belirgin bir kuraklaşma sinyali vermektedir.

Yenilikçi Yöntemlerin (ITA ve IPTA) Gizli Trendleri Yakalama Üstünlüğü, Şen (2012, 2014) metodolojileri olan ITA ve IPTA, geleneksel non-parametrik testlerin (MK ve SRHO) "trend yoktur" (beyaz) olarak değerlendirdiği alanlarda alt ve üst alt gruplardaki yönelimleri hassas bir şekilde

yakalamıştır. Geleneksel MK ve SRHO testleri tüm istasyonlarda neredeyse tamamen beyaz kalırken, yenilikçi yöntemler bu durağanlığın arkasındaki doğrusal olmayan azalış (pembe) ve artış (gri) dinamiklerini görünür kılmıştır. Bu durum, iklim çalışmalarında sadece klasik testlere bağlı kalınmasının ciddi veri ve trend kayıplarına yol açabileceğini doğrulamaktadır.

Mevsimsel Kayma ve Geçiş Ayları (Nisan-Temmuz-Eylül Dinamiği): İstasyonların önemli bir kısmında Mart, Nisan, Temmuz ve Eylül aylarında yenilikçi testler tarafından gri renkli (Artış) bloklar tespit edilmiştir. Geleneksel kış ve erken bahar yağışlarının azalıp (pembe), Nisan veya Eylül gibi geçiş periyotlarında artış eğilimi göstermesi, bölgedeki yağış rejiminde mevsimsel bir kayma (patern değişimi) yaşandığının güçlü bir göstergesidir.

İstasyonlar Arası Karakteristik Benzerlik: 17099-Ağrı, 17720-Doğubeyazıt, 17784-Erciş, 17786-Muradiye, 17880-Başkale istasyonları başta olmak üzere, tüm lokasyonlar aylık bazda oldukça senkronize ve homojen bir trend paterni sergilemiştir. Bu durum, azalış ve mevsimsel kayma eğilimlerinin yerel mikroklimatik faktörlerden ziyade, bölgeyi etkileyen makro-ölçekli iklimsel değişimler ve atmosferik sirkülasyon değişiklikleri ile ilişkili olduğunu kanıtlamaktadır.

Bu çalışmanın konuyla ilgili benzer araştırmalar ile suyun planlı ve sürdürülebilir kullanımı çalışmalarına katkı sunması beklenmektedir.

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İNSAN DERİSİNİN OBLİGAT EKTOPARAZİTLERİ: DEMODEX AKARLARININ BİYOLOJİSİ, EKOLOJİSİ

OBLIGATE ECTOPARASITES OF HUMAN SKIN: BIOLOGY AND ECOLOGY OF DEMODEX MITES

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ÖZET

Demodex akarları, insan derisinde başta kıl folikülleri ve sebase bezlerden oluşan pilosebase üniteler olmak üzere, göz kapaklarında yer alan meibomian bezlerinde kalıcı olarak yaşayan, çıplak gözle görülemeyen mikroskobik ektoparazitlerdir. Yaşamlarını sürdürebilmek için zorunlu olarak insan konak dokusuna bağımlı olan bu akarlar, konakçı dışında uzun süre canlı kalamazlar. İnsanlarda en yaygın görülen türler Demodex folliculorum ve Demodex brevis olup, bu iki tür morfolojik özellikleri, yerleşim alanları, ekolojik tercihleri ve popülasyon dinamikleri bakımından belirgin farklılıklar göstermektedir. Sebase aktivitenin yoğun olduğu alın, burun, yanaklar, çene ve periorbital bölge, Demodex kolonizasyonunun en sık gözlendiği anatomik alanlardır.

Düşük popülasyon yoğunluklarında deri mikrobiyotasıyla ekolojik denge içinde bulunabilen Demodex türleri, konakçının immünolojik durumu, hormonal profili, yaşı, sebum üretimi, kortikosteroid kullanımı ve çevresel faktörler gibi içsel ve dışsal değişkenlere bağlı olarak aşırı çoğalabilmektedir. Bu popülasyon artışı; rosacea, blefarit, perioküler dermatit, seboreik dermatit ve demodikoz gibi çeşitli dermatolojik ve oftalmolojik tablolarla ilişkilendirilmektedir. Demodex yoğunluğundaki artışa bağlı olarak mekanik foliküler hasar, inflamatuvar ve immün yanıtın uyarılması, folikül tıkanıklığı ve başta Bacillus oleronius olmak üzere bazı mikroorganizmaların taşınması gibi farklı patojenik mekanizmaların birlikte rol oynadığı düşünülmektedir. Popülasyon yoğunluğu ile inflamatuvar yanıtın şiddeti arasındaki pozitif ilişki, Demodex akarlarının yalnızca pasif bir simbiyont olarak değil, belirli koşullarda konak patolojisini doğrudan veya dolaylı biçimde etkileyebilen aktif biyolojik etkenler olarak değerlendirilmesi gerektiğini göstermektedir.

Demodex popülasyon yoğunluğunun belirlenmesinde standart yüzeyel deri biyopsisi, deri kazıntısı, kirpik epilasyonu ve direkt mikroskobik sayım temel tanı yöntemleri arasında yer almaktadır. Bununla birlikte dermoskopi gibi görüntüleme teknikleri, akarların folikül içindeki dağılımını, yoğunluğunu, hareketliliğini ve morfolojik özelliklerini doku bütünlüğü bozulmadan gerçek zamanlı olarak değerlendirme olanağı sunmaktadır. Demodex yoğunluğunu azaltmaya yönelik akarisidal, antiinflamatuvar ve antimikrobiyal ajanların etkinliği çeşitli klinik çalışmalarla desteklenmiş olsa da popülasyon kontrolüne ilişkin tanı eşikleri, tedavi süreleri ve uygulama protokolleri hâlen standardizasyon gerektiren konular arasındadır.

Son yıllarda moleküler sistematik, filogenetik analizler ve deri mikrobiyotası üzerine yapılan çalışmalar, Demodex türlerinin genetik çeşitliliğini, konakla olan özgül ilişkisini, popülasyon yapısını ve insan deri ekosistemindeki rolünü daha ayrıntılı biçimde ortaya koymaktadır. Bu alandaki araştırmaların derinleşmesiyle birlikte, Demodex popülasyonlarının izlenmesi, patojenik eşiklerinin belirlenmesi ve kontrolüne yönelik daha etkili, hedefe yönelik ve ekolojik açıdan dengeli stratejilerin geliştirilmesi mümkün olacaktır.

Anahtar Kelimeler: Demodex folliculorum, Demodex brevis, ektoparazit, deri mikrobiyotası, dermoskopi, akarisidal tedavi

ABSTRACT

Demodex mites are microscopic ectoparasites, invisible to the naked eye, that permanently inhabit the pilosebaceous units of human skin, primarily consisting of hair follicles and sebaceous glands, as well as the meibomian glands located in the eyelids. These mites are obligately dependent on human host

tissues for survival and cannot remain viable for extended periods outside the host. The most commonly encountered species in humans are Demodex folliculorum and Demodex brevis, which differ markedly in terms of morphology, habitat preference, ecological characteristics, and population dynamics. Anatomical regions with high sebaceous activity, including the forehead, nose, cheeks, chin, and periorbital area, represent the most common sites of Demodex colonization.

At low population densities, Demodex species may exist in ecological equilibrium with the normal skin microbiota. However, they may proliferate excessively depending on intrinsic and extrinsic factors such as the host's immunological status, hormonal profile, age, sebum production, corticosteroid use, and environmental conditions. This increase in population density has been associated with various dermatological and ophthalmological conditions, including rosacea, blepharitis, periocular dermatitis, seborrheic dermatitis, and demodicosis. Several pathogenic mechanisms are thought to act together in response to increased Demodex density, including mechanical follicular damage, stimulation of inflammatory and immune responses, follicular obstruction, and the carriage of certain microorganisms, particularly Bacillus oleronius. The positive association between population density and the severity of the inflammatory response indicates that Demodex mites should not be regarded merely as passive symbionts, but rather as active biological agents capable of directly or indirectly influencing host pathology under certain conditions.

Standardized skin surface biopsy, skin scraping, eyelash epilation, and direct microscopic counting remain among the principal methods used to determine Demodex population density. In addition, imaging techniques such as dermoscopy provide the opportunity to evaluate the distribution, density, motility, and morphological characteristics of mites within follicles in real time, without disrupting tissue integrity. Although the efficacy of acaricidal, anti-inflammatory, and antimicrobial agents aimed at reducing Demodex density has been supported by various clinical studies, diagnostic thresholds, treatment durations, and application protocols for population control still require further standardization.

In recent years, studies on molecular systematics, phylogenetic analyses, and the skin microbiota have provided a more detailed understanding of the genetic diversity of Demodex species, their host-specific relationships, population structure, and role within the human skin ecosystem.

As research in this field continues to expand, it is expected that more effective, targeted, and ecologically balanced strategies will be developed for monitoring Demodex populations, determining pathogenic thresholds, and controlling their abundance.

Keywords: Demodex folliculorum, Demodex brevis, ectoparasite, skin microbiota, dermoscopy, acaricidal treatment

GİRİŞ

İnsan derisi, organizmayı dış çevreden gelebilecek fiziksel, kimyasal ve biyolojik etkenlere karşı koruyan en büyük organ olmasının yanı sıra çok sayıda mikroorganizmaya yaşam alanı sağlayan dinamik bir ekosistemdir. Bakteriler, mantarlar, virüsler, arkeler ve mikroskobik eklembacaklılar gibi farklı organizmalardan oluşan deri mikrobiyotası, konak bağışıklık sistemi ile karşılıklı etkileşim içerisinde bulunarak deri homeostazının sürdürülmesinde önemli rol oynamaktadır. Bununla birlikte, konak ve mikroorganizmalar arasındaki bu hassas dengenin bozulması, çeşitli dermatolojik hastalıkların gelişmesine zemin hazırlayabilmektedir (Byrd et al., 2018). Deri mikrobiyotasının dikkat çeken üyelerinden biri olan Demodex akarları, yalnızca memelilerde yaşayan ve yaşam döngülerini tamamlayabilmek için konağa bağımlı olan obligat ektoparazitlerdir. İnsanlarda en yaygın bulunan türler Demodex folliculorum Simon, 1842 ve Demodex brevis Akbulatova, 1963 olup, her iki tür de başlıca kıl folikülleri, sebase bezler ve göz kapaklarında bulunan meibomian bezlerinde kolonize olmaktadır. İnce ve uzamış vücut yapıları sayesinde pilosebase ünitelere uyum sağlamış olan bu akarlar, sebumdan zengin bölgelerde yaşamlarını sürdürmekte ve konak dışında uzun süre canlı kalamamaktadır (Rufli & Mumcuoglu, 1981; Rather & Hassan, 2014).

Şekil 1. Demodex akarı (Civas, 2023).

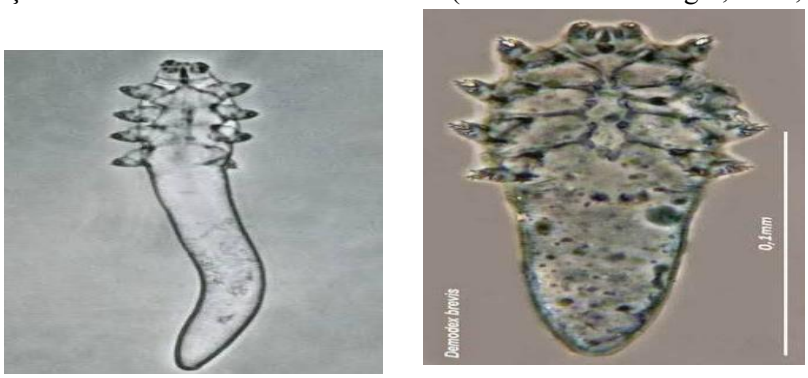
Uzun yıllar boyunca Demodex akarlarının insan deri faunasının zararsız üyeleri olduğu düşünülmüş olsa da, son yıllarda yapılan çalışmalar bu canlıların biyolojik ve ekolojik rollerinin daha karmaşık olduğunu ortaya koymuştur. Düşük popülasyon yoğunluklarında deri mikrobiyotası ile dengeli bir ilişki içerisinde bulunabilen Demodex türleri; yaşlanma, artan sebum üretimi, hormonal değişiklikler, immün sistem fonksiyonlarındaki bozulmalar, kortikosteroid kullanımı ve çevresel faktörlerin etkisiyle aşırı çoğalabilmektedir. Artan popülasyon yoğunluğu ise rosacea, demodikozis, blefarit ve seboreik dermatit gibi çeşitli dermatolojik ve oftalmolojik hastalıklarla ilişkilendirilmektedir (Forton & De Maertelaer, 2019; Rather & Hassan, 2014).
Demodex akarlarının insan derisindeki dağılımı, popülasyon dinamikleri ve konak ile olan etkileşimleri yalnızca klinik açıdan değil, aynı zamanda ekolojik açıdan da önem taşımaktadır. Sebase bezlerin yoğun bulunduğu alın, burun, yanak, çene ve periorbital bölgeler bu akarların en sık yerleştiği mikrohabitatları oluşturmaktadır. Son yıllarda deri mikrobiyotası ve moleküler sistematik alanındaki gelişmeler, Demodex türlerinin genetik çeşitliliği, konak özgüllüğü ve deri ekosistemindeki işlevleri hakkında daha ayrıntılı bilgiler sağlamış; bu akarların yalnızca pasif kommensaller değil, belirli koşullar altında konak fizyolojisini etkileyebilen biyolojik organizmalar olduğunu göstermiştir (Rather & Hassan, 2014).
Bu derlemede, insanlarda bulunan Demodex folliculorum ve Demodex brevis türlerinin taksonomik konumu, morfolojik özellikleri, yaşam döngüsü, beslenme biyolojisi ve ekolojik özellikleri güncel literatür ışığında değerlendirilmiş; ayrıca deri mikrobiyotası ile etkileşimleri, konak–parazit ilişkileri ve insan sağlığı açısından taşıdıkları önem biyolojik ve ekolojik bakış açısıyla ele alınmıştır.

2. Demodex Akarlarının Biyolojisi

2.1. Taksonomisi ve Genel Özellikleri

Demodex akarları, Arthropoda şubesi, Arachnida sınıfı, Acariformes üst takımı, Trombidiformes takımı ve Demodecidae familyası içerisinde sınıflandırılan, obligat ektoparazit olarak yaşayan yüksek derecede özelleşmiş akar grubunu oluşturmaktadır. Demodecidae familyasında yer alan türlerin tamamı yaşam döngülerini belirli bir konak üzerinde tamamlamakta olup, konak dışında uzun süre yaşamlarını sürdürememektedir. Bu özellikleri nedeniyle Demodex türleri yüksek konak özgüllüğü gösteren ektoparazitler arasında değerlendirilmektedir (Desch & Nutting, 1972; Rather & Hassan, 2014).
Bugüne kadar farklı memeli türlerinde 100'den fazla Demodex türü tanımlanmış olup, bunların büyük çoğunluğu yalnızca tek bir konak türünde yaşamaktadır. İnsanlarda ise doğal olarak bulunan iki tür D. folliculorum ve D. Brevis'tir. Bu iki tür morfolojik özellikleri, yerleşim alanları ve popülasyon dinamikleri bakımından birbirinden ayrılmaktadır. D. folliculorum çoğunlukla yüzeyel kıl foliküllerinde kümeler hâlinde bulunurken, D. brevis daha kısa yapılı olup sebase bezler ile meibomian bezlerinin derin bölgelerinde tek tek yaşamaktadır (Rufli & Mumcuoglu, 1981; Rather & Hassan, 2014).
İnsanlarda Demodex kolonizasyonu yaşamın ilk yıllarında başlayabilmekle birlikte, popülasyon yoğunluğu yaşla birlikte artış göstermektedir. Çocuklarda düşük yoğunlukta bulunan akarlar, ergenlik döneminde sebase bez aktivitesinin artmasına bağlı olarak daha sık görülmeye başlamakta, erişkin bireylerin büyük çoğunluğunda ise farklı yoğunluklarda tespit edilebilmektedir. Yaşlanma ile birlikte sebum üretimindeki değişiklikler, deri fizyolojisindeki farklılaşmalar ve bağışıklık sistemindeki değişimler, Demodex popülasyonlarının artışında etkili faktörler arasında yer almaktadır (Forton & De Maertelaer, 2019). Demodex akarlarının yaşam alanını başlıca pilosebase üniteler oluşturmaktadır.

Sebum üretiminin yoğun olduğu alın, burun, nazolabial bölge, yanaklar, çene ve göz kapakları bu akarların en sık kolonize olduğu anatomik bölgelerdir.
İnce ve silindirik vücut yapıları sayesinde dar foliküler kanallar içerisinde hareket edebilen bu akarlar, yaşamlarını büyük ölçüde konak dokusu içerisinde geçirerek dış ortamın olumsuz koşullarından korunmaktadır. Bu yüksek adaptasyon yeteneği, *Demodex* türlerinin insan deri ekosisteminde kalıcı olarak yerleşebilmesini sağlayan temel biyolojik özelliklerden biridir (Rather & Hassan, 2014).
Uzun yıllar boyunca insan deri faunasının zararsız üyeleri olarak kabul edilen *Demodex* akarlarının, günümüzde deri mikrobiyotası içerisinde dinamik bir role sahip olduğu düşünülmektedir. Düşük popülasyon yoğunluklarında konak ile dengeli bir ilişki sürdüren bu akarlar, immün sistem fonksiyonlarındaki değişiklikler, hormonal faktörler, sebum miktarındaki artış ve çevresel etkenlerin etkisiyle aşırı çoğalabilmektedir. Artan popülasyon yoğunluğu ise yalnızca biyolojik adaptasyonun bir göstergesi olmayıp, aynı zamanda konak–parazit etkileşimlerinin değişmesine ve çeşitli inflamatuvar süreçlerin ortaya çıkmasına katkıda bulunabilmektedir (Akilov & Mumcuoglu, 2003; Rather & Hassan, 2014).



Şekil 2. Demodex folliculorum ve Demodex brevis Buzoğlu (t.y.)'ndan uyarlanmıştır.

2.2. Morfolojik Özellikleri

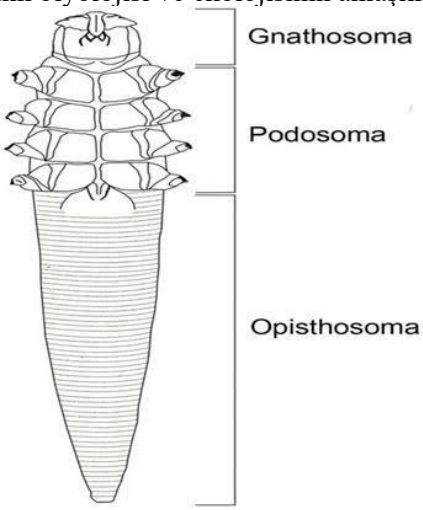
Demodex akarları, pilosebase ünitelerde yaşamaya uyum sağlamış, mikroskobik boyutlarda ve yüksek derecede özelleşmiş obligat ektoparazitlerdir. Vücutları uzamış, silindirik ve yarı saydam bir yapıya sahip olup, bu morfolojik özellikler kıl folikülleri ve yağ bezlerin dar kanallarında hareket etmelerini kolaylaştırmaktadır. Vücut genel olarak gnathosoma (ağız bölgesi), podosoma (bacakların bulunduğu gövde bölgesi) ve opisthosoma (arka vücut bölgesi) olmak üzere üç ana bölümden oluşmaktadır. Bu yapı, akarların konak dokusuna sıkı şekilde tutunmasına ve yaşam döngülerini pilosebase üniteler içerisinde sürdürmesine olanak sağlamaktadır (Desch & Nutting, 1972; Rather & Hassan, 2014).
Gnathosoma, beslenmede görev alan ağız parçalarını içermekte olup, kısa ve güçlü chelicerae ile palpuslardan oluşmaktadır. Chelicerae, folikül içerisindeki sebum, epitel hücreleri ve hücresel kalıntıların alınmasını sağlarken, palpuslar konak dokusuna tutunmada ve besin alımında rol oynamaktadır. Bu ağız yapısı, Demodex türlerinin yaşadıkları mikrohabitatın fiziksel özelliklerine uyum sağlayacak şekilde özelleşmiştir (Nutting, 1976; Rather & Hassan, 2014).
Podosoma üzerinde dört çift kısa ve segmentli bacak bulunmaktadır. Her bacak, folikül duvarına tutunmayı kolaylaştıran pençe benzeri yapılar taşımaktadır. Bacakların kısa olması nedeniyle Demodex akarlarının hareket kabiliyeti sınırlıdır ve saatte yaklaşık 8–16 mm ilerleyebildikleri bildirilmektedir. Bu nedenle akarların foliküller arasındaki geçişlerinin çoğunlukla gece saatlerinde gerçekleştiği ve ışığa duyarlı davranış sergiledikleri düşünülmektedir (Rather & Hassan, 2014).
Opisthosoma, vücudun en uzun bölümünü oluşturmakta olup çizgili bir görünüme sahiptir. Bu bölümde sindirim sistemi ve üreme organlarının büyük kısmı yer almakta, aynı zamanda vücudun esnekliğini sağlayarak dar foliküler boşluklarda hareket etmeye katkıda bulunmaktadır. Opisthosomanın uzunluğu ve şekli, türler arasında ayırt edici morfolojik karakterlerden biri olarak kabul edilmektedir (Desch & Nutting, 1972).
İnsanlarda bulunan iki Demodex türü morfolojik açıdan bazı farklılıklar göstermektedir. Demodex folliculorum yaklaşık 280–400 µm uzunluğunda olup daha ince ve uzun bir opisthosomaya sahiptir. Genellikle aynı kıl folikülü içerisinde çok sayıda birey birlikte bulunur. Buna karşılık Demodex brevis daha kısa (160–220 µm) ve daha kalın yapılıdır. Çoğunlukla sebase bezler ile meibomian bezlerinin

derin bölgelerinde tek başına yaşamaktadır. Bu farklılıklar, iki türün mikrohabitat tercihleri ve biyolojik davranışlarıyla yakından ilişkilidir (Rufli & Mumcuoglu, 1981; Rather & Hassan, 2014).

Tablo 1. Demodex folliculorum ve Demodex brevis arasındaki farklılıklar.

Özellik	***Demodex. folliculorum***	***Demodex brevis***
Boyut	0,3-0,4 mm (daha uzun)	0,15-0,3 mm (daha kısa)
Vücut şekli	İnce, uzun	Daha kısa, yuvarlak gövde
Yerleşim yeri	Kıl folikülü (yüzeysel)	Sebase bez, Meibomian bezi (derin)
Beslenme kaynağı	Folikül epitel hücreleri	Sebum (yağ salgısı)
Ana klinik tablo	Kirpik dibi iltihabı, silindirik kepek	Meibomian bez disfonksiyonu, kuru göz
Tanı zorluğu	Daha kolay (yüzeysel)	Daha zor (derin yerleşim)

Demodex türlerinde cinsel dimorfizm sınırlı olmakla birlikte erkek bireyler genellikle dişilere göre daha küçük ve daha dar yapılıdır. Erkeklerde üreme açıklığı podosomanın dorsal kısmında yer alırken, dişilerde genital açıklık ventral yüzeyde dördüncü bacak çiftinin hemen arkasında bulunmaktadır. Bu farklılıklar, türlerin tanımlanmasında ve mikroskobik incelemelerde cinsiyet ayrımının yapılmasında önemli morfolojik kriterler arasında yer almaktadır (Nutting, 1976).
Sonuç olarak, Demodex akarlarının morfolojik özellikleri, yaşamlarını insan derisinin pilosebase ünitelerinde sürdürebilmelerine olanak sağlayan önemli adaptasyonlar içermektedir. Uzamış vücut yapısı, kısa bacakları ve özelleşmiş ağız parçaları, bu akarların dar foliküler boşluklarda beslenmesini, hareket etmesini ve konak üzerinde kalıcı olarak yaşayabilmesini mümkün kılmaktadır. Bu adaptasyonlar, Demodex türlerinin biyolojisi ve ekolojisinin anlaşılmasında temel öneme sahiptir.



Şekil 3. Demodex akarının morfolojisi (Gökalp ve Kırbaş, 2020).

2.3. Yaşam Döngüsü ve Üreme Biyolojisi

Demodex akarlarının yaşam döngüsü tamamen konak üzerinde gerçekleşmekte olup, yumurta, larva, protonimf, nimf ve ergin olmak üzere beş gelişim evresinden oluşmaktadır. Yaşam döngüsünün tamamlanması yaklaşık 14–21 gün sürmekte olup bu süre; konak bireyin fizyolojik özellikleri, sebum

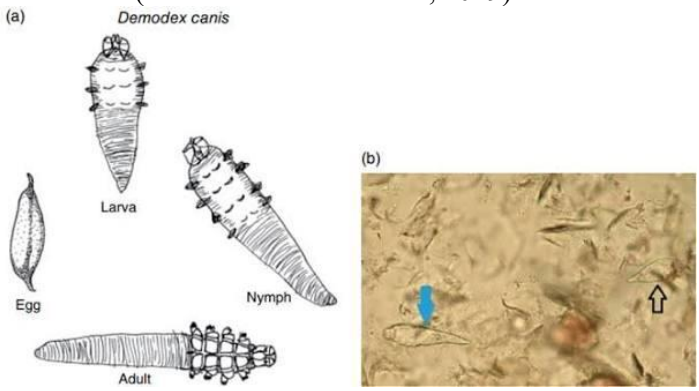
miktarı ve çevresel koşullara bağlı olarak değişebilmektedir (Desch & Nutting, 1972; Rather & Hassan, 2014).

Dişi bireyler, iğ şeklindeki yumurtalarını kıl folikülleri veya sebase bezlerin içerisine bırakmaktadır. Yumurtalardan çıkan altı bacaklı larvalar, kısa bir gelişim döneminin ardından sekiz bacaklı protonimf evresine geçmektedir. Daha sonra nimf evresini tamamlayan bireyler ergin forma dönüşmektedir. Gelişim sürecinin tamamı pilosebase üniteler içerisinde gerçekleştiğinden, yaşam döngüsünün herhangi bir döneminde konağın terk edilmesi söz konusu değildir. Bu durum, Demodex türlerinin obligat ektoparazit olarak tanımlanmasının temel nedenlerinden biridir (Nutting, 1976; Rather & Hassan, 2014). Ergin bireylerin yaşam süresinin yaklaşık 4–6 gün olduğu bildirilmektedir. Ancak yaşam döngüsünün tamamı dikkate alındığında bir bireyin yaşam süresi yaklaşık üç hafta olarak kabul edilmektedir. Ergin dişi bireyler yaşamları boyunca sınırlı sayıda yumurta bırakmakta ve üreme kapasitesi büyük ölçüde konağın sağladığı uygun çevre koşullarına bağlı kalmaktadır (Desch & Nutting, 1972; Rather & Hassan, 2014).

Demodex akarlarında çiftleşmenin, erişkin bireylerin folikül ağzına veya deri yüzeyine doğru hareket ettiği gece saatlerinde gerçekleştiği düşünülmektedir. Fotofobik özellik gösteren bu akarlar, ışığın azaldığı dönemlerde daha aktif hareket etmekte ve komşu foliküller arasında geçiş yapabilmektedir. Çiftleşmenin ardından dişi bireyler yeniden uygun pilosebase ünitelere yerleşerek yumurtalarını bırakmakta ve yeni yaşam döngüsünü başlatmaktadır (Rather & Hassan, 2014).

Demodex folliculorum ve Demodex brevis benzer gelişim evrelerine sahip olmakla birlikte, mikrohabitat tercihleri nedeniyle üreme davranışlarında bazı farklılıklar göstermektedir. D. folliculorum aynı folikül içerisinde çok sayıda bireyin bulunmasına bağlı olarak daha sık bireyler arası etkileşim sergilerken, D. brevis çoğunlukla sebase bezlerde tek başına yaşamakta ve daha sınırlı bir dağılım göstermektedir. Bu durum, iki türün popülasyon yapısını ve deri üzerindeki dağılım özelliklerini etkileyen önemli biyolojik faktörlerden biri olarak değerlendirilmektedir (Rufli & Mumcuoglu, 1981; Rather & Hassan, 2014).

Yaşam döngüsünün tamamının konak üzerinde gerçekleşmesi ve konak dışındaki yaşam süresinin oldukça kısa olması, Demodex akarlarının biyolojisinde yüksek derecede konak bağımlılığını ortaya koymaktadır. Bu özellik, türlerin insan derisindeki kalıcılığını sağlarken aynı zamanda popülasyon dinamiklerinin büyük ölçüde konağın fizyolojik durumu, sebum üretimi ve bağışıklık sistemi tarafından belirlenmesine neden olmaktadır (Forton & De Maertelaer, 2019).



Şekil 4. Demodex akarının yaşam döngüsü (Alakbarov, 2020).

2.4. Beslenme Biyolojisi

Demodex akarlarının beslenme biyolojisi, yaşamlarını sürdürdükleri pilosebase ünitelerin fizyolojik özellikleriyle yakından ilişkilidir. Bu akarlar temel olarak sebum, folikül epitelinden dökülen keratinize hücreler ve hücresel artıklarla beslenmektedir. Sebase bezlerin salgıladığı lipid bakımından zengin sebum, Demodex türleri için önemli bir besin kaynağı oluşturmakta ve aynı zamanda uygun bir çevre sağlayarak popülasyonlarının devamlılığını desteklemektedir (Rather & Hassan, 2014; Desch & Nutting, 1972).

Ağız yapıları, folikül içerisindeki yarı sıvı içeriklerin alınmasına uyum sağlayacak şekilde özelleşmiştir. Gnathosoma üzerinde bulunan kısa chelicerae ve palpuslar, sebum ile birlikte epitel hücre kalıntılarının alınmasını kolaylaştırmaktadır. Sindirim sistemi ise alınan besinlerin parçalanması ve emilmesini sağlayacak basit fakat işlevsel bir yapıya sahiptir. Bu morfolojik ve fizyolojik özellikler, Demodex

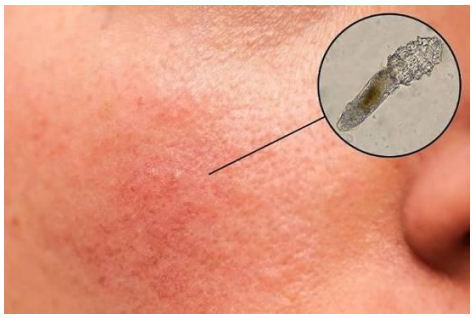
akarlarının dar foliküler boşluklarda enerji gereksinimlerini karşılayabilmelerine olanak tanımaktadır (Nutting, 1976; Rather & Hassan, 2014).

Sebum üretimi ile Demodex popülasyon yoğunluğu arasında yakın bir ilişki olduğu bildirilmektedir. Sebase bezlerin yoğun bulunduğu alın, burun, yanak ve çene gibi bölgelerde akar yoğunluğunun daha yüksek olması, besin kaynağının dağılımı ile doğrudan ilişkilendirilmektedir. Ergenlik döneminde androjen hormonlarının etkisiyle sebum üretiminin artması, Demodex kolonizasyonunun belirginleşmesine katkı sağlarken, yaşlanma ile birlikte sebase bez fonksiyonlarında meydana gelen değişiklikler de popülasyon dinamiklerini etkileyebilmektedir (Forton & De Maertelaer, 2019).

Son yıllarda yapılan çalışmalar, *Demodex* akarlarının yalnızca sebum ve hücresel artıklarla beslenmediğini, aynı zamanda deri mikrobiyotası ile dolaylı etkileşim içerisinde olabileceğini göstermektedir. Özellikle *Cutibacterium acnes, Staphylococcus epidermidis* ve *Bacillus oleronius* gibi mikroorganizmalarla olan ilişkiler hem akarların biyolojisi hem de konakta gelişebilecek inflamatuvar yanıt açısından önem taşımaktadır. Bununla birlikte, bu etkileşimlerin ayrıntılı mekanizmaları henüz tam olarak açıklığa kavuşmamış olup, günümüzde araştırılmaya devam eden konular arasında yer almaktadır (Lacey et al., 2007; Rather & Hassan, 2014).

Beslenme biyolojisi, *Demodex folliculorum* ve *Demodex brevis* türleri arasında mikrohabitat tercihlerine bağlı olarak bazı farklılıklar gösterebilmektedir. *D. folliculorum* çoğunlukla kıl foliküllerinde bulunan sebum ve folikül içeriğinden yararlanırken, *D. brevis* daha derinde yer alan sebase ve meibomian bezlerinde salgılanan lipidlerden faydalanmaktadır. Bu farklılıklar, iki türün deri üzerindeki dağılımını ve ekolojik nişlerini belirleyen önemli biyolojik özellikler arasında değerlendirilmektedir (Rufli & Mumcuoglu, 1981; Rather & Hassan, 2014).

Sonuç olarak, *Demodex* akarlarının beslenme stratejileri, konak dokusuna yüksek derecede uyum sağlamış olmalarının bir göstergesidir. Sebumdan zengin pilosebase üniteleri tercih etmeleri, özelleşmiş ağız yapıları ve besin kaynaklarını etkin biçimde kullanabilmeleri, bu akarların insan derisinde kalıcı popülasyonlar oluşturmasına ve yaşam döngülerini başarıyla sürdürmesine olanak sağlamaktadır.



Şekil 5. Demodex akarları yüz bölgesinde bulundukları yerler (Civas, 2023).

2.5. Davranış Özellikleri

Demodex akarlarının davranışları, yaşamlarını sürdürdükleri pilosebase ünitelerin fiziksel özellikleri ve konağın fizyolojik durumu ile yakından ilişkilidir. Bu akarlar yaşamlarının büyük bölümünü kıl folikülleri ve sebase bezler içerisinde geçirirken, günlük hareketleri oldukça sınırlıdır. Dar foliküler kanallara uyum sağlamış uzun ve silindirik vücut yapıları ile kısa bacakları, folikül içerisinde ilerlemelerini kolaylaştırmakta; ancak serbest hareket kabiliyetlerini önemli ölçüde sınırlandırmaktadır (Rather & Hassan, 2014).

Demodex türlerinin fotofobik (ışıktan kaçınan) davranış gösterdiği ve hareket aktivitelerinin özellikle gece saatlerinde arttığı bildirilmektedir. Gece boyunca erişkin bireylerin folikül ağızlarına doğru hareket ederek komşu foliküllere geçebildiği ve bu davranışın çiftleşme ile yeni yaşam alanlarının kolonizasyonunda önemli rol oynadığı düşünülmektedir. Gündüz saatlerinde ise çoğunlukla foliküllerin daha derin kısımlarında bulunmaları, ultraviyole ışınları ve çevresel stres faktörlerinden korunmalarına katkı sağlamaktadır (Nutting, 1976; Rather & Hassan, 2014).

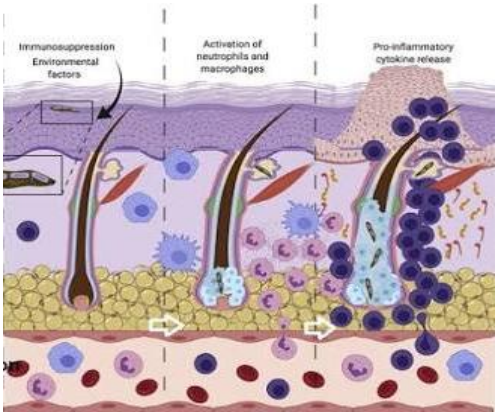
Türler arasında davranış bakımından da bazı farklılıklar bulunmaktadır. Demodex folliculorum genellikle aynı kıl folikülü içerisinde çok sayıda bireyin bir arada bulunduğu koloniler oluştururken, Demodex brevis çoğunlukla sebase bezlerin derin kısımlarında tek başına yaşamaktadır.

Bu farklı yerleşim şekli, türlerin beslenme, üreme ve popülasyon dinamiklerini etkileyen önemli biyolojik özelliklerden biridir (Rufli & Mumcuoglu, 1981; Rather & Hassan, 2014).
Demodex akarlarının konağa uyum sağlamasında davranışsal adaptasyonlar önemli bir yere sahiptir. Besin kaynağının yoğun olduğu pilosebase ünitelerin tercih edilmesi, hareketlerin büyük ölçüde folikül içerisinde gerçekleşmesi ve yaşam döngüsünün tamamının konak üzerinde sürdürülmesi, enerji kaybını en aza indirerek türlerin yaşam başarısını artırmaktadır. Ayrıca konak dışında yalnızca kısa süre canlı kalabilmeleri, bu akarların biyolojisinde konak bağımlılığının ne kadar yüksek olduğunu göstermektedir (Rather & Hassan, 2014; Forton & De Maertelaer, 2019).
Davranış özellikleri, Demodex akarlarının insan derisinde uzun süre kalıcı popülasyonlar oluşturabilmesinde önemli rol oynamaktadır. Özellikle gece aktif olmaları, uygun mikrohabitatları seçmeleri ve konak üzerinde yaşam döngülerini tamamlamaları, bu türlerin insan deri ekosistemine başarılı bir şekilde adapte olduklarını göstermektedir. Bu davranışsal adaptasyonlar, yalnızca biyolojik süreçlerin değil, aynı zamanda Demodex türlerinin ekolojik başarısının da temel belirleyicileri arasında yer almaktadır (Rather & Hassan, 2014).

3. Demodex Akarlarının Ekolojisi

3.1. Mikrohabitat Tercihi ve Deride Yerleşim Alanları

Demodex akarlarının ekolojisi, yaşamlarını sürdürdükleri deri çevresinin fiziksel ve biyolojik özellikleriyle yakından ilişkilidir. Bu akarlar, pilosebase üniteleri temel yaşam alanı olarak kullanan obligat ektoparazitlerdir. Yaşam döngülerinin tamamını insan derisi üzerinde geçirmeleri nedeniyle, uygun mikrohabitat seçimi türlerin yaşamlarını sürdürebilmeleri, beslenebilmeleri ve üreyebilmeleri açısından kritik öneme sahiptir. Sebase bezlerin yoğun olarak bulunduğu bölgeler, yüksek lipid içeriği ve uygun nem koşulları sayesinde Demodex türleri için elverişli yaşam ortamları oluşturmaktadır (Rather & Hassan, 2014).
İnsanlarda en yüksek Demodex yoğunluğu yüz bölgesinde görülmektedir. Özellikle alın, burun, nazolabial kıvrımlar, yanaklar, çene ve dış kulak yolu gibi sebum üretiminin fazla olduğu bölgeler akarların en sık kolonize olduğu alanlardır. Bunun yanında göz kapaklarında bulunan kirpik folikülleri ile meibomian bezleri de önemli yerleşim bölgeleri arasında yer almaktadır. Vücudun gövde ve ekstremiteler gibi sebase bez yoğunluğunun daha düşük olduğu bölgelerinde ise akar yoğunluğu belirgin şekilde azalmaktadır (Rufli & Mumcuoglu, 1981; Forton & De Maertelaer, 2019).
İnsanlarda bulunan iki Demodex türü, mikrohabitat tercihleri bakımından farklı özellikler göstermektedir. Demodex folliculorum çoğunlukla kıl foliküllerinin yüzeysel kısımlarında yerleşmekte ve aynı folikül içerisinde çok sayıda birey birlikte yaşayabilmektedir. Buna karşılık Demodex brevis, daha küçük yapısı sayesinde sebase bezlerin ve meibomian bezlerinin daha derin kısımlarına yerleşmekte, genellikle tek başına bulunmakta ve daha düşük yoğunlukta görülmektedir. Bu farklı yerleşim stratejileri, türlerin beslenme biçimleri, üreme davranışları ve konakla olan etkileşimlerini de etkilemektedir (Rather & Hassan, 2014).
Mikrohabitat seçimini etkileyen temel faktörlerden biri sebum miktarıdır. Sebum, Demodex akarları için hem önemli bir besin kaynağı hem de uygun sıcaklık ve nem koşullarını sağlayan bir yaşam ortamı oluşturmaktadır. Bu nedenle sebase bez aktivitesinin arttığı ergenlik döneminden itibaren akar yoğunluğunda belirgin bir artış gözlenmektedir. Benzer şekilde, hormonal değişiklikler, yaşlanma ve bireyler arasındaki fizyolojik farklılıklar da sebum üretimini etkileyerek Demodex popülasyonlarının dağılımını değiştirebilmektedir (Forton & De Maertelaer, 2019).
Mikrohabitat tercihi yalnızca beslenme olanaklarıyla sınırlı değildir. Pilosebase üniteler, dış çevresel etkilere karşı korunaklı yapıları sayesinde akarları ultraviyole ışınları, mekanik travmalar ve kuruma gibi olumsuz koşullardan da korumaktadır. Ayrıca bu mikroçevre, deri mikrobiyotasında bulunan bakteriler ve diğer mikroorganizmalar ile sürekli etkileşim hâlindedir. Bu nedenle Demodex akarlarının ekolojik başarısı; konak dokusu, deri mikrobiyotası ve çevresel koşullar arasındaki karmaşık etkileşimlerin bir sonucu olarak değerlendirilmektedir (Rather & Hassan, 2014).
Sonuç olarak, Demodex akarlarının mikrohabitat tercihleri, biyolojik özellikleri ve yaşam stratejileri ile doğrudan ilişkilidir. Sebumdan zengin pilosebase üniteleri tercih etmeleri, türlerin beslenme, üreme ve popülasyonlarının devamlılığını sağlarken, aynı zamanda insan deri ekosisteminde kalıcı olarak yerleşmelerine olanak tanımaktadır. Bu nedenle mikrohabitat seçimi, Demodex akarlarının ekolojisinin temel bileşenlerinden biri olarak kabul edilmektedir.



Şekil 6. Demodex akarlarının yerleşim yerleri Buzoğlu (t.y.)'ndan uyarlanmıştır.

3.2. Deri Mikrobiyotası ile Etkileşimleri

İnsan derisi; bakteriler, mantarlar, virüsler ve akarlar gibi çok sayıda mikroorganizmanın bir arada bulunduğu karmaşık bir ekosistemdir. Bu mikroorganizmalar arasında kurulan denge, deri homeostazının korunmasında ve konağın bağışıklık yanıtının düzenlenmesinde önemli rol oynamaktadır. Demodex akarları da insan deri mikrobiyotasının doğal bileşenlerinden biri olarak kabul edilmekte olup, sağlıklı bireylerin deri florasında düşük yoğunluklarda bulunabilmektedir. Ancak bu denge çeşitli iç ve dış faktörlerin etkisiyle bozulduğunda, akar yoğunluğunda meydana gelen artışın deri mikrobiyotasının yapısını değiştirebildiği ve inflamatuvar süreçlere katkıda bulunabildiği bildirilmektedir (Rather & Hassan, 2014; Forton & De Maertelaer, 2019).

Demodex akarları ile deri mikrobiyotası arasındaki ilişkinin çift yönlü olduğu düşünülmektedir. Bir yandan pilosebase ünitelerde bulunan mikroorganizmalar akarların yaşamını etkilerken, diğer yandan akarların hareketi ve biyolojik faaliyetleri mikroorganizmaların foliküller içerisinde taşınmasına katkıda bulunabilmektedir. Özellikle akarların yüzeyinde veya sindirim sisteminde bulunan bazı bakterilerin, akarların ölümü sonrasında çevre dokuya salınarak konağın immün sistemini uyarabileceği ileri sürülmektedir (Lacey et al., 2007; Rather & Hassan, 2014).

Demodex akarları ile ilişkilendirilen mikroorganizmalar arasında Bacillus oleronius, Cutibacterium acnes ve Staphylococcus epidermidis öne çıkmaktadır. Özellikle Bacillus oleronius'a ait bazı proteinlerin, rosacea hastalarında nötrofillerin çoğalmasını ve proinflamatuvar sitokinlerin salınımını uyarabileceği bildirilmiştir. Bununla birlikte, bu bakterilerin hastalık gelişimindeki kesin rolleri henüz tam olarak açıklanamamış olup, konuya ilişkin araştırmalar devam etmektedir (Lacey et al., 2007; Forton & De Maertelaer, 2019).

Deri mikrobiyotası ile Demodex arasındaki ilişkinin yalnızca bakterilerle sınırlı olmadığı, konağın bağışıklık sistemi tarafından da şekillendirildiği düşünülmektedir. Doğuştan ve kazanılmış bağışıklık mekanizmaları, akar popülasyonunun belirli sınırlar içerisinde tutulmasında önemli rol oynarken; immün sistemin baskılandığı durumlarda akar yoğunluğunun arttığı ve mikrobiyal dengenin değişebildiği bildirilmektedir. Bu nedenle Demodex, deri mikrobiyotası ve konak bağışıklığı arasındaki etkileşim, insan deri ekosisteminin dinamik yapısını belirleyen temel unsurlardan biri olarak değerlendirilmektedir (Akilov & Mumcuoglu, 2003).

Son yıllarda metagenomik ve yeni nesil dizileme tekniklerinin gelişmesiyle birlikte, Demodex akarlarının deri mikrobiyotası üzerindeki etkileri daha ayrıntılı olarak araştırılmaya başlanmıştır. Bu çalışmalar, akar yoğunluğundaki değişimlerin mikrobiyal çeşitlilik ve mikrobiyal denge üzerinde etkili olabileceğini göstermektedir. Bununla birlikte, gözlenen mikrobiyota değişikliklerinin hastalığın nedeni mi yoksa sonucu mu olduğu henüz tam olarak açıklığa kavuşmamıştır. Bu nedenle Demodex–mikrobiyota etkileşimi, dermatoloji ve akaroloji alanlarında güncelliğini koruyan önemli araştırma konularından biri olmaya devam etmektedir (Rather & Hassan, 2014).

3.3. Popülasyon Dinamikleri ve Demodex Popülasyonunu Etkileyen Faktörler

Demodex akarlarının insan derisindeki popülasyon yoğunluğu, konak bireyin fizyolojik özellikleri ile çevresel faktörlerin karşılıklı etkileşimi sonucunda şekillenmektedir.

Sağlıklı bireylerde düşük yoğunluklarda bulunan Demodex türleri, deri mikrobiyotasının doğal üyeleri arasında kabul edilmektedir. Ancak yaş, cinsiyet, sebum üretimi, bağışıklık sistemi, genetik yatkınlık ve çevresel koşullar gibi çeşitli faktörlerin etkisiyle akar popülasyonunda belirgin değişiklikler meydana gelebilmektedir (Rather & Hassan, 2014; Forton & De Maertelaer, 2019).

Yaş, Demodex popülasyonunu etkileyen en önemli faktörlerden biridir. Yenidoğan ve çocukluk döneminde sebase bezlerin düşük aktivite göstermesi nedeniyle akar yoğunluğu genellikle oldukça düşüktür. Ergenlik döneminde androjen hormonlarının etkisiyle sebum üretiminin artması, Demodex kolonizasyonunun belirginleşmesine katkı sağlamaktadır. Erişkin bireylerde akar görülme sıklığı artarken, ileri yaşlarda hem sebase bez fonksiyonlarındaki değişiklikler hem de bağışıklık sisteminde meydana gelen yaşlanmaya bağlı değişimler nedeniyle popülasyon yoğunluğunun daha da yükselebildiği bildirilmektedir (Rufli & Mumcuoglu, 1981; Rather & Hassan, 2014).

Sebum üretimi, Demodex akarlarının yaşamını doğrudan etkileyen temel ekolojik faktörlerden biridir. Sebum, akarlar için önemli bir besin kaynağı olmasının yanı sıra uygun sıcaklık ve nem koşullarını sağlayarak pilosebase ünitelerde elverişli bir mikroçevre oluşturmaktadır. Bu nedenle yüz bölgesi gibi sebase bezlerin yoğun bulunduğu alanlarda Demodex popülasyonunun daha yüksek olduğu bildirilmektedir. Ayrıca hormonal değişiklikler, bazı endokrin hastalıklar ve kozmetik ürünlerin kullanımının sebum miktarını etkileyerek akar yoğunluğunda değişikliklere neden olabileceği belirtilmektedir (Forton & De Maertelaer, 2019).

Konak bağışıklık sistemi de Demodex popülasyonunun kontrolünde önemli bir role sahiptir. Sağlıklı bireylerde doğal ve kazanılmış bağışıklık mekanizmaları akar yoğunluğunu belirli sınırlar içerisinde tutarken, immün sistemin baskılandığı durumlarda popülasyon artışı daha sık gözlenmektedir. Organ nakli alıcıları, HIV enfeksiyonu bulunan bireyler, hematolojik maligniteler veya immünsupresif tedavi alan hastalarda Demodex yoğunluğunun artabildiği bildirilmiştir. Bununla birlikte, popülasyon artışının yalnızca bağışıklık sistemiyle açıklanamayacağı, konağın genetik yapısı ve deri mikrobiyotasındaki değişikliklerin de bu süreçte etkili olduğu düşünülmektedir (Akilov & Mumcuoglu, 2003).

Çevresel faktörler de Demodex popülasyon dinamiklerini etkileyebilmektedir. Sıcaklık, nem, ultraviyole maruziyeti, hava kirliliği ve yaşam tarzı gibi faktörlerin deri fizyolojisini değiştirerek akar yoğunluğunu dolaylı olarak etkileyebileceği ileri sürülmektedir. Bunun yanı sıra yüz temizliği alışkanlıkları, kozmetik ürün kullanımı ve cilt bakım uygulamalarının pilosebase ünitelerin yapısını değiştirerek Demodex popülasyonları üzerinde etkili olabileceği belirtilmektedir. Ancak bu faktörlerin etkilerini ortaya koyan çalışmaların sonuçları tam olarak birbirini desteklememekte olup, daha kapsamlı araştırmalara ihtiyaç duyulmaktadır (Rather & Hassan, 2014).

Sonuç olarak, Demodex popülasyon dinamikleri tek bir faktör tarafından değil; konağın fizyolojik özellikleri, bağışıklık sistemi, sebum üretimi, deri mikrobiyotası ve çevresel koşulların birlikte etkisiyle şekillenmektedir. Bu çok yönlü etkileşim, Demodex akarlarının insan deri ekosistemindeki dağılımını belirleyen temel ekolojik mekanizmalardan biri olup, popülasyon yoğunluğunda meydana gelen değişikliklerin hem biyolojik adaptasyon hem de dermatolojik hastalıklarla ilişkisi açısından değerlendirilmesi önem taşımaktadır.

4. İnsan Sağlığı Açısından Önemi

Demodex akarları uzun yıllar boyunca insan deri mikrobiyotasının zararsız üyeleri olarak değerlendirilmiş olsa da, son yıllarda gerçekleştirilen klinik, immünolojik ve moleküler çalışmalar bu organizmaların belirli koşullar altında çeşitli dermatolojik ve oftalmolojik hastalıkların gelişiminde rol oynayabileceğini ortaya koymuştur. Sağlıklı bireylerde düşük popülasyon yoğunluklarında bulunan Demodex türleri çoğunlukla herhangi bir klinik belirti oluşturmamakta, ancak akar yoğunluğunun artması ve konağın bağışıklık dengesinin bozulması durumunda fırsatçı özellik göstererek inflamatuva süreçlere katkıda bulunabilmektedir (Rather & Hassan, 2014; Forton & De Maertelaer, 2019).

Demodex yoğunluğundaki artış en sık demodikozis ile ilişkilendirilmektedir. Demodikozis, akar popülasyonunun normal sınırların üzerine çıkması sonucunda gelişen ve eritem, papül, püstül, kaşıntı ile foliküler inflamasyon gibi klinik bulgularla karakterize bir deri hastalığıdır. Bunun yanı sıra, *Demodex* akarlarının özellikle papülopüstüler rosacea, blefarit, meibomian bez disfonksiyonu ve bazı seboreik dermatit olgularında hastalığın şiddetini artırabileceği bildirilmektedir. Bununla birlikte, bu hastalıkların patogenezinde Demodex'in tek başına etken olmadığı; konağın bağışıklık sistemi, deri mikrobiyotası ve çevresel faktörlerle birlikte değerlendirilmesi gerektiği vurgulanmaktadır (Lacey et al., 2009).

Şekil 7. Demodex akarının ilişkilendirildiği dermatolojik hastalıklar (Elos Klinik, 2025).

Akarların hastalık oluşumuna katkısının yalnızca mekanik etkilerden kaynaklanmadığı düşünülmektedir. Foliküllerde oluşturdukları mekanik irritasyonun yanı sıra, taşıyabilecekleri bakteriler ve ölüm sonrasında açığa çıkan antijenik yapıların konakta inflamatuvar yanıtı uyarabileceği bildirilmektedir. Özellikle Bacillus oleronius ile ilişkilendirilen antijenlerin, bazı rosacea hastalarında immün yanıtı tetikleyebileceği ileri sürülmektedir. Ancak bu mekanizmaların ayrıntıları henüz tam olarak açıklanamamış olup, konu günümüzde aktif olarak araştırılmaktadır (Lacey et al., 2007; Rather & Hassan, 2014).

Günümüzde Demodex akarları yalnızca hastalık etkeni olarak değil, aynı zamanda insan deri ekosisteminin doğal bileşenleri olarak da değerlendirilmektedir. Bu nedenle akarların varlığından çok, popülasyon yoğunluğu, konağın bağışıklık durumu ve deri mikrobiyotasındaki değişikliklerin birlikte değerlendirilmesi önerilmektedir. Son yıllarda geliştirilen moleküler yöntemler ve mikrobiyota analizleri sayesinde Demodex–konak etkileşiminin daha iyi anlaşılması, bu akarların dermatolojik hastalıklardaki rolünün açıklığa kavuşturulmasına katkı sağlamaktadır (Forton & De Maertelaer, 2019).

Sonuç olarak, Demodex akarları sağlıklı bireylerde çoğunlukla deri mikrobiyotasının doğal üyeleri olarak yaşamlarını sürdürmekle birlikte, uygun biyolojik ve çevresel koşullar altında fırsatçı davranış göstererek çeşitli dermatolojik ve oftalmolojik hastalıkların gelişimine katkıda bulunabilmektedir. Bu nedenle Demodex akarlarının biyolojisi, ekolojisi ve konakla olan etkileşimlerinin daha iyi anlaşılması, hastalıkların patogenezinin aydınlatılması ve yeni tanı ile tedavi yaklaşımlarının geliştirilmesi açısından önem taşımaktadır.

5. Güncel Araştırmalar ve Gelecek Perspektifleri

Son yıllarda moleküler biyoloji, genomik ve metagenomik alanlarında yaşanan gelişmeler, Demodex akarlarının biyolojisi ve ekolojisinin daha ayrıntılı olarak anlaşılmasına önemli katkılar sağlamıştır. Geleneksel mikroskobik yöntemlerin yanında moleküler tanımlama tekniklerinin kullanılmaya başlanması, Demodex türlerinin genetik çeşitliliği, filogenetik ilişkileri ve konak özgüllüğünün daha doğru şekilde değerlendirilmesine olanak sağlamıştır. Özellikle DNA temelli analizler sayesinde morfolojik olarak birbirine oldukça benzeyen türlerin ayırt edilmesi kolaylaşmış ve farklı Demodex popülasyonlarının genetik yapısı hakkında yeni bilgiler elde edilmiştir (Rather & Hassan, 2014).

Deri mikrobiyotası üzerine gerçekleştirilen araştırmalar da Demodex akarlarının insan deri ekosistemindeki rolüne ilişkin bakış açısını değiştirmiştir. Yeni nesil dizileme (Next Generation Sequencing, NGS) teknolojileri sayesinde deri mikrobiyotasını oluşturan bakteri, mantar ve diğer mikroorganizmaların Demodex popülasyonları ile olan etkileşimleri daha ayrıntılı olarak incelenebilmektedir. Bu çalışmalar, akar yoğunluğundaki değişimlerin deri mikrobiyal çeşitliliğini etkileyebileceğini ve buna bağlı olarak konak bağışıklık yanıtında farklılıklar oluşabileceğini göstermektedir. Bununla birlikte, gözlenen mikrobiyota değişikliklerinin neden mi yoksa sonuç mu olduğu konusu hâlen araştırılmaktadır (Byrd et al., 2018).

Günümüzde araştırmalar yalnızca Demodex akarlarının dermatolojik hastalıklarla ilişkisine odaklanmamakta, aynı zamanda bu organizmaların deri ekosistemindeki biyolojik işlevlerini ortaya koymayı amaçlamaktadır. Özellikle konak bağışıklık sistemi ile akarlar arasındaki moleküler etkileşimler, inflamatuvar yanıt mekanizmaları ve deri bariyer fonksiyonları üzerindeki etkiler son yıllarda önem kazanan araştırma konuları arasında yer almaktadır. Ayrıca farklı coğrafi bölgelerde yaşayan bireylerde Demodex popülasyonlarının genetik çeşitliliğinin incelenmesi, konak–parazit ortak evriminin anlaşılmasına katkı sağlayabilecek önemli araştırma alanlarından biri olarak değerlendirilmektedir (Forton & De Maertelaer, 2019).

Gelecekte yapılacak çalışmaların, Demodex akarlarının yalnızca patojenik potansiyeline değil, aynı zamanda sağlıklı deri mikrobiyotasındaki işlevlerine de odaklanması beklenmektedir. Çok merkezli epidemiyolojik araştırmalar, genomik analizler ve deri mikrobiyotasını bütüncül olarak değerlendiren çalışmalar sayesinde, Demodex türlerinin insan deri ekosistemindeki biyolojik ve ekolojik rolleri daha kapsamlı biçimde ortaya konulabilecektir. Elde edilecek bu bilgiler, hem dermatolojik hastalıkların patogenezinin aydınlatılmasına hem de yeni tanı ve tedavi yaklaşımlarının geliştirilmesine katkı sağlayacaktır.

Sonuç olarak, moleküler biyoloji ve mikrobiyota araştırmalarındaki gelişmeler, Demodex akarlarının biyolojisi ve ekolojisine ilişkin bilgi birikimini önemli ölçüde artırmıştır. Bununla birlikte, konak–parazit etkileşimi, mikrobiyota ile ilişkiler ve popülasyon dinamikleri gibi birçok konu hâlen araştırılmaya devam etmektedir. Bu nedenle disiplinler arası çalışmaların artırılması, Demodex akarlarının insan deri ekosistemindeki yerinin daha iyi anlaşılmasına ve gelecekte geliştirilecek koruyucu ile tedavi edici yaklaşımlara bilimsel temel oluşturacaktır.

5.1. Araştırmalardaki Bilgi Boşlukları ve Gelecek Çalışmalar İçin Öneriler

Demodex akarları üzerine son yıllarda önemli ilerlemeler kaydedilmiş olmasına rağmen, bu organizmaların biyolojisi, ekolojisi ve konakla olan ilişkilerine dair birçok konu hâlen tam olarak açıklığa kavuşturulamamıştır. Özellikle sağlıklı bireylerde bulunan Demodex popülasyonlarının deri homeostazındaki işlevleri ile popülasyon yoğunluğundaki değişimlerin dermatolojik hastalıkların nedeni mi yoksa sonucu mu olduğu konusu güncelliğini korumaktadır. Bu nedenle, Demodex akarlarının yalnızca fırsatçı patojenler olarak değil, insan deri ekosisteminin doğal bileşenleri olarak da değerlendirilmesi gerektiği vurgulanmaktadır (Forton & De Maertelaer, 2019; Rather & Hassan, 2014).

Mevcut çalışmaların önemli bir kısmı, akar yoğunluğu ile çeşitli dermatolojik hastalıklar arasındaki ilişkiyi incelemekle birlikte, bu ilişkinin altında yatan moleküler mekanizmalar henüz tam olarak ortaya konulamamıştır. Özellikle konak bağışıklık sistemi, deri mikrobiyotası ve Demodex akarları arasındaki karşılıklı etkileşimlerin çok yönlü olarak değerlendirilmesi gerekmektedir. Bu kapsamda genomik, transkriptomik, proteomik ve metagenomik yaklaşımların birlikte kullanıldığı disiplinler arası araştırmaların, mevcut bilgi eksikliklerinin giderilmesine katkı sağlayacağı düşünülmektedir (Byrd et al., 2018).

Gelecekte gerçekleştirilecek çalışmalarda farklı yaş grupları, farklı coğrafi bölgeler ve çeşitli dermatolojik hastalık gruplarının karşılaştırmalı olarak değerlendirilmesi, Demodex popülasyonlarının dağılımı ve ekolojik özelliklerinin daha iyi anlaşılmasını sağlayacaktır. Ayrıca standart örnekleme yöntemlerinin geliştirilmesi ve moleküler tanı tekniklerinin yaygınlaştırılması, araştırma sonuçlarının karşılaştırılabilirliğini artıracaktır.

Sonuç olarak, Demodex akarları ile ilgili gelecekte yapılacak çalışmaların yalnızca akar yoğunluğunu belirlemeye odaklanması yerine, konak–parazit etkileşimlerini, deri mikrobiyotasını ve bağışıklık yanıtını birlikte değerlendiren bütüncül bir yaklaşımla planlanması gerekmektedir. Bu yaklaşım, hem Demodex biyolojisinin ve ekolojisinin daha iyi anlaşılmasına hem de bu akarlarla ilişkili dermatolojik hastalıkların tanı ve tedavisinde yeni stratejilerin geliştirilmesine katkı sağlayacaktır.

6. Sonuç

Demodex akarları, yaşam döngülerini tamamen insan derisi üzerinde sürdüren ve pilosebase ünitelere yüksek düzeyde uyum sağlamış obligat ektoparazitlerdir. İnsanlarda en yaygın olarak bulunan Demodex folliculorum ve Demodex brevis türleri; morfolojik özellikleri, yaşam döngüleri, beslenme stratejileri ve davranışsal adaptasyonları sayesinde deri ekosisteminde kalıcı popülasyonlar oluşturabilmektedir.

Bu biyolojik özellikler, türlerin konak üzerinde uzun süre yaşamlarını sürdürebilmelerini ve insan deri mikrobiyotasının doğal bileşenleri arasında yer almalarını sağlamaktadır.

Demodex akarlarının ekolojisi; mikrohabitat tercihleri, deri mikrobiyotası ile etkileşimleri, popülasyon dinamikleri ve konak bağışıklık sistemiyle kurdukları ilişkiler doğrultusunda şekillenmektedir. Sebumdan zengin pilosebase üniteleri tercih etmeleri, deri mikrobiyotası ile sürekli etkileşim içinde bulunmaları ve popülasyon yoğunluklarının yaş, bağışıklık durumu, hormonal değişiklikler ve çevresel faktörlerden etkilenmesi, bu akarların insan deri ekosisteminin dinamik bir parçası olduğunu göstermektedir. Güncel çalışmalar, Demodex popülasyonundaki değişimlerin yalnızca akar biyolojisi ile değil, aynı zamanda konağın fizyolojik özellikleri ve deri mikrobiyotasındaki değişikliklerle de yakından ilişkili olduğunu ortaya koymaktadır (Rather & Hassan, 2014; Forton & De Maertelaer, 2019).

Son yıllarda moleküler biyoloji ve yeni nesil dizileme teknolojilerindeki gelişmeler, Demodex akarlarının biyolojisi ve ekolojisine ilişkin bilgi birikimini önemli ölçüde artırmıştır. Özellikle konak–parazit etkileşimi, deri mikrobiyotası ile ilişkiler ve immünolojik mekanizmalar üzerine yapılan araştırmalar, bu organizmaların yalnızca fırsatçı patojenler olarak değil, aynı zamanda insan deri ekosisteminin doğal üyeleri olarak değerlendirilmesi gerektiğini göstermektedir. Bununla birlikte, akar yoğunluğundaki artışın dermatolojik hastalıkların nedeni mi yoksa mevcut deri değişikliklerinin bir sonucu mu olduğu konusu hâlen tam olarak açıklığa kavuşmamıştır.

Sonuç olarak, Demodex akarlarının biyolojisi ve ekolojisinin bütüncül bir yaklaşımla değerlendirilmesi, insan deri ekosisteminin daha iyi anlaşılmasına katkı sağlamaktadır. Gelecekte gerçekleştirilecek moleküler, immünolojik ve mikrobiyota temelli çalışmaların, Demodex türlerinin konak ile olan ilişkilerini daha ayrıntılı ortaya koyacağı ve bu organizmaların dermatolojik hastalıklardaki rollerinin daha net anlaşılmasına katkı sağlayacağı düşünülmektedir. Bu doğrultuda elde edilecek bilimsel veriler, hem temel akaroloji araştırmalarına hem de dermatoloji alanında geliştirilecek yeni tanı, korunma ve tedavi yaklaşımlarına önemli katkılar sunacaktır.

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FORKLİFT ÇATALLARININ TASARIM, ANALİZ VE TEST SÜREÇLERİNİN BÜTÜNLEŞİK OLARAK DEĞERLENDİRİLMESİ

INTEGRATED EVALUATION OF FORKLIFT FORK DESIGN, ANALYSIS, AND TESTING PROCESSES

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ÖZET

Bu çalışma, 3.5 ton taşıma kapasiteli bir forkliftin çatallarının, ISO 2328 standardına uygun olarak tasarlanması, ISO 2330 standardında belirtilen koşullar altında sonlu elemanlar yöntemi (FEM) ile analiz edilmesi ve deneysel olarak teste tabi tutulması süreçlerini bütünleşik bir şekilde ele almaktadır. Forklift çatallarının, iş güvenliği ve operasyonel verimlilik açısından taşıdığı kritik önem vurgulanarak, yapısal hasarların önlenmesinde doğru tasarım, malzeme seçimi ve periyodik kontrolün rolü detaylandırılmıştır. Çalışmanın literatürden temel farkı; sonlu elemanlar yöntemi ile yapılan statik analize ek olarak, ürünün gerçek test koşulları altında doğrulanmasıdır. Bu sayede, sayısal analiz sonuçları ile deneysel bulgular arasındaki korelasyonun incelenmesi ve sapmaların ortaya konulması amaçlanmıştır. Bu kapsamda yapılan korelasyon çalışmasında, D=500 mm yük uygulama noktasında sonlu elemanlar analizi sonucunda yaklaşık 52 mm deplasman öngörülürken, fiziksel testlerde aynı noktada 60 mm deplasman ölçülmüştür. Bu sonuçlar, analiz ve test verileri arasında yük merkezinde yaklaşık %15 oranında bir sapma bulunduğunu göstermiştir. Testlerde elde edilen daha yüksek deplasman değerleri, hem gerçek malzemenin analiz modelinde tanımlanan malzeme özelliklerine kıyasla daha yüksek elastik deformasyon kapasitesine sahip olabileceğini hem de gerçek test düzeneğindeki (test bench) fikstür esnemelerinden ve bağlantı boşluklarından kaynaklanabileceği değerlendirilmiştir. Elde edilen bu bulguların, güvenlik standartlarını karşılayacak şekilde optimize edilmiş, daha hafif ve uzun ömürlü çatal tasarımlarının geliştirilmesine katkı sunması hedeflenmiştir.

ABSTRACT

This study presents an integrated approach to the design of forklift forks with a rated load capacity of 3.5 tons in accordance with ISO 2328, their finite element method (FEM) analysis under the loading conditions specified in ISO 2330, and their experimental validation through physical testing. The critical role of forklift forks in ensuring occupational safety and operational efficiency is emphasized, while the importance of proper design, material selection, and periodic inspection in preventing structural failures is discussed in detail. The primary contribution of this study, distinguishing it from previous research, is the experimental validation of the numerical results obtained from the finite element analysis under actual test conditions. Accordingly, a correlation analysis was conducted to evaluate the agreement between the numerical predictions and the experimental measurements and to identify possible discrepancies. The correlation study revealed that, at a load application distance of D = 500 mm, the finite element analysis predicted a displacement of approximately 52 mm, whereas the physical tests measured a displacement of 60 mm at the same location. These findings indicate an approximately 15%

difference between the numerical and experimental results at the load center. The higher displacement values observed during the physical tests may be attributed to the actual material exhibiting greater elastic deformation capacity than that assumed in the numerical model, as well as to fixture compliance and connection clearances within the experimental test bench. The findings of this study are expected to contribute to the development of optimized forklift fork designs that satisfy safety standards while offering reduced weight and extended service life.

INTRODUCTION

Forklifts are industrial material handling vehicles designed to transport loads from one location to another. Depending on the physical characteristics of the load, various attachments can be integrated into the forklift, enabling the handling, loading, and stacking of different types of materials. The type of forklift used varies according to the operating environment in which it is employed (Demir, 2024).

The lifting mechanism of a forklift is a critical system that is subjected to the highest stress levels and continuous loading during operation. Therefore, periodic inspection of the lifting equipment and a thorough understanding of the functionality of its components play a vital role in preventing occupational accidents and material damage resulting from improper use. Machine components designed to withstand heavy mechanical loads are subjected to various strength tests during the manufacturing process and are typically tested under loads several times greater than their rated working load. The relationship between the maximum applied test load and the design load defines the safety factor of the component. However, due to unpredictable operating conditions and mechanical wear that develops over time, these components require regular inspection. Furthermore, certain components should be replaced as part of preventive maintenance even if no visible signs of failure are present, since damage mechanisms such as material fatigue may not always be detectable through visual inspection (MEB, 2011).

The load-carrying forks used in forklifts are the primary components that come into direct contact with the load and enable its handling and transportation. In addition to supporting the load, the forks are the principal load-bearing elements that directly influence the structural integrity of the entire mast system. At the same time, they should possess a compact cross-section and low weight while maintaining good ductility and adequate low-temperature impact resistance (Ge et al., 2019). Therefore, forklift forks are considered critical components for ensuring both operator safety and overall workplace safety.

Proper adjustment of fork spacing according to the load's center of gravity and ensuring that the load is balanced during handling and stacking are fundamental requirements for safe forklift operation (MEB, 2011). The use of appropriately sized pallets, positioning the forks as far apart as practicable under the load, and distributing the load evenly across both forks contribute to reducing structural stresses. Furthermore, avoiding the handling of loads with a single fork helps prevent excessive stresses on the forks, thereby enhancing operational safety and extending the service life of the equipment (Erel, 2015).

Structural damage that may occur in forklift forks during load lifting through the mast system can pose serious safety risks to both the operator and nearby personnel. Such damage may result in sudden load loss or equipment failure, thereby increasing the likelihood of occupational accidents (Zhou, 2022). However, the design of forklift forks, which serve as the primary load-bearing components, faces several engineering challenges, including material inefficiency, structural fatigue, and performance degradation associated with long-term service (Bekele, 2025). Furthermore, the ability of these components to operate safely throughout their service life depends not only on appropriate design parameters but also on operators adhering to safe operating practices and established working procedures.

In particular, striking the fork tips against fixed surfaces during load engagement or subjecting the mast system to irregular impact loads are among the primary factors that compromise the structural integrity of the equipment and adversely affect its service life. In this context, ensuring that the design, operation, and periodic inspection of forklift forks are carried out in accordance with applicable safety regulations and international standards is of critical importance for maintaining operational safety.

Furthermore, to prevent existing or potential damage that may develop during service, these systems should undergo periodic inspection at least once a year in accordance with the applicable regulations. If cracks, permanent deformation, or other structural defects are identified during visual inspections, the necessary corrective actions should be implemented promptly to ensure occupational safety (Yazıcı, 2015).

Recent studies on the structural integrity and performance of forklift forks have primarily focused on finite element method (FEM)-based optimization and material behavior. In a study conducted for a 10-ton capacity forklift, Mahdieh, Nazari, and Ghlaim (2024) compared the performance of different steel alloys (St37 and St52) using FEM simulations and experimental testing. Their findings demonstrated that the St52 alloy exhibited superior mechanical performance; however, its strength should be further enhanced through heat treatment to ensure adequate safety. These results emphasize the importance of considering material selection and manufacturing processes in an integrated manner. Similarly, Zhang et al. (2020) combined numerical simulation with mathematical modeling to analyze the stress distribution in a forklift fork and carried out structural optimizations aimed at improving fatigue life. Their study confirmed that stress concentrations in the heel region of the fork are the primary cause of fatigue-induced failures.

In addition, recent studies have also highlighted significant advances in design optimization. Kumaran, Muthuram, and Chealvan (2025) performed topology optimization of a forklift fork using the ANSYS Direct Optimization module and achieved up to a 48% reduction in the maximum equivalent stress, thereby significantly extending the service life of the component. Similarly, Jiang, Lian, and Wu (2025) analyzed the fork carriage structure of an automated guided vehicle (AGV) used in intelligent warehousing systems through finite element analysis and proposed a structural optimization that reduced the overall weight by 11.5% while satisfying the required performance criteria. These findings demonstrate that FEM-based optimization not only enhances structural safety but also contributes to sustainability objectives by reducing material consumption and improving energy efficiency.

This study covers the design of a forklift fork with a rated load capacity of 3.5 tons according to ISO 2328, the finite element method performed using the Hyperworks software under the conditions specified in ISO 2330, and the experimental validation carried out on a test platform. The distinguishing aspect of this study compared with previous research is the validation of the product under actual test conditions in addition to the static analysis performed using the finite element method. As a future extension of this work, fatigue analysis will be conducted to determine the long-term behavior of the fork under repeated loading and unloading cycles. Furthermore, by considering the deviations between the finite element method results and actual experimental conditions, subsequent studies may enable reliable model validation based solely on numerical analyses.

METHODOLOGY

The lifting operation of the load in forklifts is performed by the mast system. The mast system is illustrated in Figure 1.

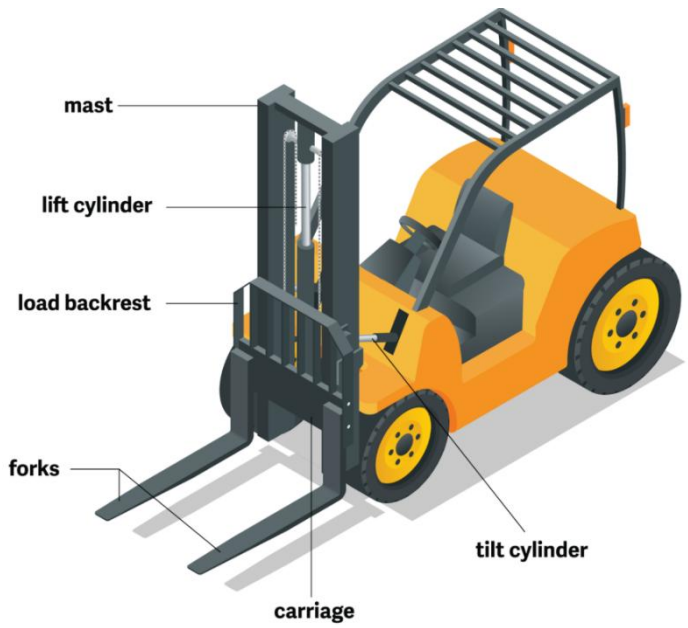

Figure 1. Mast Detail Part Display (Kadison, 2024)

The load handling system of a forklift consists of an integrated structure in which all components support and interact with each other. The forks, which directly carry the load, transfer the applied weight to the fork carriage, the platform to which they are attached. A support structure known as the load backrest is positioned behind the forks to prevent the load from falling backward toward the operator. The primary movements of the system are provided by hydraulic cylinders; while the lift cylinders enable the vertical lifting and lowering of the load, the tilt cylinders control the forward and backward inclination of the forks and carriage. The main structural framework supporting all these components is the mast assembly. These guided rail structures form the backbone of the forklift and provide essential support to ensure that the elevated load remains stable and safely positioned during operation (Erel, 2015).

In this study, the fork design of a forklift with a rated lifting capacity of 3.5 tons was developed. The structural behavior of the designed fork was analyzed using the finite element method (FEM) through the Hyperworks software. During the analysis process, the loading conditions and design criteria specified in the relevant standards were taken into consideration. The findings obtained from the numerical analyses were compared with the results of experimental tests conducted using the developed test setup, and the performance and reliability of the design were evaluated.

Fork Design According to ISO 2328 Standard

This international standard defines the dimensional requirements and additional specifications necessary to ensure the interchangeability of forklift carriages and hook-type forklift forks for forklifts with lifting capacities up to 10,999 kg. The standard also specifies the compatibility requirements of carriage attachments to be used according to the fork type. Forks are classified into two different types, Type A and Type B, and are further categorized into five classes based on their load capacities (International Organization for Standardization, 2007). For the 3.5-ton capacity forklift, Class 3 is used (Table 1).

The required design parameters were created in the CATIA V5R21 three-dimensional CAD software (Figure 2). These parameters were applied and constrained on a two-dimensional sketch, and the three-dimensional model was subsequently generated (Figure 3).

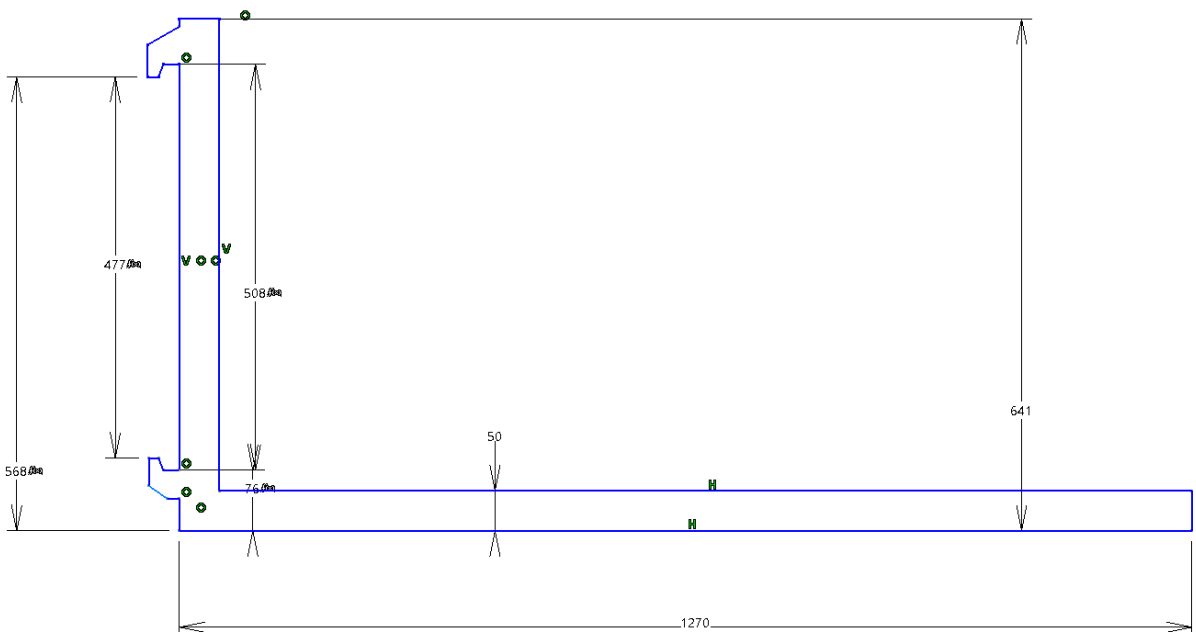

Figure 2. 2D Sketch Parameters

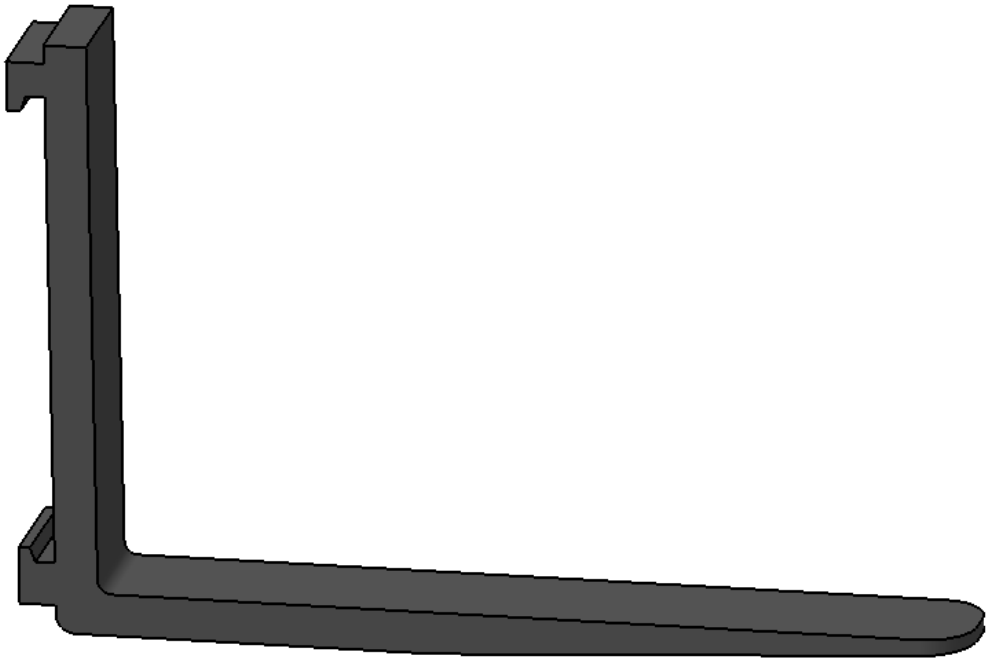

Figure 3. 3D Computer-Aided Design Model

Table 1. ISO 2328 Class 3 fork detail dimensions.

Class	Truck rated capacity (kg/mm)	Fork arm type	a	c1	h1	h2	m1	m2	k1	Lower hook v
3	2 501 to 4 999 / 500 and 600	A	76	22	568	477	40	38	17	115
3	2 501 to 4 999 / 500 and 600	B	203		695					

Test Condition According to ISO 2330 Standard

This International Standard specifies the manufacturing, testing, and marking requirements for solid-section fork arms intended for mass production and various assembly applications. The fundamental testing philosophy of this standard is based on the verification of each fork arm produced in series by subjecting it to a static load representing the worst-case conditions that may be encountered during field operation. During the test procedure, the absence of permanent deformation is considered an indication that the yield strength of the fork arm has not been exceeded.

- The fork arms should be made of solid material.
- The end section is made thin so that it can easily grip and stack the load.

In this context, the test procedure according to ISO 2330 is shown in Table 2.

Table 2. Yield Test Procedure Under ISO 2330

	Yield Test
Procedure	Apply the appropriate proof load gradually and without impact at a distance D. The load shall be applied twice and maintained for 30 seconds.
Requirement	Measurements shall be taken from the upper surface of the fork blade tip after the first test and after the second test. The comparison between these two measurements shall demonstrate that no permanent deformation has occurred.

The test load shall correspond to three times the specified capacity C of the fork arm (Table 3). Considering the gravitational acceleration (9.81 m/s²), the static load was calculated as 103005 N. The fork was tested under a force of 106450 N, which was obtained by applying an additional safety margin of approximately 3.3% to account for test equipment tolerances, sensor accuracy, and the self-weight of the loading fixture.

Table 3. Test Load Calculation

C	3500	kg
Ft	3500X3X9.81	N
Test Load	FtX1.033	N
Test Load	106450	N

Execution of the Test

For the execution of this test, loading was performed using a vertical actuator. An experimental setup was developed to accurately simulate the static loading conditions specified in ISO 2330. The test setup is based on the principle of applying a gradually increasing and controlled force through a load cell integrated into a vertical actuator positioned perpendicular to the load-bearing surface of the fork. Using this approach, the fork was subjected to a test load exceeding its nominal load capacity at a specified load center distance.

The test procedure was designed in two stages. During the first stage, referred to as the preloading phase, the fork was loaded up to a certain percentage of the test load specified by the standard to verify whether any possible seating effects or clearances existed within the test setup. Subsequently, the main test phase was initiated, during which the load was increased at a constant rate until reaching the predetermined maximum test value and maintained at this level for 30 s, as specified by the standard. Throughout the loading and subsequent unloading processes, real-time deformation and displacement data were recorded.

The acceptance criterion of the test, as explicitly defined in ISO 2330, is the absence of any permanent deformation in the fork after the removal of the test load. This criterion is considered the primary evidence that the yield strength of the fork has not been exceeded and that the material remains within the elastic region. The experimental data obtained were directly compared with the results of the finite element method performed under the same boundary conditions in the subsequent stage, with the aim of validating the numerical model.

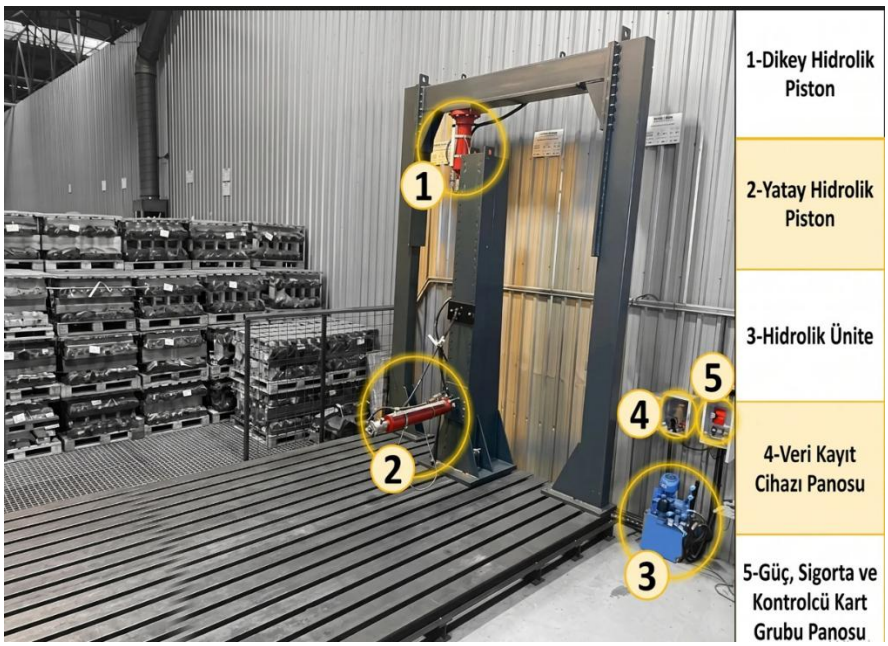

Figure 4. General View of The Test Unit.

The test unit shown in Figure 4 is used to perform controlled static loading tests on specific components. The test specimen is rigidly fixed to the ground through the channels located on the base structure. Horizontal and vertical loading conditions are generated by a hydraulic power unit and applied to the specimen in a controlled manner. During the test, displacement, applied load, and energy variations of the specimen are monitored through the control system, while the acquired data are simultaneously recorded using a data acquisition and recording system. In addition, emergency stop and circuit breaker mechanisms are integrated into the system to ensure operational safety against unexpected conditions that may occur during testing.

As shown in Figure 5, a loading fixture with dimensions of 250 × 250 × 20 mm was mounted at the load center distance of the fork, D = 500 mm. The target load was applied using a hydraulic actuator with a capacity of 30 tons. The cylindrical component welded to the loading fixture ensured the alignment of the axial force generated by the actuator and contributed to the uniform transfer of the applied load to the test specimen. During the experiment, the displacement of the actuator was continuously monitored and controlled using a linear scale integrated into the hydraulic piston.

Figure 5. Mounting of the Forklift Fork on the Test Bench Unit

FEM Analysis

The finite element method (FEM) is one of the most widely used numerical analysis techniques in computer-aided simulations. FEM eliminates the need for producing physical prototypes and enables the analysis of any part or component of a system under specified operating conditions. Furthermore, it allows design modifications to be implemented based on the analysis results, thereby improving product reliability and performance.

Hyperworks 2017.2 software was used for the static analysis. Within the software environment, a fine mesh structure was generated, the applied load was defined, and the component was constrained according to its operating position. The analysis input parameters are presented in Table 4.

The software interface is presented in Figure 6, while the constraint locations and load application points of the component are shown in Figure 7.

Table 4. Hyperworks Analysis Inputs

Element	466403 nodes
Elements Size (Avg)	2 mm
Element Type	Hexa Solid
Analysis Type	Nonlinear Quasi-Static
Applied Force	106450 N

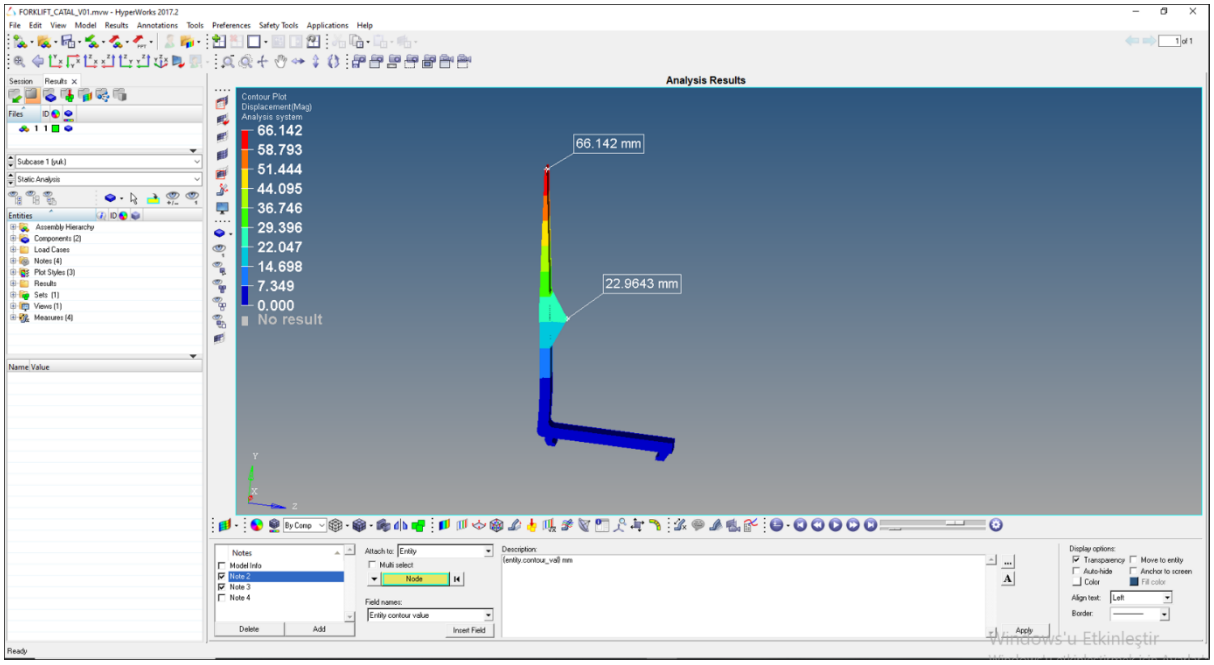

Figure 6. Hyperworks Analytics Interface

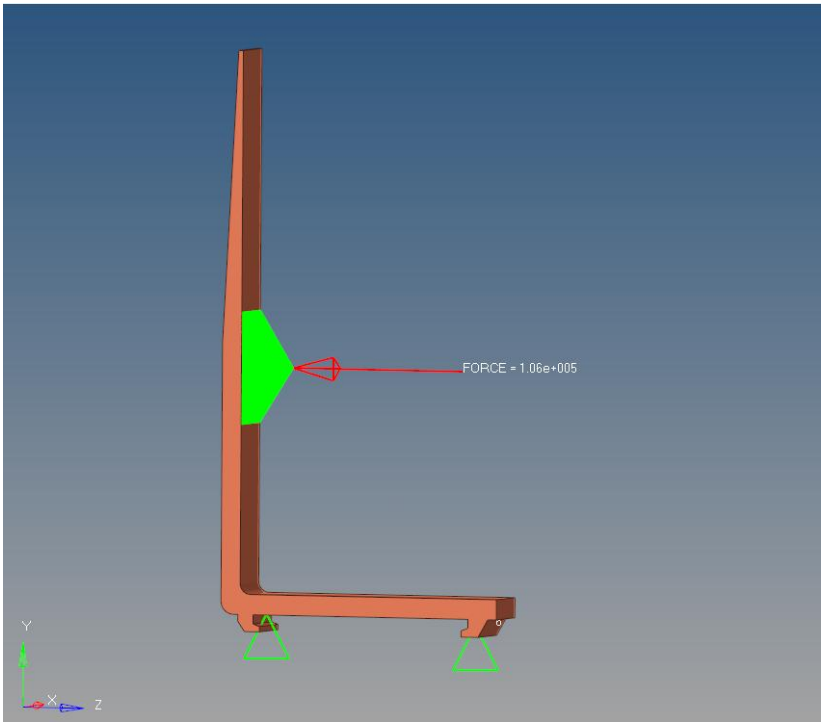

Figure 7. Fixing Point and Force Application Area

The analysis configuration of the component was maintained in accordance with its operating principle under field conditions. The applied load was transferred through the same region as the 25 cm loading plate used in the test bench setup. The component was constrained at the guide points.

RESULTS

In this section, the findings obtained from the experimental tests of the 3.5-ton capacity forklift fork conducted according to ISO 2330 and the finite element analyses performed in the Hyperworks environment are presented comparatively. The results are evaluated in two main categories: static structural analysis and experimental validation.

Finite Element Method Results

The developed three-dimensional solid model was constrained and loaded to represent the test conditions specified in ISO 2330. The static structural analysis results demonstrated that the maximum equivalent stress was concentrated, as expected, in the critical region known as the fork heel, where a significant cross-sectional transition occurs. The maximum stress value observed throughout the component remained below the yield strength of the selected material, indicating that the design satisfies the criterion of being subjected to a test load equivalent to three times the rated lifting capacity, as specified by the standard.

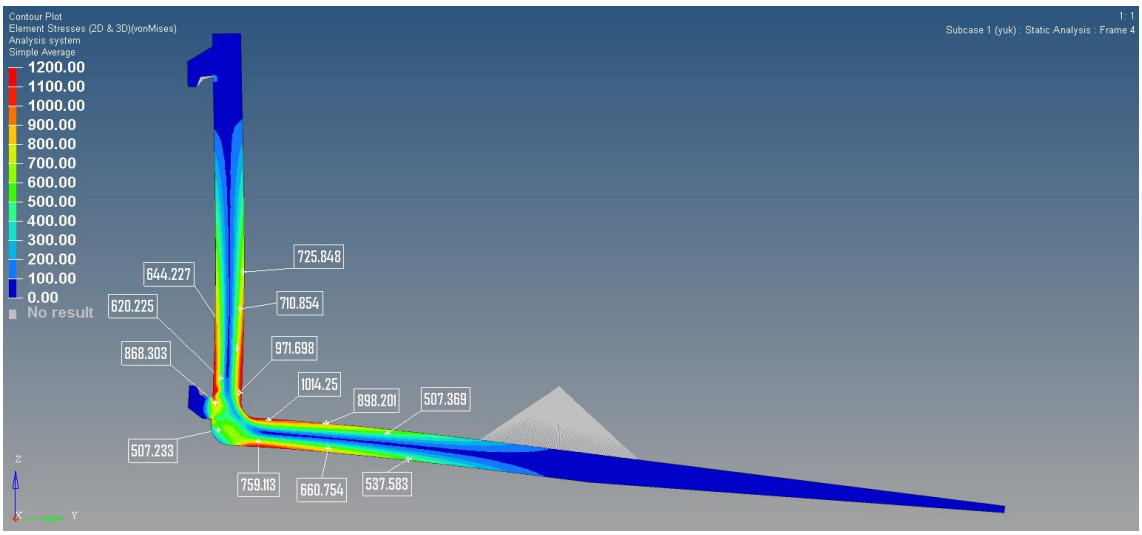

Figure 8. Stress Distributions

In the finite element analysis, it was observed that the equivalent stress values calculated in some localized regions slightly exceeded the yield strength of the material. However, this condition was not interpreted as an indication that the component underwent overall plastic deformation or lost its structural integrity. The exceedance of the yield strength only suggests that plastic deformation may initiate locally within these specific regions. The occurrence of localized peak stresses at sharp geometric transitions, small radii, contact areas, or load application points is a commonly encountered phenomenon in finite element analyses. Such local stress concentrations generally occur within very small volumes and do not directly affect the overall load-carrying capacity or functional performance of the component. In the investigated model, the regions exceeding the yield strength exhibited a highly localized characteristic, and no widespread plastic deformation behavior was observed (Figure 8).
Furthermore, it is considered that the stress concentrations occurring in these regions can be reduced through design optimization studies. In particular, increasing the transition radii, revising the cross-sectional reduction geometry in the fork approach region, and implementing geometric improvements to achieve a more uniform load distribution are expected to reduce the peak stress values. The maximum deformation was observed at the tip region of the fork, and this deformation level was determined to be within an acceptable range that does not hinder the functional operation of the component. According to the analysis results, a displacement of 52 mm was obtained at the load center distance of D = 500 mm, where the load was applied, while a displacement of 141 mm was observed at the fork tip (Figure 9).

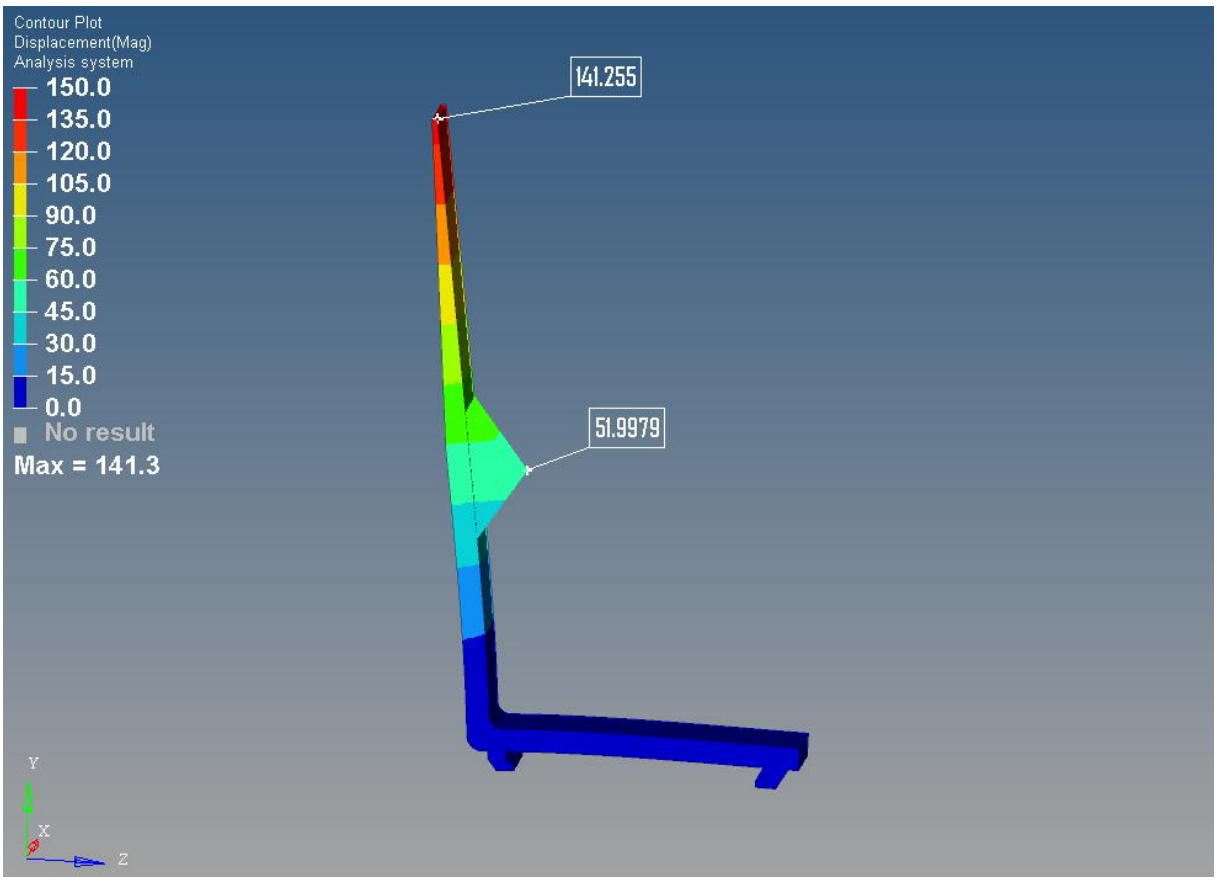

Figure 9. Fork Displacement Value

Experimental Test Results

The DEWE-43A is a high-precision data acquisition (DAQ) system widely used in engineering applications, automotive testing, and research and development activities. The system converts analog signals obtained from various sensors, such as voltage, force, temperature, pressure, vibration, and displacement, into digital data with high sampling accuracy and transfers them to a computer environment. The monitoring, processing, and recording of the acquired data are performed using Dewesoft software. The data monitoring and control interface of the software is presented in Figure 10. Through the Dewesoft interface, the data obtained from the measurement equipment integrated into the system can be visualized, analyzed, and recorded in real time. Within the scope of this study, displacement measurements were performed using a linear scale to investigate the structural behavior of forklift forks under static loading conditions. Simultaneously, the applied force values and the amount of energy dissipated by the system were monitored. In addition, the operating pressure of the hydraulic actuator used for the loading process was continuously monitored to ensure that the test procedure was maintained under controlled conditions.

By this means, the force, displacement, energy, and hydraulic pressure parameters were recorded synchronously throughout the loading process. The obtained data were used to evaluate the mechanical performance of the fork and to validate the experimental results.

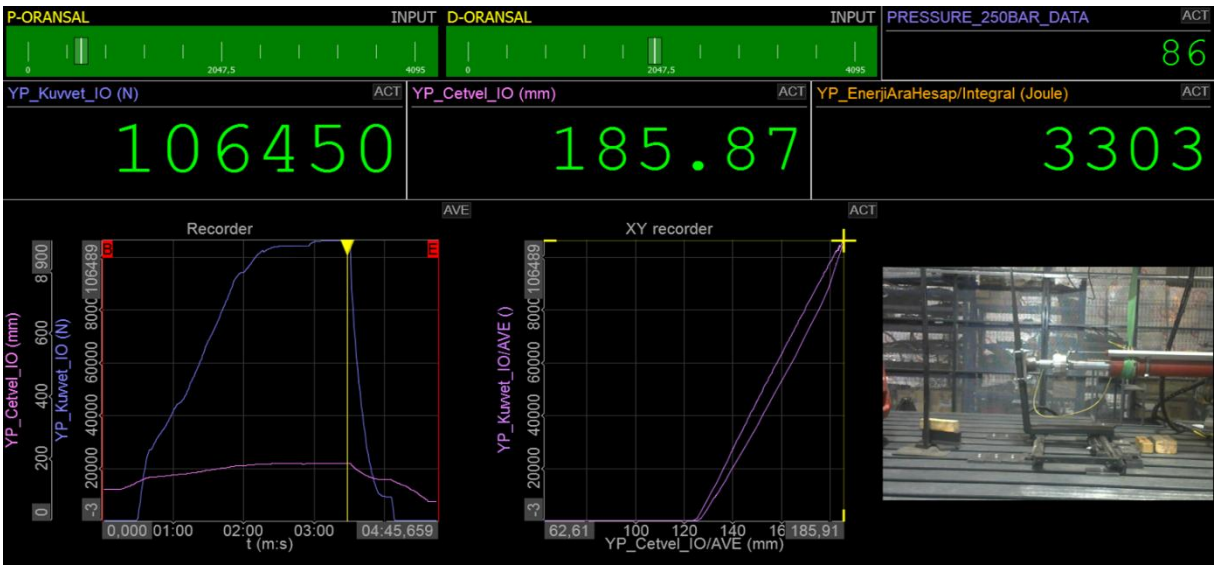

Figure 10. Dewesoft Program Control Interface

Since the test specimen is a fork used in forklifts with a nominal load capacity of 3500 kg, the relevant standard requirements specify that the static load test shall be performed under a load equivalent to three times the rated capacity. Accordingly, an equivalent load of 10,500 kg was applied to the fork during the test. The corresponding force value was determined as 106,450 N by considering the measurement accuracy of the load cell, sensor tolerances, and an additional safety margin of approximately 3.3%.
The force applied by the hydraulic actuator did not reach the target value instantaneously due to the operating characteristics of the system; instead, it increased linearly throughout the loading process until reaching the maximum force level. The time required to reach the maximum force value and the duration of maintaining this load level were evaluated using the force–time curve. This loading procedure was repeated twice. The obtained force–time graph is presented in Figure 11.

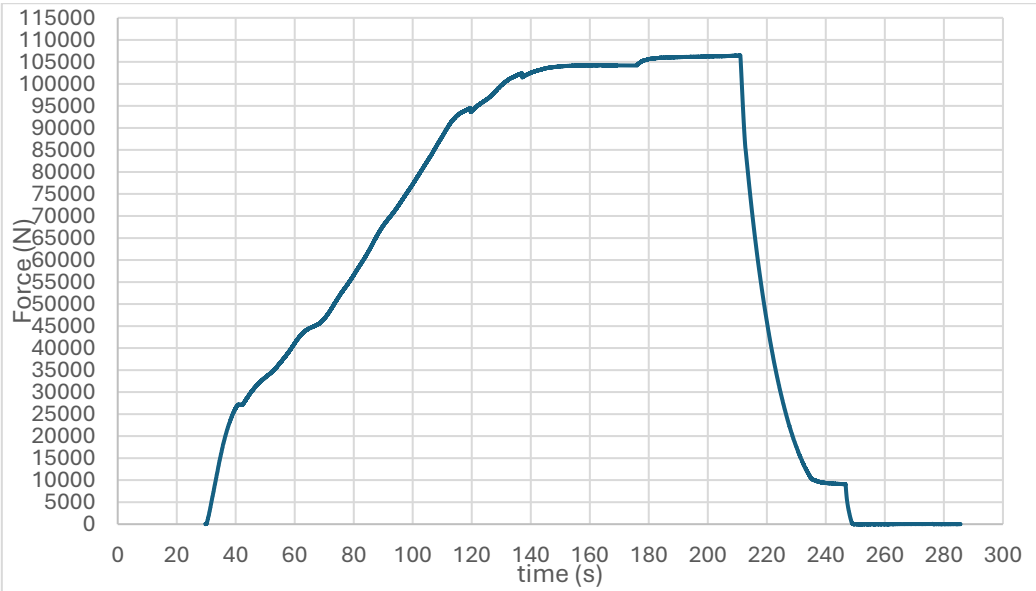

Figure 11. Force-Time Graph

As a result of the linear increase in the applied force, the deformation and displacement behavior of the fork also exhibited a linear trend. When the maximum load level was reached, a displacement of 60 mm occurred between the initial position and the maximum load condition at the load center point of D = 500 mm, according to the measurements obtained from the linear scale under the applied force. At this

location, displacement measurements were taken only at the load application point using a precision linear scale in order to maintain measurement accuracy.

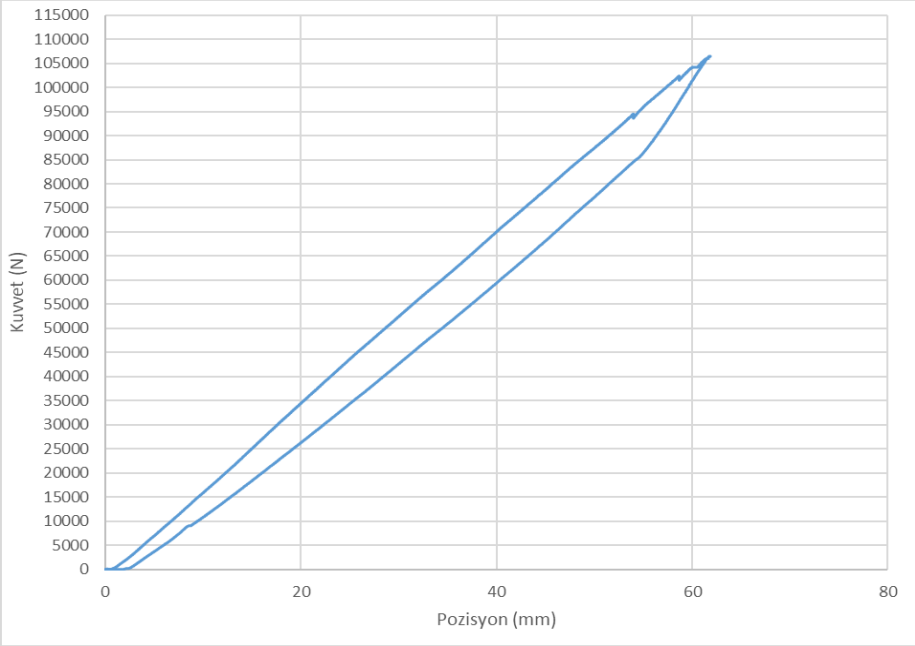

Figure 12. Force-Displacement Graph

When the maximum load level was reached, a displacement of 60 mm was measured between the initial position and the maximum load condition at the load center point of D = 500 mm under the applied force, based on the linear scale measurements (Figure 12). Within the scope of the numerical analysis, the displacement value obtained at the same loading point (D = 500 mm) was calculated as 51.99 mm (approximately 52 mm) (Figure 9). At this point, in order to maintain data reliability and measurement accuracy, the theoretical displacement at the fork tip was not estimated through extrapolation; instead, the experimental and numerical validation was directly performed based on the D = 500 mm measurement point where the displacement was obtained.

Figure 13. Fork Displacement on the Test Bench.

As a result of the evaluation of the force–displacement data, it was determined that the position value measured by the linear scale, after the applied load was completely removed and the force level returned to zero, was identical to the initial reference position. The observed 1 mm difference was considered to be within the sensor tolerance range. In other words, no permanent difference was observed between the displacement values measured before and after loading. This result indicates that the deformations occurring during the test were entirely elastic in nature and that the material returned to its original geometry after the removal of the load.

The experimental findings demonstrate that no permanent deformation, bending, or dimensional change occurred in the fork structure despite the application of the maximum test load. The displacements observed during loading remained within the elastic behavior limits of the material; upon removal of the load, the stored elastic strain energy was released, allowing the structure to return to its original position. Therefore, no residual displacement or plastic deformation was detected as a result of the test (Figure 14).

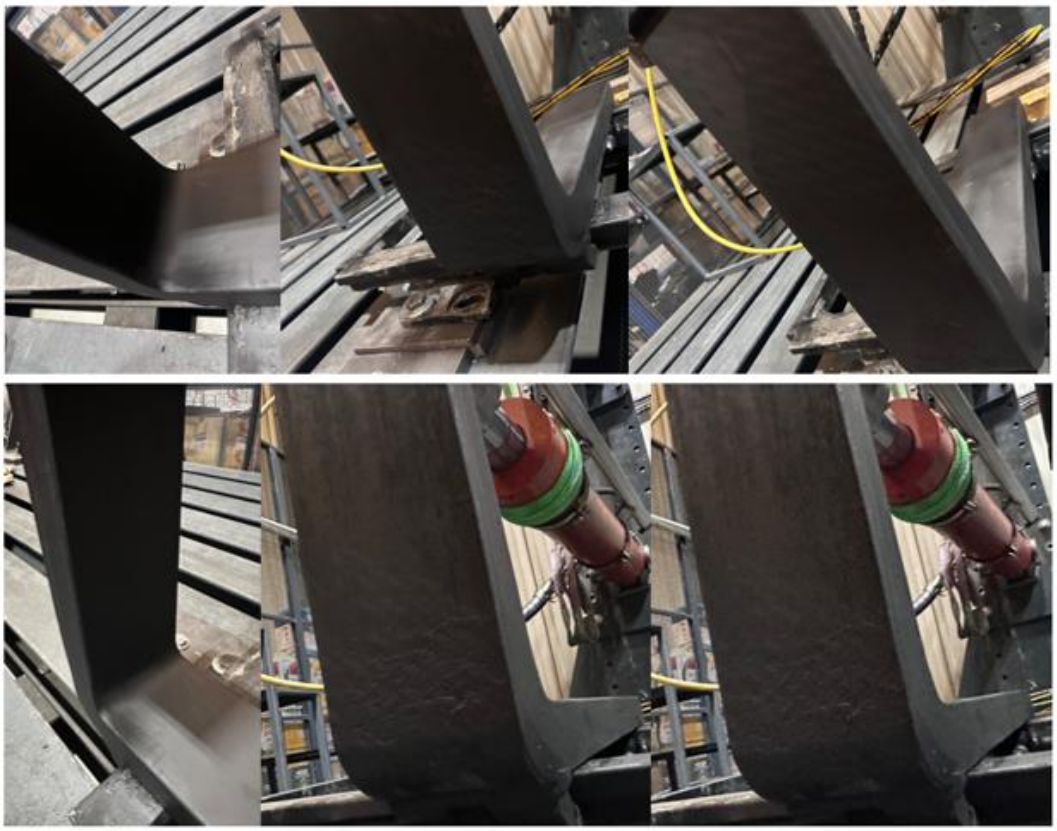

Figure 14. Post-Test Visual Inspection Procedure

The obtained results indicate that the applied load level did not exceed the yield strength of the fork and that the structural integrity was maintained. Therefore, it was concluded that the test specimen exhibited sufficient stiffness and strength under the applied static loading conditions and preserved its functional and geometrical characteristics after the removal of the load.

CONCLUSION

The evaluation of the proportional deviations between the analysis and test results not only confirmed the accuracy of the numerical model but also revealed the extent to which the material model represents actual operating conditions. The selection of an appropriate material supported by proper heat treatment processes significantly enhances the durability and impact resistance of the fork, thereby directly contributing to operational safety.

In the correlation study, the finite element analysis predicted a displacement of approximately 52 mm at the load application point of D = 500 mm, whereas a displacement of 60 mm was measured at the

same location during the physical tests. These results indicate an approximately 15% deviation between the numerical and experimental data at the load center.

The higher displacement values obtained from the experimental tests suggest that the actual material may possess a higher elastic deformation capability compared with the linear (idealized) material properties defined in the numerical model. In addition, it is considered that structural clearances and compliance within the test bench setup contributed to the measured displacement values. This additional deformation capability of the material contributes to the redistribution of stress under loading conditions and the attenuation of localized stress concentrations.

Therefore, the regions identified in the numerical analyses as areas exhibiting local yielding or the onset of deformation were observed not to produce permanent deformation at the same level during the physical tests. The experimental results demonstrate that the localized stress concentrations identified in the analyses did not reach a level that adversely affected the structural integrity, and that the actual material behavior provided additional deformation capacity in these regions, enabling a more effective redistribution of the applied loads.

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ÖĞRETMENLERİN AFET TEHDİDİ İÇİN PSİKOLOJİK HAZIRLIK DÜZEYLERİNİN *DEĞERLENDİRİLMESİ: ESKİŞEHİR İLİ ÖRNEĞİ*

EVALUATION OF TEACHERS' PSYCHOLOGICAL PREPAREDNESS LEVELS FOR DISASTER THREATS: THE CASE OF ESKIŞEHIR

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ÖZET

Bu çalışma, afet hazırlığının genellikle ihmal edilen ancak kritik bir bileşeni olan psikolojik hazırlık konusunu merkeze alarak, öğretmenlerin afet tehdidine yönelik psikolojik hazırlık düzeylerini sosyodemografik ve fiziksel çevre değişkenleri bağlamında incelemeyi amaçlamaktadır. Tanımlayıcı ve kesitsel modelde tasarlanan araştırmanın evrenini, Eskişehir ilinde görev yapan öğretmenler oluşturmaktadır. Araştırmanın verileri, basit seçkisiz örnekleme yöntemiyle ulaşılan 376 öğretmenden "Kişisel Bilgi Formu", "Çevresel ve Afet Deneyimi Değerlendirme Formu" ve "Afet Tehdidi İçin Psikolojik Hazırlık Ölçeği" kullanılarak toplanmıştır.

Elde edilen bulgulara göre, öğretmenlerin genel psikolojik hazırlık düzeyleri cinsiyet, eğitim durumu, medeni durum ve branş gibi sosyodemografik özellikler ile ev tipi ve bina yaşı gibi fiziksel niteliklere göre istatistiksel olarak anlamlı bir farklılık göstermemektedir. Bununla birlikte, 56 yaş ve üzeri bireyler ile 6-10 yıl ve 20 yıl üzeri mesleki kıdeme sahip öğretmenlerin duygusal ve psikolojik tepki yönetimi becerilerinin daha yüksek olduğu saptanmıştır. Araştırmanın en dikkat çekici bulgusu, yapısal güvenliğe yönelik algının psikolojik hazırlık üzerindeki güçlü etkisidir; yaşadığı konutun ve görev yaptığı okulun depreme dayanıklı olduğunu düşünen öğretmenlerin psikolojik hazırlık düzeyleri anlamlı derecede yüksek bulunmuştur. Ayrıca ağır afet deneyimlerinin tek başına genel hazırlık puanını artırmadığı, sadece durumsal çevre bilgisi üzerinde etkili olduğu görülmüştür.

Sonuç olarak, öğretmenlerin afet tehdidine karşı psikolojik hazırlıkları salt demografik özellikler veya doğrudan travmatik deneyimlerden ziyade; mesleki deneyim, çevresel farkındalık ve en önemlisi algılanan yapısal kurumsal güvenlik duygusuyla şekillenmektedir. Çalışma, kriz anında rehberlik rolü üstlenen öğretmenler için geliştirilecek afet müdahale programlarının bütüncül bir yaklaşımla, yapısal güvenlik algısını ve psikolojik dayanıklılığı artıracak şekilde tasarlanması gerektiğini ortaya koymaktadır.

Anahtar Kelimeler: Psikolojik Hazırlık, Öğretmenler, Afet Yönetimi, Afet Tehdidi, Yapısal Güvenlik Algısı

ABSTRACT

Focusing on psychological preparedness, which is an often neglected but critical component of disaster preparedness, this study aims to examine teachers' psychological preparedness levels for disaster threats in the context of sociodemographic and physical environment variables. The population of the research, which was designed in a descriptive and cross-sectional model, consists of teachers working in the province of Eskişehir. The research data were collected from 376 teachers, reached through the simple random sampling method, using the "Personal Information Form", "Environmental and Disaster Experience Evaluation Form", and "Psychological Preparedness for Disaster Threat Scale".

According to the findings, the general psychological preparedness levels of teachers do not show a statistically significant difference based on sociodemographic characteristics such as gender, educational status, marital status, and teaching branch, or physical attributes like house type and building age. However, it was determined that individuals aged 56 and over, as well as teachers with a professional seniority of 6-10 years and over 20 years, have higher emotional and psychological

response management skills. The most striking finding of the research is the strong effect of perceived structural safety on psychological preparedness; the psychological preparedness levels of teachers who think that their residence and the school they work in are earthquake-resistant were found to be significantly higher. Furthermore, it was observed that severe disaster experiences alone did not increase the general preparedness score, but only had an effect on the situational environment knowledge.
In conclusion, teachers' psychological preparedness against disaster threats is shaped by professional experience, environmental awareness, and most importantly, the perceived sense of structural and institutional safety, rather than merely demographic characteristics or direct traumatic experiences. The study reveals that disaster response programs to be developed for teachers, who take on a guiding role in times of crisis, should be designed with a holistic approach to increase the perception of structural safety and psychological resilience.
Keywords: Psychological Preparedness, Teachers, Disaster Management, Disaster Threat, Perceived of Structural Safety

NOT: Bu çalışma, Bilecik Şeyh Edebali Üniversitesi Lisansüstü Eğitim Enstitüsü bünyesinde yürütülen ve Ayşe Gül AKCA tarafından hazırlanan "Öğretmenlerin Afet Tehdidine Karşı Psikolojik Hazırlıklarının Bireysel Afet Direnci Üzerine Etkisi ve Fiziksel Deprem Hazır Bulunuşluk Düzeylerinin Belirlenmesi: Eskişehir İli Örneği" başlıklı yüksek lisans tezinden üretilmiştir.

GİRİŞ

Afetler, Türkiye başta olmak üzere dünya genelinde ciddi can ve mal kayıplarına yol açmasının yanı sıra bireyler ve toplumlar üzerinde kalıcı psikososyal etkiler bırakan yıkıcı olaylar olarak öne çıkmaktadır (Bıçakçı ve Ergüney Okumuş, 2023; Karancı ve İkizer, 2017). Doğal afetlerin tamamen önlenmesi mümkün olmasa da afet öncesinde geliştirilen hazırlık stratejileri ve bütüncül yaklaşımlar sayesinde bu olayların yol açtığı zararların azaltılması ve müdahale süreçlerinin daha etkin yönetilmesi mümkündür (Işık vd., 2012; Ejeta vd., 2015; İnal vd., 2019).
Bununla birlikte, mevcut uygulamaların büyük ölçüde fiziksel ve lojistik hazırlıklara odaklandığı, psikolojik hazırlık boyutunun ise çoğu zaman ihmal edildiği görülmektedir (Boylan, 2016; Roudini vd., 2017). Oysa afet anında bireylerin doğru ve hızlı kararlar verebilmesi, yalnızca mevcut fiziksel hazırlık düzeyi ile değil; aynı zamanda bilişsel farkındalıkları ve duygusal tepkilerini yönetebilme becerileri ile yakından ilişkilidir (Agarwal vd., 2020; Boylan ve Lawrence, 2020). Bu açıdan psikolojik hazırlık, afetlere karşı direnç geliştirmede temel bir bileşen olarak değerlendirilmektedir.
Afet anında yaşanan yoğun stres, korku ve belirsizlik; bireylerin karar verme, risk değerlendirme ve dikkat kapasitelerini olumsuz etkileyerek zamanında ve doğru müdahalede bulunmayı güçleştirmektedir (Boylan, 2016; Leach ve Ansell, 2008; DiTirro, 2018). Bu nedenle psikolojik hazırlık; bireyin tehdidi doğru algılaması, duygusal tepkilerini yönetebilmesi ve etkili başa çıkma stratejileri geliştirebilmesi açısından afet yönetiminin temel bir bileşeni olarak değerlendirilmektedir. Bu kapasitenin yetersizliği ise afet anında işlevsel davranışların gösterilmesini engelleyerek bireysel ve toplumsal riskleri artırmaktadır. Bu risklerin azaltılmasında toplumun temel yapı taşlarını eğiten ve kriz anında rehberlik rolü üstlenen öğretmenlerin hazırlık düzeyi önem taşımaktadır. Ayrıca öğretmenler sosyal sermayeyi, ekonomik kalkınmayı, bilgi ve iletişim ile toplumsal yeterliliğin gelişmesine katkıda bulunarak eğitim toplumunun dayanıklılığının artmasını önemli oranda desteklemektedir (Parrot, 2023). Dolayısıyla öğretmenlerin afet hazırlıkları sadece fiziksel önlemlerle sınırlandırılmadan psikolojik hazırlığında sürece dahil edilerek bütüncül bir bakış açısıyla gerçekleştirilmelidir. Literatürde yer alan çalışmalarda yüksek düzeydeki psikolojik hazırlığın daha fazla maddi hazırlık, afet sırasında daha etkili başa çıkma ve sonrasında ruh sağlığı problemi yaşama ihtimalinin azalmasıyla ilişkili olduğunu ortaya koymaktadır (Guterman 2005; Morrissey ve Reser 2003; Roudini vd. 2017). Akca (2026) tarafından öğretmenler ile yapılan çalışmada ise öğretmenlerin afet tehdidine yönelik psikolojik hazırlıklarının, bireysel afet direncini pozitif yönde ve anlamlı düzeyde artırdığı belirtilmiştir.
Atalay (2024) tarafından yapılan araştırmada da afet anında fiziksel hazırlıkların işlevsel kılınabilmesi için bireylerin psikolojik olarak da hazırlanmalarının hayati önem taşıdığı, ancak bu konunun literatürde halen yeterince ele alınmayan ve yeni gündeme gelen bir alan olduğu ifade edilmektedir. Psikolojik hazırlık literatüründe de öğretmenler örnekleminde çalışmaların sınırlı olduğu görülmektedir. Ayrıca Türkdoğan Görgün vd. (2023) çalışmalarından da anlaşılacağı üzere; yaş, cinsiyet, eğitim durumu ve

afet deneyimi gibi sosyodemografik faktörlerin bireylerin genel afet hazırlığını nasıl etkilediğine dair çeşitli araştırmalar bulunmasına rağmen, doğrudan afet tehdidine yönelik 'psikolojik hazırlık' kapasitesini etkileyen sosyodemografik belirleyicileri inceleyen çalışmalar oldukça sınırlıdır. Mevcut araştırmalar ise cinsiyet, mesleki deneyim veya geçmiş afet yaşantısı gibi değişkenlerin psikolojik hazırlık üzerindeki yordayıcı etkileri konusunda kendi içinde çelişkili bulgular sunmaktadır. Bu bağlamda, psikolojik hazırlığı şekillendiren sosyodemografik faktörlerin kapsamlı ve bütüncül bir biçimde ele alınmasına ihtiyaç duyulmaktadır. Bu çalışma, literatürdeki bu boşluğu doldurarak öğretmenlerin psikolojik hazırlık düzeylerini farklı değişkenler açısından incelemeyi amaçlamaktadır. Bu kapsamda şu hipotezler test edilmiştir:

H1: Öğretmenlerin afet tehdidine yönelik psikolojik hazırlık düzeyleri sosyodemografik (yaş, cinsiyet, medeni durum vb.) ve mesleki özelliklerine (branş, hizmet süresi vb.) göre anlamlı farklılık göstermektedir.

H2: Öğretmenlerin afet tehdidine yönelik psikolojik hazırlık düzeyleri konut ve fiziksel çevre özellikleri (yaşanılan ev tipi, binanın yaşı, mülkiyet durumu vb.*)* değişkenlerine göre farklılaşmaktadır.

H3: Öğretmenlerin afet tehdidine yönelik psikolojik hazırlık düzeyleri, afet deneyim özelliği (afete maruz kalma, afette evin yıkılması, yakınını kaybetme vb.*)* değişkenlerine göre anlamlı bir farklılık göstermektedir.

Sonuç olarak, bu araştırmanın öğretmenlerin psikolojik hazırlık düzeylerini sosyodemografik değişkenler açısından inceleyerek literatürdeki boşluğu doldurması ve bu alanda geliştirilecek eğitim ve müdahale programlarına bilimsel katkı sağlaması amaçlanmaktadır.

YÖNTEM

Araştırma Modeli ve Amacı

Bu çalışma, öğretmenlerin sosyo-demografik özellikleri bakımından afet tehdidine yönelik psikolojik hazırlık düzeylerinin farklılık gösterip göstermediğini incelemek amacıyla gerçekleştirilen tanımlayıcı ve kesitsel bir araştırmadır. Literatürde afet hazırlığı çalışmalarının çoğunlukla fiziksel hazırlık boyutuna odaklandığı, psikolojik hazırlığın ise yeterince ele alınmadığı görülmektedir. Ayrıca mevcut çalışmaların genellikle toplum geneline odaklandığı, öğretmenleri merkeze alan araştırmaların sınırlı olduğu dikkat çekmektedir. Bu çalışma ile öğretmenler özelinde psikolojik hazırlık düzeylerinin incelenerek literatürdeki bu boşluğa katkı sağlanması amaçlanmaktadır.

Evren ve Örneklem

Araştırmanın evrenini, 2022–2023 eğitim-öğretim yılı verilerine göre Eskişehir ilinde görev yapan toplam 12.317 öğretmen oluşturmaktadır (MEB, 2024). Örneklemin belirlenmesinde olasılık temelli örnekleme yöntemlerinden basit seçkisiz örnekleme yöntemi kullanılmıştır (Büyüköztürk vd., 2017).

Araştırma kapsamında Şubat–Mart 2025 tarihleri arasında veri toplama süreci yürütülmüş ve yüz yüze ile çevrim içi yöntemlerle toplam 389 öğretmene ulaşılmıştır. Eksik doldurulan 13 anket çalışma dışında bırakılmış ve analizler 376 öğretmen üzerinden gerçekleştirilmiştir. Örneklem büyüklüğünün belirlenmesinde Karasar (2014) tarafından önerilen formül esas alınmıştır.

Veri Toplama Araçları

Araştırmada veriler; Kişisel Bilgi Formu, Çevresel Değerlendirme Formu ve Afet Tehdidi İçin Psikolojik Hazırlık Ölçeği (ATPHÖ) kullanılarak toplanmıştır.

Çalışmada öğretmenlerin psikolojik hazırlık düzeylerini ölçmek amacıyla, Zulch (2019) tarafından geliştirilen ve 26 madde ile dört alt boyuttan oluşan Psychological Preparedness for Disaster Threat Scale (PPDTS-26) kullanılmıştır. Ölçek, Görgün vd. (2023) tarafından Türkçe'ye uyarlanmış ve geçerlilik-güvenirlik çalışmaları yapılmıştır.

Uyarlama sonrasında ölçek, Dış Durumsal Çevrenin Bilgisi ve Yönetimi (9 madde), Duygusal ve Psikolojik Tepkilerin Yönetimi (9 madde) ve Sosyal Çevrenin Yönetimi (3 madde) olmak üzere üç alt boyuttan ve toplam 21 maddeden oluşmaktadır. Ölçek, 4'lü Likert tipinde derecelendirilmekte olup (1=Kesinlikle Katılmıyorum, 4=Kesinlikle Katılıyorum), elde edilen yüksek puanlar afet tehdidine yönelik daha yüksek psikolojik hazırlık düzeyini ifade etmektedir.

Türkçe formun güvenirlik analizleri sonucunda Cronbach's Alpha katsayısı toplam ölçek için 0,95 olarak bulunmuş; alt boyutlara ilişkin güvenirlik katsayıları ise sırasıyla 0,91, 0,93 ve 0,83 olarak rapor edilmiştir.

Veri Analizi

Verilerin analizi SPSS 31.0 programı kullanılarak gerçekleştirilmiştir. Tanımlayıcı istatistikler frekans, yüzde, ortalama ve standart sapma değerleri ile sunulmuştur. Ölçeğin geçerliliği Açımlayıcı Faktör Analizi ile, güvenirliği ise Cronbach alfa katsayısı ile değerlendirilmiştir. Normal dağılım gösteren değişkenlerin iki grup karşılaştırmalarında Bağımsız Örneklem t testi, üç ve daha fazla grup karşılaştırmalarında Tek Yönlü Varyans Analizi (ANOVA) kullanılmıştır. Anlamlı bulunan durumlarda post hoc analizler uygulanmıştır. $p < 0,05$ istatistiksel olarak anlamlı kabul edilmiştir.

Sınırlılıklar

Araştırmanın yalnızca Eskişehir ilinde görev yapan öğretmenler ile yürütülmesi, bulguların genellenebilirliğini sınırlamaktadır. Farklı sosyo-kültürel özelliklere sahip bölgelerde yapılacak çalışmalar farklı sonuçlar ortaya koyabilir. Ayrıca verilerin öz-bildirim yöntemine dayalı olarak toplanması, katılımcıların yanıtlarında önyargı veya sosyal beğenirlik etkisinin bulunma olasılığını artırmaktadır. Katılımcıların veri toplama sürecindeki ruh halleri ve çevresel faktörler de elde edilen sonuçları etkileyebilecek diğer sınırlılıklar arasında yer almaktadır.

BULGULAR

Öğretmenlerin Bireysel ve Sosyo-Demografik Özelliklerine İlişkin Veriler

Tablo 1'de öğretmenlerin bireysel ve sosyo-demografik özelliklerine ilişkin veriler sunulmuştur.

Tablo 1. Öğretmenlerin Bireysel ve Sosyo-Demografik Özelliklerine İlişkin Veriler

Değişkenler		n	%
Cinsiyet	Kadın	235	62,5
	Erkek	141	37,5
Yaş	20-35 Yaş	55	14,6
	36-45 yaş	174	46,3
	46-55 Yaş	118	31,4
	56 yaş ve üzeri	29	7,7
Eğitim düzeyi	Ön Lisans/Lisans	284	75,5
	Lisans üstü	92	24,5
Medeni durum	Bekar	50	13,3
	Evli	299	79,5
	Boşanmış/Dul	27	7,2
Aylık gelir durumu	30.000-45.000 TL	13	3,5
	46.000-55.000 TL	80	21,3
	56.000-65.000 TL	189	50,3
	66.000-75.000 TL	69	18,4
	76.000 ve üzeri	25	6,6
Hane halkı sayısı	1-2 kişi	64	17,0
	3-4 kişi	278	73,9
	5 ve üzeri	34	9,0
Çevrenizdeki ekonomik seviye	Çok düşük	16	4,3
	Düşük	68	18,1
	Orta	242	64,4
	Yüksek	50	13,3
	Çok Yüksek	0	0,0
Branş	Sayısal-fen grubu	56	14,9
	Sözel-sosyal grubu	96	25,5

	Mesleki eğitim grubu	55	14,6
	Sanat, spor ve tasarım grubu	27	7,2
	Temel eğitim grubu	142	37,8
Hizmet süresi	0-5 Yıl	14	3,7
	6-10 Yıl	34	9,0
	11-15 Yıl	103	27,4
	16-20 Yıl	77	20,5
	20 Yıl ve üzeri	148	39,4
	Toplam	**376**	**100**

Çalışmaya katılan 376 öğretmenin büyük çoğunluğunu kadınlar (%62,5) oluştururken, erkeklerin oranı %37,5'tir. Katılımcıların yaş dağılımında en yüksek pay %46,3 ile 36–45 yaş grubuna ait olup, bunu %31,4 ile 46–55 yaş grubu izlemektedir. Öğretmenlerin %14,6'sı 20–35 yaş, %7,7'si ise 56 yaş ve üzerindedir. Eğitim düzeyi bakımından katılımcıların %75,5'i ön lisans/lisans, %24,5'i ise lisansüstü eğitim mezunudur. Medeni durum açısından öğretmenlerin %79,5'i evli, %13,3'ü bekâr ve %7,2'si boşanmış veya duldur.

Katılımcıların gelir dağılımında en büyük grubu %50,3 ile 56.000–65.000 TL gelir aralığında bulunan öğretmenler oluştururken, bunu %21,3 ile 46.000–55.000 TL ve %18,4 ile 66.000–75.000 TL gelir grupları izlemektedir. Öğretmenlerin büyük çoğunluğu (%73,9) 3–4 kişilik hanelerde yaşarken, %17'si 1–2 kişilik, %9'u ise 5 ve üzeri kişiden oluşan hanelerde yaşamaktadır.

Çevresel ekonomik seviye algısı incelendiğinde, katılımcıların çoğunluğu çevrelerini orta düzeyde (%64,4) olarak değerlendirmiş; düşük (%18,1) ve çok düşük (%4,3) algılar daha sınırlı düzeyde kalırken, yüksek düzey algısı %13,3 olarak belirlenmiştir. Branş dağılımında temel eğitim öğretmenleri (%37,8) en yüksek orana sahip olup, bunu sözel-sosyal (%25,5), sayısal-fen (%14,9), mesleki eğitim (%14,6) ve sanat-spor-tasarım (%7,2) alanları takip etmektedir.

Mesleki deneyim açısından öğretmenlerin %39,4'ü 20 yıl ve üzeri hizmet süresine sahip olup, bunu %27,4 ile 11–15 yıl ve %20,5 ile 16–20 yıl deneyime sahip öğretmenler izlemektedir.

Tablo 2'de öğretmenlerin yaşadıkları konutların fiziksel özellikleri ve yapı güvenliğine ilişkin görüşleri sunulmuştur.

Tablo 2. Öğretmenlerin Yaşadıkları Konutların Fiziksel Özellikleri ve Yapı Güvenliğine İlişkin Görüşleri

Değişkenler		n	%
Yaşanılan ev tipi	Apartman dairesi	267	71,0
	Müstakil ev	31	8,2
	Site İçinde daire	70	18,6
	Diğer-Lojman	8	2,1
Ev sahipliği durumu	Kiracı	83	22,1
	Ev sahibi	278	73,9
	Aile yanında	15	4,0
Yaşanılan binanın yaşı	0-5 yıl	62	16,5
	6-10 yıl	97	25,8
	11-15 yıl	93	24,7
	16 yıl ve üzeri	124	33,0
Yaşanılan binada ikamet üresi	0-5 yıl	151	40,2
	6-10 yıl	97	25,8
	11-15 yıl	81	21,5
	16 yıl ve üzeri	47	12,5
Yaşanılan binanın depreme dayanıklılık durumu	Bilmiyorum	154	41,0
	Dayanıklı	210	55,9
	Dayanıklı değil	12	3,2
	Evet	211	56,1

Görev yapılan okulun depreme dayanıklılığı	Hayır	165	43,9
	Toplam	**376**	**100**

Tabloya göre öğretmenlerin büyük çoğunluğu apartman dairesinde (%71,0) yaşamakta iken %18,6'sı site içi dairelerde, %8,2'si müstakil evlerde ve %2,1'i diğer konut türlerinde ikamet etmektedir. Katılımcıların %73,9'u ev sahibi, %22,1'i kiracı ve %4,0'ı aile yanında yaşamaktadır.
Yaşanılan binaların çoğunluğunu 16 yıl ve üzeri yapılar (%33,0) oluştururken, bunu 6–10 yıl (%25,8), 11–15 yıl (%24,7) ve 0–5 yıl (%16,5) yaşındaki binalar izlemektedir. Aynı binada ikamet süresi bakımından öğretmenlerin %40,2'si 0–5 yıldır, %25,8'i 6–10 yıldır yaşamaktadır.
Depreme dayanıklılık algısı incelendiğinde, katılımcıların %55,9'u yaşadığı binayı depreme dayanıklı olarak değerlendirirken, %41,0'ı bu konuda bilgi sahibi olmadığını belirtmiştir. Görev yapılan okullar açısından ise öğretmenlerin %56,1'i okullarının depreme dayanıklı olduğunu, %43,9'u ise dayanıklı olmadığını düşünmektedir.
Tablo 3'te öğretmenlerin afet deneyimlerine ve bu bağlamdaki risk durumlarına ilişkin görüşleri yer almaktadır.

Tablo 3. Öğretmenlerin Afet Deneyimlerine ve Bu Bağlamdaki Risk Durumlarına İlişkin Görüşleri

Değişkenler		n	%
Afete maruz kalma	Evet	135	35,9
	Hayır	241	64,1
Afette evin yıkılması	Evet	9	2,4
	Hayır	367	97,6
Afette kendisinin/yakının enkaz altında kalma durumu	Evet	20	5,3
	Hayır	356	94,7
Çadır veya konteynerda kalma durumu	Evet	18	4,8
	Hayır	358	95,2
Depremde yakını kaybetme durumu	Evet	22	5,9
	Hayır	354	94,1
	Toplam	**376**	**100**

Öğretmenlerin %35,9'u geçmişte en az bir kez afet deneyimi yaşadığını, %64,1'i ise herhangi bir afete maruz kalmadığını belirtmiştir. Afet nedeniyle yaşanılan evin yıkılması (%2,4), enkaz altında kalma veya yakınının enkaz altında kalması (%5,3), depremde yakın kaybı yaşama (%5,9) ve çadır ya da konteynerde geçici barınma deneyimi (%4,8) gibi doğrudan afet etkilerine maruz kalma oranlarının oldukça düşük düzeyde olduğu görülmektedir.

Öğretmenlere Uygulanan Afet Tehdidi İçin Psikolojik Hazırlık Ölçeği'nin (ATPHÖ) Betimleyici İstatistikleri ile Geçerlilik ve Güvenirlik Bulguları

Öğretmenlere uygulanan afet tehdidi için psikolojik hazırlık ölçeği'nin betimleyici istatistikleri ile geçerlilik ve güvenirlik bulguları Tablo 4'te sunulmuştur.

Tablo 4. Afet Tehdidi İçin Psikolojik Hazırlık Ölçeği'nin (ATPHÖ) Betimleyici İstatistikleri, Geçerlilik ve Güvenirlik Analizi Sonuçları

Ölçek ve alt faktörler	Ort. ± S.S	Min. - Max.	Skewness ± S.H	Kurtosis ± S.H	Cronbach's Alpha
Afet Tehdidi İçin Psikolojik Hazırlık Ölçeği (ATPHÖ)	2,99±0,51	1-4	-0,25±0,13	0,76±0,25	0,940
Dış durumsal çevre bilgisi ve yönetimi	3,09±0,55	1-4	-0,45±0,13	0,75±0,25	0,910

Duygusal Psikolojik Tepki Yönetimi	2,91±0,61	1-4	-0,35±0,13	0,59±0,25	0,952

Ort.: Ortalama, S.S.: Standart Sapma, Min.: Minimum, Max.: Maximum; S.H.: Standart Hata.

Afet Tehdidi İçin Psikolojik Hazırlık Ölçeği toplam puan ortalaması 2,99 ± 0,51 olup, öğretmenlerin psikolojik hazırlık düzeylerinin orta seviyede olduğu görülmektedir. Alt boyutlar incelendiğinde, Dış Durumsal Çevre Bilgisi ve Yönetimi puanı 3,09 ± 0,55 ile görece daha yüksek bulunurken, Duygusal Psikolojik Tepki Yönetimi puanı 2,91 ± 0,61 olarak belirlenmiş ve bu boyutta da orta düzeyde bir hazırlığa işaret etmiştir.

Afet Tehdidi İçin Psikolojik Hazırlık Ölçeği (ATPHÖ) ve alt boyutlarına ait çarpıklık ve basıklık değerleri incelendiğinde, tüm değerlerin ±1,96 sınırları içerisinde yer aldığı belirlenmiştir. Elde edilen bu sonuçlar, ATPHÖ ve alt boyut puanlarının normal dağılım varsayımını karşıladığını göstermektedir (Kalaycı, 2005).

Tablo 4.7. Afet Tehdidi İçin Psikolojik Hazırlık Ölçeği (ATPHÖ) Alt Boyutlarına Ait Cronbach's Alpha Güvenirlik Katsayıları

Ölçek	Alt Boyut	Cronbach's Alpha	Standartlaştırılmış Cronbach's Alpha	Madde Sayısı
Afet Tehdidi İçin Psikolojik Hazırlık	Dış Durumsal Çevre Bilgisi	0,909	0,910	9
	Duygusal Psikolojik Tepki Yönetimi	0,949	0,949	9
	Sosyal Çevre Yönetimi	0,897	0,897	2
	Genel	0,944	0,944	20

Afet Tehdidine Karşı Psikolojik Hazırlık Ölçeği Sosyal Çevre Yönetimi alt boyutuna ait Cronbach's Alpha değeri 0,949 olarak hesaplanmıştır.

Ancak Sosyal Çevre Yönetimi alt faktörü altında yer alan 21 numaralı soruya Cronbach's Alpha değeri ait olduğu alt boyutun Cronbach's Alpha değerinden büyük bulunması nedeniyle ilgili soru ölçekten çıkarılarak analiz tekrarlanmıştır. Yapılan yeniden analiz sonucunda ölçeğe ait Cronbach's Alpha ve standartlaştırılmış Cronbach's Alpha değerleri 0,897 olarak hesaplanmıştır. Sonuç olarak elde edilen güvenirlik katsayıları, ölçeklerin ve alt boyutlarının kabul edilebilir iç tutarlılığa sahip olduğunu göstermektedir.

Ölçeğin yapı geçerliliğini incelemek amacıyla açımlayıcı faktör analizi (AFA) uygulanmıştır. Faktör analizine uygunluk Kaiser-Meyer-Olkin (KMO) örneklem yeterlilik testi ve Bartlett Küresellik Testi ile değerlendirilmiştir. KMO değerinin 0,60'ın üzerinde olması ve Bartlett testinin istatistiksel olarak anlamlı bulunması ($p<0,05$) analiz için uygunluk kriteri olarak kabul edilmiştir.

Faktör yapısının belirlenmesinde Temel Bileşenler Analizi (Principal Component Analysis) yöntemi kullanılmış ve yorumlanabilirliğini artırmak amacıyla Varimax rotasyonu uygulanmıştır. Faktör sayısının belirlenmesinde özdeğerin 1'in üzerinde olması kriteri esas alınmıştır. Maddelerin faktör yüklerinin en az 0,40 olması kabul edilmiş, bu değerin altında kalan veya birden fazla faktörde yüksek yük alan maddeler analizden çıkarılmıştır.

Afet Tehdidi İçin Psikolojik Hazırlık Ölçeği'nin orijinal formu üç alt boyuttan oluşmaktadır. Bu çalışmada gerçekleştirilen Açımlayıcı Faktör Analizi (AFA) sonucunda, yapılan analizlerde ölçeğin iki faktörlü bir yapı sergilediği görülmüştür. Nihai formda ölçek toplam 20 maddeden oluşmuş; 1–9. maddeler Dış Durumsal Çevre Bilgisi ve Yönetimi, 10–20. maddeler ise Kişinin Duygusal ve Psikolojik Tepkisinin Yönetimi alt boyutunu oluşturmuştur. Böylece ölçeğin orijinal üç boyutlu yapısı, bu çalışma örnekleminde iki boyutlu bir yapı olarak doğrulanmıştır. KMO değeri 0,945 olarak bulunmuş ve Bartlett testi anlamlı sonuç vermiştir ($p<0,001$). Toplam açıklanan varyans ise %64,009'dur. Cronbach's Alpha katsayıları ölçek için 0,940 iken alt boyutlar için sırasıyla 0,910 ve 0,952 olarak hesaplanmıştır.

Öğretmenlerin Afet Tehdidi İçin Psikolojik Hazırlık Düzeylerinin Sosyodemografik Değişkenlere Göre Değerlendirilmesi

Tablo 5'te Öğretmenlerin sosyodemografik ve mesleki özellik değişkenlerine göre Afet Tehdidi İçin Psikolojik Hazırlık (ATPHÖ) ve alt boyutları puanlarının karşılaştırılması gerçekleştirilmiştir.

Tablo 5. Öğretmenlerin Sosyodemografik ve Mesleki Özellik değişkenlerine Göre Afet Tehdidi İçin Psikolojik Hazırlık (ATPHÖ) Ölçeği ve Alt Boyut Puanlarının Karşılaştırılması

Değişken	Grup	n	ATPHÖ (Ort± SS)	t/z	p	Dış durumsal çevre bilgisi ve yönetimi	t/z	p	Duygusal Psikolojik Tepki Yönetimi	t/z	p
Cinsiyet	Kadın	235	2,96±0,51	-1,39	0,166	3,08±0,55	-0,67	0,504	2,87±0,62	-1,62	0,105
	Erkek	141	3,04±0,52			3,12±0,57			2,98±0,59		
Yaş	20–35[A]	55	2,99±0,51	1,999	0,114	3,12±0,64	0,495	0,686	2,87±0,60	2,878	**0,036***
	36–45[B]	174	2,95±0,52			3,06±0,53			2,85±0,63	**D>A, B,C**	
	46–55[C]	118	3,01±0,51			3,09±0,55			2,95±0,60		
	≥56[D]	29	3,19±0,46			3,19±0,54			3,19±0,45		
Eğitim	Ön lisans/lisans	284	3,00±0,51	0,35	0,727	3,10±0,54	0,33	0,738	2,92±0,60	0,29	0,776
	Lisansüstü	92	2,98±0,52			3,07±0,60			2,90±0,65		
Medeni durum	Bekar	50	2,93±0,61	0,439	0,645	2,98±0,64	1,29	0,276	2,89±0,67	0,032	0,968
	Evli	299	3,00±0,49			3,11±0,53			2,91±0,60		
	Boşanmış/ Dul	27	2,99±0,58			3,08±0,61			2,92±0,65		
Aylık gelir	30–45 bin[A]	13	2,93±0,53	1,154	0,331	2,77±0,53	2,813	**0,025***	3,06±0,78	0,773	0,544
	46–55 bin[B]	80	2,92±0,53			3,03±0,61	D>B, C>A		2,83±0,66		
	56–65 bin[C]	189	3,00±0,50			3,09±0,53			2,93±0,57		
	66–75 bin[D]	69	3,08±0,51			3,24±0,54			2,95±0,62		
	≥76 binE	25	2,90±0,51			3,00±0,46			2,83±0,63		
Hane halkı	1–2 kişi	64	3,06±0,48	1,004	0,367	3,08±0,52	0,18	0,836	3,04±0,56	2,154	0,118
	3–4 kişi	278	2,97±0,52			3,09±0,56			2,87±0,62		

	≥5 kişi	34	3,05±0,49			3,14±0,54			2,97±0,63		
Ekonomik seviye	Çok düşük	16	2,76±0,63	2,193	0,088	2,86±0,66	2,09	0,101	2,68±0,70	1,478	0,22
	Düşük	68	2,91±0,55			3,00±0,58			2,83±0,62		
	Orta	242	3,02±0,49			3,11±0,54			2,94±0,58		
	Yüksek	50	3,05±0,52			3,18±0,54			2,95±0,70		
Branş	Sayısal	56	2,88±0,44	1,209	0,306	3,03±0,56	0,731	0,571	2,75±0,47	1,57	0,182
	Sözel	96	2,96±0,46			3,06±0,55			2,89±0,54		
	Mesleki	55	3,01±0,59			3,07±0,54			2,95±0,72		
	Sanat	27	3,05±0,57			3,05±0,64			3,05±0,58		
	Temel eğitim	142	3,04±0,52			3,15±0,54			2,95±0,66		
Hizmet süresi	0–5 yıl[A]	14	2,80±0,60	2,788	0,026*	2,89±0,57	1,648	0,162	2,72±0,71	2,681	0,031*
	6–10 yıl[B]	34	3,15±0,50	B,E>A,C		3,19±0,66			3,11±0,60	B,E>A,C	
	11–15 yıl[C]	103	2,90±0,39			3,03±0,48			2,79±0,49		
	16–20 yıl[D]	77	2,96±0,63			3,04±0,62			2,89±0,73		
	≥20 yıl[E]	148	3,06±0,50			3,15±0,53			2,98±0,60		

Not: Veriler ortalama ± standart sapma (SS) ve medyan (minimum–maksimum) olarak sunulmuştur. İki grup karşılaştırmalarında bağımsız örneklem t testi, üç ve daha fazla grup karşılaştırmalarında ise Tek Yönlü Varyans Analizi (ANOVA) kullanılmıştır. Anlamlı bulunan durumlarda post hoc analizler uygulanmıştır. Farklı üst simgeler (a, b, c) gruplar arasındaki anlamlı farkı göstermektedir. $p < 0,05$ istatistiksel olarak anlamlı kabul edilmiştir.

Bu çalışmada öğretmenlerin afet tehdidine yönelik psikolojik hazırlık düzeyleri (ATPHÖ) ile alt boyutları olan dış durumsal çevre bilgisi ve yönetimi ile duygusal-psikolojik tepki yönetimi, çeşitli sosyodemografik ve mesleki değişkenler açısından incelenmiştir. Cinsiyet değişkenine göre yapılan analizlerde kadın ve erkek katılımcılar arasında ATPHÖ toplam puanı (p=0,166), dış durumsal çevre bilgisi ve yönetimi (p=0,504) ve duygusal-psikolojik tepki yönetimi (p=0,105) açısından istatistiksel olarak anlamlı bir fark bulunmamıştır (p>0,05). Bu bulgu, psikolojik hazırlık düzeyinin cinsiyetten bağımsız olduğunu göstermektedir.

Yaş gruplarına göre yapılan değerlendirmede ATPHÖ toplam puanı (p=0,114) ve dış durumsal çevre bilgisi ve yönetimi (p=0,686) açısından anlamlı fark saptanmazken, duygusal-psikolojik tepki yönetimi alt boyutunda istatistiksel olarak anlamlı fark bulunmuştur (p=0,036). İleri analizlerde ≥56 yaş grubunun diğer yaş gruplarına göre daha yüksek puanlara sahip olduğu belirlenmiştir (D>A,B,C). Bu durum, yaş ilerledikçe bireylerin duygusal baş etme becerilerinin arttığını düşündürmektedir.

Eğitim düzeyine göre yapılan analizlerde ön lisans/lisans ve lisansüstü mezunlar arasında ATPHÖ toplam puanı (p=0,727), dış çevre bilgisi (p=0,738) ve duygusal tepki yönetimi (p=0,776) açısından anlamlı fark bulunmamıştır.

Benzer şekilde medeni durum değişkenine göre de bekar, evli ve boşanmış/dul gruplar arasında tüm alt boyutlarda anlamlı farklılık saptanmamıştır (p>0,05). Bu bulgular, eğitim düzeyi ve medeni durumun psikolojik hazırlık üzerinde belirleyici olmadığını göstermektedir.

Aylık gelir düzeyine göre yapılan analizlerde ATPHÖ toplam puanı (p=0,331) ve duygusal-psikolojik tepki yönetimi (p=0,544) açısından anlamlı fark bulunmazken, dış durumsal çevre bilgisi ve yönetimi alt boyutunda anlamlı farklılık saptanmıştır (p=0,025). Post-hoc analizlerde özellikle daha yüksek gelir grubunda yer alan bireylerin düşük gelir grubuna göre daha yüksek puanlara sahip olduğu görülmüştür. Bu durum, ekonomik düzey arttıkça bireylerin çevresel farkındalıklarının ve bilgiye erişimlerinin arttığını düşündürmektedir.

Hane halkı büyüklüğüne göre yapılan analizlerde ATPHÖ toplam puanı (p=0,367), dış çevre bilgisi (p=0,836) ve duygusal tepki yönetimi (p=0,118) açısından anlamlı fark bulunmamıştır. Aynı şekilde algılanan ekonomik seviyeye göre yapılan değerlendirmede de tüm alt boyutlarda istatistiksel olarak anlamlı farklılık saptanmamıştır (p>0,05). Bu durum, nesnel gelir değişkeni etkili iken, bireyin algıladığı ekonomik durumun psikolojik hazırlık üzerinde belirleyici olmadığını göstermektedir.

Branş değişkenine göre yapılan analizlerde sayısal, sözel, mesleki, sanat ve temel eğitim öğretmenleri arasında ATPHÖ toplam puanı (p=0,306), dış çevre bilgisi (p=0,571) ve duygusal tepki yönetimi (p=0,182) açısından anlamlı fark bulunmamıştır. Bu bulgu, öğretmenlerin branşlarının psikolojik hazırlık düzeyi üzerinde etkili olmadığını göstermektedir.

Hizmet süresine göre yapılan analizlerde ATPHÖ toplam puanı (p=0,026) ve duygusal-psikolojik tepki yönetimi (p=0,031) açısından istatistiksel olarak anlamlı fark bulunmuştur. İleri analizlerde özellikle 6–10 yıl ve ≥20 yıl hizmet süresine sahip bireylerin, 0–5 yıl ve 11–15 yıl gruplarına göre daha yüksek puanlara sahip olduğu belirlenmiştir (B,E>A,C). Buna karşın dış durumsal çevre bilgisi ve yönetimi alt boyutunda anlamlı fark saptanmamıştır (p=0,162). Bu bulgular, mesleki deneyimin artmasının psikolojik hazırlık ve duygusal baş etme becerilerini artırdığını, ancak bu ilişkinin doğrusal olmadığını göstermektedir.

Genel olarak değerlendirildiğinde, afet tehdidine yönelik psikolojik hazırlığın büyük ölçüde yaş, gelir düzeyi ve mesleki deneyim gibi faktörlerle ilişkili olduğu; buna karşın cinsiyet, eğitim düzeyi, medeni durum ve branş gibi temel sosyodemografik değişkenlerin belirleyici olmadığı görülmektedir. Bu sonuçlar, psikolojik hazırlığın daha çok deneyim ve kaynaklara erişimle ilişkili dinamik bir yapı olduğunu ortaya koymaktadır.

Tablo 6'da Öğretmenlerin konut ve fiziksel çevre özelliklerine göre Afet Tehdidi İçin Psikolojik Hazırlık (ATPHÖ) ve Alt Boyutları puanlarının karşılaştırılması gerçekleştirilmiştir.

Tablo 6. Öğretmenlerin Konut ve Fiziksel Çevre Özellikleri Değişkenlerine Göre Afet Tehdidi İçin Psikolojik Hazırlık (ATPHÖ) Ölçeği ve Alt Boyut Puanlarının Karşılaştırılması

Değişken	Grup	n	ATPHÖ (Ort±SS)	t/z	p	Dış durumsal çevre bilgisi ve yönetimi	t/z	p	Duygusal Psikolojik Tepki Yönetimi	t/z	p
Ev tipi	Apartman	267	2,98±0,51	0,426	0,735	3,10±0,53	0,138	0,937	2,89±0,62	1,073	0,361
	Müstakil	31	3,01±0,63			3,03±0,68			2,99±0,68		
	Site	70	3,04±0,44			3,10±0,57			2,99±0,49		
	Lojman	8	2,86±0,77			3,06±0,63			2,69±0,97		
Ev sahipliği	Kiracı	83	3,01±0,50	0,174	0,841	3,14±0,48	0,437	0,646	2,91±0,62	0,217	0,805
	Ev sahibi	278	2,99±0,50			3,08±0,57			2,92±0,59		
	Aile yanında	15	2,93±0,72			3,07±0,63			2,81±0,84		

Bina yaşı	0–5 yıl	629	3,03±0,44	0,204	0,894	3,10±0,53	0,623	0,6	2,97±0,51	0,607	0,611
	6–10 yıl	97	2,98±0,45			3,14±0,52			2,85±0,58		
	≥16 yıl	124	2,98±0,58			3,04±0,59			2,93±0,64		
Yaşanılan Binada İkamet Süresi	0-5 yıl	151	2,95±0,52	1,697	0,167	3,05±0,56	1,633	0,181	2,86±0,61	1,332	0,264
	6-10 yıl	97	3,02±0,46			3,15±0,56			2,91±0,57		
	11-15 yıl	81	3,08±0,5			3,16±0,52			3,02±0,6		
	16 yıl ve üzeri	47	2,92±0,58			2,99±0,58			2,86±0,69		
Yaşanılan Binanın Depreme Dayanıklılığı	Bilmiyorum	154	2,88±0,49	9,089	**0,000 ****	2,97±0,51	7,057	**0,001 ****	2,81±0,62	7,188	**0,001 ****
	Dayanıklı	210	3,09±0,48	**B> A, C**		3,18±0,56	**B > A**		3,01±0,56	**B> A, C**	
	Dayanıksız	12	2,74±0,80			2,96±0,72			2,55±0,98		
Okul dayanıklılığı	Evet	211	3,07±0,50	3,334	**0,001 ****	3,15±0,58	2,414	**0,016 ***	3,00±0,58	3,305	**0,001 ****
	Hayır	165	2,89±0,51			3,01±0,51			2,80±0,63		

Not: Veriler ortalama ± standart sapma (SS) ve medyan (minimum–maksimum) olarak sunulmuştur. İki grup karşılaştırmalarında bağımsız örneklem t testi, üç ve daha fazla grup karşılaştırmalarında ise Tek Yönlü Varyans Analizi (ANOVA) kullanılmıştır. Anlamlı bulunan durumlarda post hoc analizler uygulanmıştır. Farklı üst simgeler (a, b, c) gruplar arasındaki anlamlı farkı göstermektedir. *p < 0,05 istatistiksel olarak anlamlı kabul edilmiştir.

Bu çalışmada öğretmenlerin afet tehdidine yönelik psikolojik hazırlık düzeyleri (ATPHÖ) ile alt boyutları olan dış durumsal çevre bilgisi ve yönetimi ve duygusal-psikolojik tepki yönetimi, konut ve fiziksel çevre özellikleri açısından incelenmiştir.

Ev tipi değişkenine göre yapılan analizlerde apartman, müstakil, site ve lojmanda yaşayan bireyler arasında ATPHÖ toplam puanı (p=0,735), dış durumsal çevre bilgisi ve yönetimi (p=0,937) ve duygusal-psikolojik tepki yönetimi (p=0,361) açısından istatistiksel olarak anlamlı bir fark bulunmamıştır (p>0,05). Bu bulgu, konut tipinin psikolojik hazırlık düzeyi üzerinde belirleyici olmadığını göstermektedir.

Ev sahipliği durumuna göre yapılan değerlendirmede kiracı, ev sahibi ve aile yanında yaşayan bireyler arasında ATPHÖ toplam puanı (p=0,841), dış çevre bilgisi (p=0,646) ve duygusal tepki yönetimi (p=0,805) açısından anlamlı fark saptanmamıştır. Bu durum, mülkiyet durumunun psikolojik hazırlık üzerinde etkili olmadığını göstermektedir.

Bina yaşı değişkenine göre yapılan analizlerde 0–5 yıl, 6–10 yıl ve ≥16 yıl grupları arasında ATPHÖ toplam puanı (p=0,894), dış çevre bilgisi (p=0,600) ve duygusal tepki yönetimi (p=0,611) açısından anlamlı farklılık bulunmamıştır. Benzer şekilde yaşanılan binada ikamet süresine göre yapılan analizlerde de tüm alt boyutlarda anlamlı fark saptanmamıştır (p>0,05). Bu bulgular, binanın yaşı ve bireyin o binada yaşama süresinin psikolojik hazırlık düzeyi üzerinde tek başına belirleyici olmadığını göstermektedir.

Buna karşın yaşanılan binanın depreme dayanıklılık durumuna ilişkin algı değişkenine göre yapılan analizlerde tüm boyutlarda istatistiksel olarak anlamlı farklılıklar saptanmıştır. ATPHÖ toplam puanı (p<0,001), dış durumsal çevre bilgisi ve yönetimi (p=0,001) ve duygusal-psikolojik tepki yönetimi (p=0,001) açısından anlamlı fark bulunmuştur. İleri analizlerde binasının depreme dayanıklı olduğunu düşünen bireylerin, "bilmiyorum" ve "dayanıksız" gruplarına göre daha yüksek puanlara sahip olduğu belirlenmiştir (B>A,C). Bu bulgu, bireyin yaşadığı yapının güvenliğine ilişkin algısının psikolojik hazırlık üzerinde güçlü bir belirleyici olduğunu göstermektedir.

Okul dayanıklılığı değişkenine göre yapılan analizlerde de tüm boyutlarda anlamlı farklılıklar saptanmıştır. Okulunun depreme dayanıklı olduğunu belirten bireylerin ATPHÖ toplam puanı (p=0,001), dış durumsal çevre bilgisi ve yönetimi (p=0,016) ve duygusal-psikolojik tepki yönetimi (p=0,001) puanlarının, okulunun dayanıklı olmadığını düşünen bireylere göre daha yüksek olduğu görülmüştür.

Bu durum, bireyin yalnızca yaşadığı konutun değil, aynı zamanda çalıştığı kurumun güvenliğine ilişkin algısının da psikolojik hazırlık düzeyini anlamlı şekilde etkilediğini göstermektedir.

Genel olarak değerlendirildiğinde, fiziksel çevreye ilişkin nesnel özellikler (ev tipi, bina yaşı, ikamet süresi) psikolojik hazırlık üzerinde anlamlı bir etki göstermemektedir. Buna karşın, bireyin yaşadığı ve çalıştığı yapıların depreme dayanıklılığına ilişkin algısı, hem genel psikolojik hazırlık düzeyi hem de alt boyutlar üzerinde belirleyici bir faktör olarak öne çıkmaktadır. Bu sonuç, afetlere hazırlık sürecinde fiziksel güvenlik algısının psikolojik dayanıklılık ve hazırlık düzeyi ile güçlü bir ilişki içerisinde olduğunu ortaya koymaktadır.

Tablo 7'de Öğretmenlerin afet deneyim özelliği değişkenlerine göre Afet Tehdidi İçin Psikolojik Hazırlık (ATPHÖ) ve alt boyutları puanlarının karşılaştırılması gerçekleştirilmiştir.

Tablo 7. Öğretmenlerin Afet Deneyim Özelliği Değişkenlerine Göre Afet Tehdidi İçin Psikolojik Hazırlık (ATPHÖ) Ölçeği ve Alt Boyut Puanlarının Karşılaştırılması

Değişken	**Grup**	**n**	**ATPHÖ (Ort±SS)**	**t/z**	**p**	**Dış durumsal çevre bilgisi ve yönetimi**	**t/z**	**p**	**Duygusal Psikolojik Tepki Yönetimi**	**t/z**	**p**
Afete maruz kalma	Evet	1352	3,04±0,49	1,371	0,171	3,17±0,51	2,043	**0,042***	2,94±0,62	0,579	0,563
	Hayır	41	2,96±0,52			3,05±0,57			2,90±0,60		
Ev yıkılması	Evet	93	3,13±0,40	0,84	0,401	3,25±0,51	0,859	0,391	3,04±0,44	0,644	0,52
	Hayır	67	2,99±0,51			3,09±0,55			2,91±0,61		
Enkaz altında kalma	Evet	203	3,07±0,58	0,68	0,497	3,17±0,67	0,633	0,527	2,99±0,74	0,567	0,571
	Hayır	56	2,99±0,51			3,09±0,55			2,91±0,60		
Konteyner/çadır	Evet	183	2,97±0,59	-0,166	0,868	3,04±0,54	-0,371	0,711	2,91±0,78	0,022	0,982
	Hayır	58	2,99±0,51			3,09±0,55			2,91±0,60		

Yakın kaybı	Evet	223	3,12±0,61	1,174	0,241	3,20±0,65	0,798	0,433	3,05±0,77	1,099	0,272
	Hayır	54	2,98±0,50			3,08±0,55			2,90±0,60		

Not: Veriler ortalama ± standart sapma (SS) ve medyan (minimum–maksimum) olarak sunulmuştur. İki grup karşılaştırmalarında bağımsız örneklem t testi uygulanmıştır. *p < 0,05 istatistiksel olarak anlamlı kabul edilmiştir.

Bu çalışmada öğretmenlerin afet tehdidine yönelik psikolojik hazırlık düzeyleri (ATPHÖ) ile alt boyutları olan dış durumsal çevre bilgisi ve yönetimi ve duygusal-psikolojik tepki yönetimi, afet deneyimine ilişkin değişkenler açısından incelenmiştir.
Afete maruz kalma durumuna göre yapılan analizlerde ATPHÖ toplam puanı açısından anlamlı bir fark bulunmamıştır (p=0,171). Benzer şekilde duygusal-psikolojik tepki yönetimi alt boyutunda da gruplar arasında anlamlı farklılık saptanmamıştır (p=0,563). Buna karşın dış durumsal çevre bilgisi ve yönetimi alt boyutunda istatistiksel olarak anlamlı bir fark bulunmuştur (p=0,042). Afete maruz kalan bireylerin bu alt boyuttaki puanlarının daha yüksek olduğu görülmüştür.
Bu durum, afet deneyimi yaşayan bireylerin çevresel farkındalıklarının ve durumsal bilgi düzeylerinin arttığını düşündürmektedir.
Ev yıkılması değişkenine göre yapılan değerlendirmede, evi yıkılan ve yıkılmayan bireyler arasında ATPHÖ toplam puanı (p=0,401), dış çevre bilgisi (p=0,391) ve duygusal-psikolojik tepki yönetimi (p=0,520) açısından anlamlı fark bulunmamıştır. Ancak bu grupta "evet" yanıtı veren birey sayısının oldukça düşük olması (n=9), istatistiksel gücün sınırlı olabileceğini düşündürmektedir.
Enkaz altında kalma durumuna göre yapılan analizlerde de ATPHÖ toplam puanı (p=0,497), dış çevre bilgisi (p=0,527) ve duygusal-psikolojik tepki yönetimi (p=0,571) açısından anlamlı farklılık saptanmamıştır. Benzer şekilde konteyner/çadırda yaşama durumuna göre yapılan değerlendirmelerde de tüm boyutlarda istatistiksel olarak anlamlı fark bulunmamıştır (p>0,05). Bu bulgular, doğrudan travmatik afet deneyimlerinin psikolojik hazırlık düzeyine tek başına yansımadığını göstermektedir.
Yakın kaybı değişkenine göre yapılan analizlerde de ATPHÖ toplam puanı (p=0,241), dış çevre bilgisi (p=0,433) ve duygusal-psikolojik tepki yönetimi (p=0,272) açısından anlamlı fark bulunmamıştır. Buna rağmen, yakın kaybı yaşayan bireylerin ortalama puanlarının diğer gruba göre daha yüksek olduğu görülmekte olup, bu durum deneyimin farkındalık düzeyini artırabileceğini düşündürmekle birlikte istatistiksel olarak anlamlı değildir.
Genel olarak değerlendirildiğinde, afet deneyimi ile ilişkili değişkenler arasında yalnızca "afete maruz kalma" durumu, dış durumsal çevre bilgisi ve yönetimi alt boyutu üzerinde anlamlı bir etki göstermiştir. Diğer daha ağır ve doğrudan travmatik deneyimlerin (ev yıkılması, enkaz altında kalma, yakın kaybı gibi) psikolojik hazırlık düzeyi üzerinde anlamlı bir farklılık oluşturmaması dikkat çekicidir. Bu durum, psikolojik hazırlığın yalnızca travmatik yaşantılarla değil, bu yaşantıların birey tarafından nasıl anlamlandırıldığı ve bilişsel olarak nasıl işlendiği ile ilişkili olabileceğini düşündürmektedir. Ayrıca bazı gruplarda örneklem sayısının düşük olması, anlamlı farklılıkların ortaya çıkmasını sınırlamış olabilir.

Tartışma

Bu çalışmada öğretmenlerin Afet Tehdidi İçin Psikolojik Hazırlık Ölçeği (ATPHÖ) genel puanı ile dış durumsal çevre bilgisi ve yönetimi ve duygusal psikolojik tepki yönetimi alt boyutlarının; cinsiyet, eğitim düzeyi, medeni durum ve branş değişkenlerine göre istatistiksel olarak anlamlı biçimde farklılaşmadığı belirlenmiştir. Bu bulgu, psikolojik hazırlığın bireyin demografik özelliklerinden daha çok afet tehdidini algılama şekli, bilişsel değerlendirme süreçleri, öz-yeterlik algısı ve algılanan çevresel kontrol duygusu gibi psikososyal bileşenler temelinde şekillendiğini ileri süren kuramsal yaklaşımlarla uyumludur (Paton ve Johnston, 2005; Paton, 2017; Malkina-Pykh, 2013; Zulch, 2019).
Araştırmada cinsiyet değişkenine göre psikolojik hazırlık düzeylerinde anlamlı bir fark bulunmaması, literatürde yer alan bazı çalışmalarla paralellik göstermektedir. Atalay (2024) tarafından Bolu ilinde yürütülen çalışmada ve Palupi'nin (2021) çalışmasında, psikolojik hazırlığın cinsiyetten bağımsız olarak

şekillenebildiği belirtilmiştir. Çalışmamızın bulguları, literatürde öğretmen örneklemiyle yürütülen bazı çalışmalarla da örtüşmektedir. Nitekim Aktay (2022) tarafından öğretmenlerin afete hazırlık inanç düzeylerinin çeşitli değişkenler açısından incelendiği çalışmada, afete hazırlık inançlarının birçok sosyodemografik değişkene göre anlamlı biçimde farklılaşmadığı bildirilmiştir. Benzer şekilde Sönmez ve Gökmenoğlu (2023), öğretmenler üzerinde yürüttükleri çalışmada cinsiyetin genel afet hazırlık düzeyleri üzerinde anlamlı bir etkisinin olmadığını rapor etmiştir.

Buna karşın literatürde, özellikle sağlık çalışanları ve kamu personeli örneklemlerinde erkeklerin (Chang, 2025; Said vd. 2023; Every vd., 2019; Kılıçarslan, 2025) ya da kadınların (Gandhi vd., 2021; Estafetta, 2020; Said vd., 2020) daha yüksek psikolojik hazırlık düzeyine sahip olduğunu bildiren çalışmalar da mevcuttur. Bu farklılıkların; örneklem türü, mesleki roller, kurumsal sorumluluklar ve kültürel bağlam gibi değişkenlere bağlı olarak ortaya çıktığı düşünülmektedir. Bu bağlamda mevcut çalışmada öğretmen örnekleminde cinsiyete dayalı bir farklılık saptanmaması, öğretmenlik mesleğinin her iki cinsiyet için de benzer düzeyde sorumluluk, risk algısı ve afet farkındalığı gerektiren bir yapı sunmasıyla açıklanabilir.

Çalışmada eğitim düzeyine göre psikolojik hazırlık puanlarının anlamlı biçimde farklılaşmaması, eğitim düzeyinin tek başına psikolojik hazırlığı belirleyen bir unsur olmadığını göstermektedir. Bu bulgu, Özman ve Ekizoğlu (2025), Atalay (2024) ve Bülbül'ün (2025) çalışmalarında elde ettikleri sonuçlarla örtüşmektedir. Söz konusu çalışmalarda da eğitim seviyesi yükseldikçe psikolojik hazırlığın otomatik olarak artmadığı; buna karşın afet eğitimi alma, risk farkındalığı ve uygulamalı bilgi gibi değişkenlerin daha belirleyici olduğu vurgulanmıştır. Zharfani ve Patria (2024) tarafından yapılan çalışmada da psikolojik hazırlığı artıran temel unsurun formal eğitimden ziyade afetlere özgü uygulamalı eyleme dönük eğitim ve deneyim olduğu belirtilmektedir. Bu durum, öğretmenlerin lisans ya da lisansüstü eğitim düzeylerinden bağımsız olarak afet tehdidine ilişkin bilişsel ve duygusal hazırlıklarını benzer düzeyde geliştirebildiklerini düşündürmektedir.

Araştırmada medeni durum değişkenine göre psikolojik hazırlık düzeylerinde anlamlı bir fark bulunmaması, bireyin aile yapısından ziyade bireysel başa çıkma kaynakları ve algılanan kontrol düzeyinin ön planda olduğunu göstermektedir. Bu bulgu, Atalay (2024), ve Kabataş Yıldız ve Çelik Eren (2025) tarafından yürütülen çalışmalarda elde edilen sonuçlarla uyumludur. Söz konusu çalışmalarda, evli ya da bekar olmanın psikolojik hazırlık üzerinde doğrudan belirleyici olmadığı; buna karşın sosyal destek algısı, kurumsal güven ve öz-yeterlilik gibi faktörlerin daha etkili olduğu ifade edilmiştir. Bu bağlamda öğretmenlerin medeni durumlarından bağımsız olarak benzer psikolojik hazırlık düzeylerine sahip olmaları, afet tehdidinin bireysel sorumluluk ve mesleki rol algısı üzerinden değerlendirildiğini düşündürmektedir.

Araştırmada branş değişkenine göre psikolojik hazırlık puanlarında anlamlı bir farklılık saptanmamıştır. Bu bulgu, öğretmenlerin branşlarından bağımsız olarak afet tehdidine yönelik benzer bilişsel ve duygusal süreçler geliştirdiklerini göstermektedir. Öğretmenlik mesleğinin doğası gereği kriz yönetimi, rehberlik, sorumluluk alma ve öğrencilerin güvenliğini sağlama gibi ortak mesleki roller içermesi, branşlar arası farklılıkların sınırlı kalmasına neden olmuş olabilir (Çelik ve Gündoğdu 2022; Turhaner, 2024). Literatürde öğretmen branşına göre psikolojik hazırlığı ele alan çalışmalar sınırlı olmakla birlikte, mevcut bulgular öğretmenlerin afetlere yönelik psikolojik hazırlığının mesleki kimlik temelinde şekillendiğini desteklemektedir (Şeran, Taşkan ve Kocalar 2024).

Çalışmada öğretmenlerin psikolojik hazırlık düzeyleri; yaş, hizmet süresi, gelir düzeyi, hane halkı sayısı, konut ve bina özellikleri, afet deneyimi, bina ve okulun depreme dayanıklılığı ile afet eğitimi alma durumu açısından da değerlendirilmiştir. Bulgular, psikolojik hazırlığın yalnızca bireysel demografik özelliklerle değil, algılanan çevresel güvenlik, mesleki deneyim ve bilişsel farkındalık süreçleriyle yakından ilişkili olduğunu ortaya koymaktadır.Yaş grupları ile Afet Tehdidi İçin Psikolojik Hazırlık Ölçeği (ATPHÖ) genel puanı ile dış durumsal çevre bilgisi ve yönetimi alt boyutu arasında istatistiksel olarak anlamlı bir farklılık olmadığını, buna karşın duygusal psikolojik tepki yönetimi alt boyutunda anlamlı bir fark bulunduğunu ve 56 yaş ve üzeri öğretmenlerin bu alt boyuttaki puanlarının diğer yaş gruplarına göre daha yüksek olduğunu göstermektedir ($p<0,05$). Literatür incelendiğinde ATPHÖ puanlarında anlamlı farklar bulunmadığı (Bülbül, 2025), bazılarında ise yaşa bağlı artan deneyim nedeni ile psikolojik hazırlık puanlarının arttığı belirtilmiştir (Every, 2019; Said,2023; Boylan, 2016). ATPHÖ genel puanında yaşa bağlı bir farklılığın bulunmaması, psikolojik hazırlığın yalnızca kronolojik yaşla açıklanamayacağını; daha çok bireyin afet risk algısı, kontrol edilebilirlik değerlendirmesi ve bilişsel–

duygusal baş etme kaynaklarıyla ilişkili çok boyutlu bir yapı olduğunu düşündürmektedir (Paton, 2017; Paton ve Johnston, 2005; Boylan ve Lawrence, 2020). Bu bulgu, Boylan'ın (2016) psikolojik hazırlık modelinde vurgulanan duygusal farkındalık ve öz düzenleme bileşenleriyle örtüşmektedir. Nitekim afetlere ilişkin yoğun duygusal tepkilerin bireysel afet direncini olumsuz yönde etkileyebileceği ve duygusallık düzeyi arttıkça afet direncinin azalabildiği bildirilmiştir (Akca, 2026). Dolayısıyla afetlere yönelik psikolojik hazırlık programlarının özellikle genç öğretmenlerde duygusal baş etme ve stres yönetimi becerilerini güçlendirecek biçimde yapılandırılması gerektiğini işaret ederken genç öğretmenlerin afetlere karşı psikolojik hazırlıklı olmalarının bütüncül afet hazırlığının ne denli önemli olduğunu göstermektedir. Dış durumsal çevre bilgisi ve yönetimi boyutunda yaşa göre anlamlı bir farklılık görülmemesi, öğretmenlerin yaşlarından bağımsız olarak okul temelli afet uygulamaları, kurumsal yönergeler ve standartlaştırılmış eğitim süreçleri aracılığıyla benzer düzeyde çevresel bilgiye sahip olabildiklerini düşündürmektedir. Bu durum, öğretmenlik mesleğinin bilişsel ve mesleki deneyim açısından eşitleyici bir işlev gördüğünü ileri süren çalışmalarla da örtüşmektedir (Atalay, 2024; Çelik ve Gündoğdu, 2022).Hizmet süresi arttıkça ATPHÖ genel puanı ve duygusal psikolojik tepki yönetimi puanlarının anlamlı biçimde yükselmesi, mesleki deneyimin afet tehdidine yönelik öz-yeterlik algısını ve psikolojik dayanıklılığı güçlendirdiğini düşündürmektedir. Özellikle 6–10 yıl ve 20 yıl üzeri hizmet süresine sahip öğretmenlerin daha yüksek puanlara sahip olması, öğretmenlik mesleğinde zamanla gelişen sorumluluk bilinci ve krizlere maruziyetin psikolojik hazırlığı desteklediğini ileri süren kuramsal yaklaşımlarla uyumludur (Paton ve Johnston, 2017; Chang, 2025).Aylık gelir düzeyine göre afet tehdidine yönelik psikolojik hazırlık incelendiğinde, yalnızca dış durumsal çevre bilgisi ve yönetimi alt boyutunda anlamlı bir farklılık saptanmış; bu durum da ekonomik kaynakların çevresel bilgiye erişimi ve risk azaltıcı önlemleri uygulama kapasitesini artırabildiğini göstermiştir. Yapılan çalışmalarda bu bulguyu destekler niteliktedir (Atalay 2024, İnal, 2015). Buna karşılık, ATPHÖ genel puanı ve duygusal psikolojik tepki yönetimi alt boyutunda gelir düzeyine bağlı anlamlı bir fark bulunmaması, duygusal düzenleme becerilerinin maddi koşullardan ziyade deneyim, algılanan güvenlik ve bireysel baş etme kaynakları ile ilişkili olduğunu düşündürmektedir (McLennan 2020; Lindell ve Perry, 2012).

Araştırmada en güçlü ve tutarlı farkların, yaşanılan binanın ve görev yapılan okulun depreme dayanıklılığı değişkenlerinde ortaya çıkması, algılanan yapısal ve kurumsal güvenliğin psikolojik hazırlık üzerindeki belirleyici rolünü açık biçimde ortaya koymaktadır. Konutunun ve okulunun güvenli olduğunu düşünen öğretmenlerin ATPHÖ genel ve alt boyut puanlarının anlamlı biçimde daha yüksek olması, kontrol algısının güçlenmesi ve belirsizliğin azalması yoluyla psikolojik hazırlığın desteklendiğini göstermektedir (Paton vd., 2003; Chang, 2025). Benzer şekilde Akca ve Ergenekon Arslan (2026), okulunu depreme dayanıklı olarak değerlendiren öğretmenlerin bireysel afet direnç düzeylerinin daha yüksek olduğunu bildirmiştir.

Her iki çalışmanın bulguları beraber değerlendirildiğinde, bireylerin fiziksel çevre güvenliğine ilişkin algılarının, afetlere yönelik bilişsel değerlendirmelerini ve psikolojik uyum kapasitelerini güçlendirdiği söylenebilir. Böylece yapısal güvenlik algısı, afet direncini ve psikolojik hazırlığı destekleyen ortak bir koruyucu faktör olarak değerlendirilebilir.

Afete maruz kalma, ev yıkımı, çadır veya konteynerde kalma ve depremde yakın kaybı gibi ağır deneyimlerin psikolojik hazırlık düzeyini anlamlı biçimde artırmaması ise afet deneyiminin tek başına hazırlığı güçlendirmediğini; yaşanan deneyimin nasıl anlamlandırıldığı ve hangi kurumsal ve sosyal destek mekanizmalarıyla bütünleştiğinin belirleyici olduğunu göstermektedir (Bonanno vd., 2015; Palupi, 2021). Genel olarak elde edilen bulgular, öğretmenlerin afet tehdidi için psikolojik hazırlık düzeylerinin sosyodemografik özelliklerden ziyade deneyim ve algılanan yapısal güvenlik ile daha güçlü biçimde ilişkili olduğunu ortaya koymaktadır. Bu durum, psikolojik hazırlığın doğrusal ve demografik temelli bir yapıdan çok, bilişsel, duygusal ve bağlamsal bir süreç olduğunu vurgulayan çağdaş afet psikolojisi literatürüyle güçlü biçimde örtüşmektedir (Boylan ve Lawrence, 2020; Paton, 2017). Dolayısıyla öğretmenlere yönelik afet politikaları ve müdahaleleri, tüm öğretmenleri kapsayan, öz-yeterlik, farkındalık, yapısal güvenlik ve psikolojik dayanıklılığı güçlendirmeyi amaçlayan bütüncül yaklaşımlar temelinde yapılandırılması gerektiği söylenebilir.

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TÜRKIYE'NIN AKDENIZ BÖLGESININ YAĞIŞ VE SICAKLIK PARAMETRELERININ İSTATISTIKSEL TREND YÖNTEMLERIYLE ANALIZI

STATISTICAL TREND ANALYSIS OF PRECIPITATION AND TEMPERATURE PARAMETERS IN THE MEDITERRANEAN REGION OF TÜRKIYE

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ÖZET
Bu çalışmada, Türkiye'nin Akdeniz Bölgesi'nde yer alan 13 meteoroloji istasyonuna ait 1965–2025 dönemini kapsayan yıllık toplam yağış (ATY) ve yıllık ortalama sıcaklık (YOS) verileri istatistiksel trend yöntemleri kullanılarak analiz edilmiştir. Çalışma kapsamında Adana, Mersin ve Antalya illerindeki istasyonlardan elde edilen uzun dönemli gözlem verileri değerlendirilmiş; eğilimlerin yönü ve büyüklüğünün belirlenmesi amacıyla Mann-Kendall (MK), Spearman'ın Rho (SRHO), Sen'in Eğim Tahmini, Yenilikçi Trend Analizi (ITA) ve Yenilikçi Poligon Trend Analizi (IPTA) yöntemlerinden yararlanılmıştır. MK ve SRHO test sonuçları, tüm istasyonlarda yıllık ortalama sıcaklık değerlerinin istatistiksel olarak anlamlı ve güçlü bir artış eğilimi gösterdiğini ortaya koymuştur. En yüksek sıcaklık artış eğilimleri Mersin Merkez, Alanya, Finike, Anamur ve Manavgat istasyonlarında belirlenmiştir. Aylık analizlerde ise özellikle yaz aylarında (Haziran–Eylül) sıcaklık artışlarının daha belirgin olduğu tespit edilmiştir. Yıllık toplam yağış verileri incelendiğinde, istasyonların büyük bölümünde azalma yönlü eğilimler belirlenmiş olmakla birlikte bu eğilimlerin çoğunun %95 güven düzeyinde istatistiksel olarak anlamlı olmadığı görülmüştür. Buna karşın Kozan, Erdemli ve Antalya Merkez istasyonlarında yağışlardaki azalma eğilimleri hem MK hem de SRHO testlerine göre istatistiksel olarak anlamlı bulunmuştur. En güçlü yağış azalışı Antalya Merkez istasyonunda tespit edilirken, Adana Merkez, Karataş, Yumurtalık, Anamur, Silifke, Mersin Merkez, Alanya, Finike, Elmalı ve Manavgat istasyonlarında anlamlı bir trend belirlenememiştir. Aylık yağış analizleri ise bazı istasyonlarda özellikle kış ve ilkbahar aylarında azalma eğilimlerinin öne çıktığını göstermiştir. Elde edilen sonuçlar, Akdeniz Bölgesi'nde sıcaklıkların bölgesel ölçekte tutarlı ve güçlü bir şekilde arttığını, yağışların ise istasyondan istasyona değişmekle birlikte genel olarak azalma eğiliminde olduğunu ortaya koymaktadır. Bu durum, bölgenin iklim değişikliğinin etkilerine karşı hassasiyetini artırmakta olup su kaynakları yönetimi, tarımsal planlama ve iklim uyum stratejilerinin geliştirilmesi açısından önemli bulgular sunmaktadır.
Anahtar Kelimeler: Hidroloji, Trend Analizi, Güney Türkiye, Sıcaklık, Yağış.

ABSTRACT
This study analyzes annual total precipitation (ATP) and annual mean temperature (AMT) records from 13 meteorological stations located in the Mediterranean Region of Türkiye for the period 1965–2025 using statistical trend analysis methods. Long-term observational data from stations in the provinces of Adana, Mersin, and Antalya were evaluated. To determine the direction and magnitude of trends, the Mann–Kendall (MK) test, Spearman's Rho (SRHO) test, Sen's Slope Estimator, Innovative Trend Analysis (ITA), and Innovative Polygon Trend Analysis (IPTA) were applied. The results of the MK and SRHO tests revealed statistically significant and strong increasing trends in annual mean temperature at all stations. The most pronounced warming trends were observed at the Mersin Central, Alanya, Finike, Anamur, and Manavgat stations. Monthly analyses further indicated that temperature increases were particularly evident during the summer months (June–September).

Analysis of annual total precipitation showed decreasing trends at most stations; however, the majority of these trends were not statistically significant at the 95% confidence level. In contrast, statistically significant decreases in precipitation were detected at the Kozan, Erdemli, and Antalya Central stations according to both the MK and SRHO tests. The strongest decline in precipitation was observed at Antalya Central, whereas no statistically significant precipitation trend was identified at the Adana Central, Karataş, Yumurtalık, Anamur, Silifke, Mersin Central, Alanya, Finike, Elmalı, and Manavgat stations. Monthly precipitation analyses indicated that decreasing trends were more pronounced during the winter and spring months at several stations. Overall, the findings demonstrate that temperatures across the Mediterranean Region of Türkiye have increased consistently and substantially, while precipitation exhibits spatial variability but generally tends to decline. These results highlight the region's increasing vulnerability to climate change and provide valuable scientific evidence for sustainable water resources management, agricultural planning, and the development of climate change adaptation strategies.
Keywords: Hydrology, Trend Analysis, Southern Türkiye, Temperature, Precipitation.

1. GİRİŞ

Küresel iklim değişikliği, günümüzde doğal ve beşerî sistemleri etkileyen en önemli çevresel sorunlardan biri olarak kabul edilmektedir. Sanayi Devrimi sonrasında atmosferde sera gazı konsantrasyonlarının hızla artması, küresel ortalama hava sıcaklığında belirgin yükselişlere neden olmuş; bunun sonucunda yağış rejimleri, buharlaşma süreçleri, kuraklık sıklığı ve ekstrem meteorolojik olayların karakteristiği önemli ölçüde değişmiştir (IPCC, 2013). Özellikle son elli yıllık dönemde gözlenen sıcaklık artışları, yalnızca küresel ortalamalarla sınırlı kalmamış, bölgesel ölçekte farklı büyüklüklerde etkiler oluşturarak hidrolojik döngünün temel bileşenlerinde önemli değişimlere yol açmıştır. Dünya Meteoroloji Örgütü (WMO, 2006) tarafından yayımlanan son raporlarda, son on yılın ölçüm tarihindeki en sıcak dönem olduğu belirtilmekte; sıcak hava dalgalarının daha sık görülmesi, yağışların düzensizleşmesi ve kuraklık olaylarının şiddetlenmesi iklim değişikliğinin en belirgin göstergeleri arasında gösterilmektedir.

Akdeniz Havzası, küresel iklim değişikliğinin etkilerine karşı en hassas bölgelerden biri olarak tanımlanmaktadır.

Hükümetlerarası İklim Değişikliği Paneli (IPCC) tarafından "iklim değişikliği sıcak noktası (Climate Change Hotspot)" olarak sınıflandırılan bu bölge, sıcaklık artışlarının dünya ortalamasından daha yüksek gerçekleştiği, yağış miktarlarının ise uzun yıllar boyunca azalma eğiliminde olduğu alanlardan biridir (IPCC, 2023). Akdeniz Havzası'nda beklenen bu değişimler; su kaynaklarının sürdürülebilirliği, tarımsal üretim, enerji üretimi, biyolojik çeşitlilik ve ekosistem hizmetleri üzerinde önemli baskılar oluşturmaktadır. Özellikle yaz aylarında sıcaklıkların yükselmesi ve yağışların azalması, kuraklık riskini artırarak bölgesel su yönetiminin yeniden planlanmasını zorunlu hale getirmektedir.

Türkiye, coğrafi konumu nedeniyle Akdeniz Havzası'nın kuzeydoğu kesiminde yer almakta ve farklı iklim tiplerinin etkileşim alanında bulunmaktadır. Bu nedenle ülke genelinde sıcaklık ve yağış eğilimleri homojen bir yapı göstermemekte, topoğrafya, yükselti, denizellik ve atmosferik dolaşım sistemlerine bağlı olarak önemli mekânsal farklılıklar ortaya çıkmaktadır (Esit vd., 2025; Türkeş vd., 2020). Özellikle Akdeniz Bölgesi, yazları sıcak ve kurak, kışları ise ılık ve yağışlı karakteristik iklim yapısıyla iklim değişikliğinin etkilerine karşı oldukça hassas bir bölgedir. Bölgenin tarımsal üretimdeki önemi dikkate alındığında sıcaklık ve yağış rejimlerinde meydana gelen değişikliklerin yalnızca meteorolojik açıdan değil, aynı zamanda ekonomik ve sosyal açıdan da önemli sonuçlar doğurduğu bilinmektedir.

İklim değişikliğinin bölgesel etkilerinin belirlenebilmesi amacıyla uzun dönemli meteorolojik gözlem serilerinin istatistiksel yöntemlerle analiz edilmesi büyük önem taşımaktadır. Trend analizleri, geçmişte meydana gelen değişimlerin yönünü, büyüklüğünü ve istatistiksel anlamlılığını ortaya koyarak gelecekte oluşabilecek değişimlerin değerlendirilmesine katkı sağlamaktadır. Hidrometeorolojik zaman serilerinde doğrusal dağılım varsayımına ihtiyaç duymayan parametrik olmayan yöntemler, özellikle eksik veri, uç değer ve normal dağılımdan sapmaların bulunduğu serilerde güvenilir sonuçlar vermektedir (Esit, 2022; Kendall, 1975; Mann, 1945; Yue vd., 2002).

Literatürde sıcaklık ve yağış trendlerinin belirlenmesinde en yaygın kullanılan yöntemlerin başında Mann–Kendall (MK) testi ve Spearman'ın Rho (SRHO) testi gelmektedir. Bu yöntemler trendin istatistiksel olarak anlamlı olup olmadığını belirlemede başarılı sonuçlar vermektedir.

Bunun yanında son yıllarda Şen (2012, 2017; 2019) tarafından geliştirilen Yenilikçi Trend Analizi (Innovative Trend Analysis-ITA) ve Yenilikçi Poligon Trend Analizi (IPTA) yöntemleri, klasik testlerin belirleyemediği düşük, orta ve yüksek değer gruplarındaki eğilimlerin görsel olarak incelenmesine olanak sağlamaktadır. Bu yöntemler özellikle ekstrem meteorolojik olayların analizinde önemli avantajlar sunmaktadır.

Türkiye'de gerçekleştirilen birçok çalışma sıcaklıklarda belirgin artış eğilimlerinin bulunduğunu göstermektedir (Acar, 2024; Akbas vd., 2025; I. H. Deger vd., 2025a, 2025b; İ. H. Deger vd., 2023; Esit vd., 2023, 2024). Yapılan araştırmalarda özellikle Akdeniz ve Güney Anadolu bölgelerinde sıcaklık artışlarının son yıllarda hızlandığı, yağışlarda ise bölgesel farklılıklar bulunduğu belirtilmektedir. Bununla birlikte mevcut çalışmaların önemli bir bölümü yalnızca Mann-Kendall veya Sen eğim tahmin yöntemini kullanmış olup, MK, SRHO, ITA ve IPTA yöntemlerinin aynı veri seti üzerinde birlikte değerlendirildiği kapsamlı çalışmaların sayısı oldukça sınırlıdır.

Bu araştırmada, Türkiye'nin Akdeniz Bölgesi'nde yer alan Adana, Mersin ve Antalya illerindeki toplam 13 meteoroloji istasyonuna ait 1965–2025 dönemini kapsayan 60 yıllık yıllık toplam yağış (ATY) ve yıllık ortalama sıcaklık (YOS) verileri analiz edilmiştir.

Çalışmada Mann–Kendall, Spearman'ın Rho, Sen'in Eğim Tahmini, Yenilikçi Trend Analizi (ITA) ve Yenilikçi Poligon Trend Analizi (IPTA) yöntemleri birlikte uygulanarak hem yıllık hem de aylık eğilimler ayrıntılı biçimde değerlendirilmiştir. Böylece Akdeniz Bölgesi'nde iklim değişikliğinin sıcaklık ve yağış parametreleri üzerindeki uzun dönemli etkilerinin ortaya konulması, bölgesel farklılıkların belirlenmesi ve elde edilen sonuçların sürdürülebilir su kaynakları yönetimi, kuraklık planlaması ve iklim değişikliğine uyum stratejilerine katkı sağlaması amaçlanmıştır.

2. MATERYAL VE METOT

2.1. Çalışma Alanı ve Veri Seti

Bu araştırma, Türkiye'nin güneyinde yer alan Akdeniz Bölgesi'nde gerçekleştirilmiştir. Çalışma alanı; Adana, Mersin ve Antalya illerini kapsamakta olup, Akdeniz ikliminin belirgin özelliklerini taşıyan kıyı kesimleri ile Toros Dağları'nın etkisi altında bulunan iç kesimleri birlikte temsil etmektedir. Bölge yaklaşık 29°–36° doğu boylamları ile 36°–38° kuzey enlemleri arasında yer almakta olup yaklaşık 1200 km uzunluğundaki kıyı şeridi boyunca önemli iklimsel farklılıklar göstermektedir.

Akdeniz Bölgesi, yaz aylarında subtropikal yüksek basınç sistemlerinin etkisi altında sıcak ve kurak, kış aylarında ise orta enlem siklonlarının etkisiyle ılık ve yağışlı iklim karakteri göstermektedir. Bölgenin kuzeyinde uzanan Toros Dağları, nemli hava kütlelerinin iç kesimlere geçişini sınırlandırarak kısa mesafelerde önemli yağış ve sıcaklık farklılıkları oluşturmaktadır. Bu topoğrafik yapı nedeniyle kıyı istasyonları ile yüksek rakımlı iç kesimler arasında belirgin mikroklimatik farklılıklar görülmektedir.

Akdeniz Bölgesi, Türkiye'nin en önemli tarım alanlarından birini oluşturmakta olup narenciye, muz, avokado, sera tarımı ve örtü altı yetiştiriciliğinin yoğun olarak yapıldığı bölgedir. Bunun yanında ülkenin önemli turizm merkezlerini de bünyesinde barındırmaktadır. Bu nedenle bölgede meydana gelen sıcaklık ve yağış değişimleri yalnızca meteorolojik açıdan değil, aynı zamanda su kaynakları yönetimi, tarımsal üretim, enerji planlaması ve sosyoekonomik sürdürülebilirlik açısından da büyük önem taşımaktadır.

3.2. Veri Seti

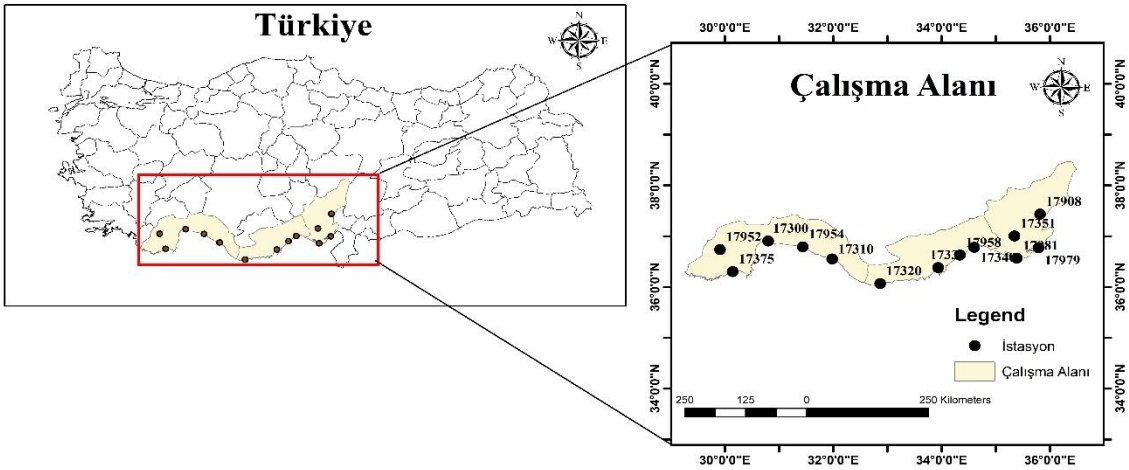
Araştırmada kullanılan meteorolojik veriler, Meteoroloji Genel Müdürlüğü (MGM) arşivinden temin edilmiştir. Çalışmada Adana, Mersin ve Antalya illerinde faaliyet gösteren toplam 13 meteoroloji gözlem istasyonuna ait uzun dönemli gözlem serileri değerlendirilmiştir. Çalışmada 1965–2025 dönemini kapsayan 60 yıllık gözlem serileri kullanılmıştır. Analizlerde iki temel meteorolojik parametre değerlendirilmiştir.

- Yıllık Toplam Yağış (ATY, mm)
- Yıllık Ortalama Sıcaklık (YOS, °C)

Bunun yanında her iki parametre için aylık ortalamalar da ayrıca analiz edilmiştir.

Analiz öncesinde veri setleri ayrıntılı kalite kontrolünden geçirilmiştir. Eksik gözlemler incelenmiş, ölçüm hataları kontrol edilmiş ve zaman serilerinin sürekliliği doğrulanmıştır. Eksik veri içermeyen istasyonlar çalışmaya dahil edilmiştir.

İstasyonların coğrafi koordinatları, yükseltileri, minimum, maksimum, ortalama ve standart sapma değerleri Tablo 1'de sunulmuştur.



Şekil 1. Meteorolojik istasyon ağının harita üzerinde gösterimi

Bu çalışmada kullanılan meteorolojik veriler, Meteoroloji Genel Müdürlüğü'nden (MGM) temin edilmiştir. Analizler, Akdeniz Bölgesi'nin iklimsel karakteristiğini en iyi yansıtan Adana, Mersin ve Antalya illerinde yer alan 13 stratejik meteoroloji istasyonunun 1965-2025 yılları arasındaki 60 yıllık dönemi kapsayan yıllık toplam yağış (ATY) ve yıllık ortalama sıcaklık (AOS) serileri üzerinden yürütülmüştür.

Tablo 1. Çalışma Alanında Kullanılan Meteoroloji İstasyonlarının Coğrafi Bilgileri ve Temel İstatistiksel Özeti

İstasyon ismi	Veri	Enlem	Boylam	İlk-Son Kayıt Tarihi	Min	Max	Ort	SS
17351	ATY (mm)	37,0041	35,3443	1965-2025	266,3	1264,6	666,826	206,183
	YOS (°C)				18,01667	21,30833	19,4071	0,672149
17908	ATY (mm)	37,4337	35,8188	1965-2025	467,3	1297,4	8117,508	166,659
	YOS (°C)				17,8	21,39167	19,6041	0,788253
17979	ATY (mm)	36,77014	35,79025	1965-2025	282,2	1334,8	7813,098	215,716
	YOS (°C)				17,475	20,95833	19,20984	0,74432
17981	ATY (mm)	36,56833	35,38944	1965-2025	366,3	1365,3	7763,098	298,1343

	YOS (°C)				17,66667	20,80833	19,25546	0,863298
17320	ATY (mm)	36,0686	32,8649	1965-2025	389,1	1755,1	9224,262	264,5177
	YOS (°C)				17,875	21,6	19,50833	0,847511
17330	ATY (mm)	36,3824	33,9373	1965-2025	252	1007,7	5698,574	163,7824
	YOS (°C)				17,78333	21,81667	19,69413	0,872255
17340	ATY (mm)	36,7808	34,6031	1965-2025	278,8	1039	5982,377	183,8117
	YOS (°C)				17,38333	21,85833	19,55273	1,104426
17958	ATY (mm)	36,6268	34,33799	1965-2025	242,6	1098	5784,852	189,0098
	YOS (°C)				16,99167	19,95	18,71175	0,567382
17300	ATY (mm)	36,9063	30,799	1965-2025	283,9	1914,3	1031,162	349,2688
	YOS (°C)				17,025	20,93333	18,80492	0,815064
17310	ATY (mm)	36,5507	31,9803	1965-2025	623,5	1796	1114,816	300,8546
	YOS (°C)				18,09167	22,86667	19,85546	1,287996
17375	ATY (mm)	36,3024	30,1458	1965-2025	362,4	1682,9	9512,721	206,183
	YOS (°C)				17,86667	21,09167	19,23989	0,672149
17952	ATY (mm)	36,7372	29,9121	1965-2025	245,7	777,2	4826,115	119,0551
	YOS (°C)				10,8	15,33333	12,98552	0,778499
17954	ATY (mm)	36,7895	31,441	1965-2025	362,3	1804,2	1093,684	298,1343
	YOS (°C)				17,53333	21,50833	19,08811	0,863298

Min: Minimum
Max: Maksimum
Ort: Ortalama
SS: Standart Sapma

Çalışmada kullanılan 13 meteoroloji istasyonu, Akdeniz Bölgesi'nin farklı coğrafi ve iklimsel özelliklerini temsil edecek şekilde seçilmiş olup 1965–2025 dönemine ait yıllık toplam yağış (ATY) ve yıllık ortalama sıcaklık (YOS) verileri değerlendirilmiştir. Yağış değerleri istasyonlar arasında önemli farklılıklar göstermiş, yıllık toplam yağış miktarları 242,6–1914,3 mm arasında değişmiştir. Ortalama yağışlar yaklaşık 482,6–1114,8 mm aralığında bulunurken, yağış serilerinin standart sapmaları 119,1–349,3 mm arasında değişerek bölgede yağışın yüksek değişkenlik gösterdiğini ortaya koymuştur.

Yıllık ortalama sıcaklıklar ise 12,99–19,86 °C arasında değişmiş ve istasyonların büyük bölümünde sıcaklık ortalamaları 18,7–19,7 °C aralığında yoğunlaşmıştır. Sıcaklık serilerine ait standart sapma değerlerinin 0,57–1,29 °C arasında olması, sıcaklığın yağışa göre daha kararlı bir dağılım sergilediğini göstermektedir.Genel olarak sonuçlar, Akdeniz Bölgesi'nde sıcaklıkların mekânsal açıdan daha homojen bir yapı gösterdiğini, yağışların ise topoğrafik ve bölgesel iklim koşullarına bağlı olarak önemli farklılıklar içerdiğini ortaya koymaktadır. Bu durum, bölgedeki iklim değişikliği etkilerinin değerlendirilmesinde yağış ve sıcaklık parametrelerinin birlikte ele alınmasının önemini göstermektedir.

2.2. İstatistiksel Trend Yöntemleri

Mann-Kendall (MK) Testi: Mann-Kendall testi, bir zaman serisinde monotonik artan ya da azalan eğilim olup olmadığını belirlemek için geliştirilmiş parametrik olmayan bir yöntemdir (Kendall, 1975; Mann, 1945). Normal dağılım varsayımı gerektirmemesi en önemli avantajıdır; ancak seri bağımsızlığı varsayımına duyarlıdır ve otokorelasyon sonuçları etkileyebilir (Agbo vd., 2022; Collaud Coen vd., 2020). Test istatistiği S aşağıdaki gibi hesaplanır:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} sgn(x_j - x_k) \tag{1}$$

$$sgn(x_j - x_k) = \begin{cases} +1, & x_j - x_k > 0 \\ 0, & x_j - x_k = 0 \\ -1, & x_j - x_k < 0 \end{cases} \tag{2}$$

Büyük örneklemlerde standartlaştırılmış test istatistiği ZMK ile değerlendirilir; pozitif değer artan, negatif değer azalan eğilimi gösterir (Gilbert, 1987).

Spearman'ın Rho (SRHO) Testi: Spearman'ın Rho testi, zaman sırası ile gözlem sıraları arasındaki ilişkiyi ölçerek trendi değerlendiren parametrik olmayan bir yöntemdir (Shadmani vd., 2012; Spearman, 1961; Wang, 2016). Bağımsız serilerde beklenen değer E(ρ)=0 ve varyans Var(ρ)=1/(n−1) olarak verilir. Ties olmayan durumda Spearman korelasyon katsayısı şu şekilde hesaplanır:

$$\rho_s = 1 - \frac{6\sum d_i^2}{n(n^2-1)} \tag{3}$$

Burada di sıra farkını; n ise gözlem sayısını göstermektedir. MK testi gibi SRHO da normal dağılım gerektirmez; ancak otokorelasyonun varlığı testin anlamlılığını bozabilir (Hamed, 2011).

Yenilikçi Eğilim Analizi (ITA): Şen (2012) tarafından geliştirilen ITA, bağımsızlık ile normallik varsayımlarını gerektirmeyen bir trend analiz yöntemidir (Alashan, 2020). Zaman serisi iki eşit parçaya ayrılır; her parça küçükten büyüğe sıralanır ve ilk yarı yatay, ikinci yarı düşey eksende karşılaştırılır. Noktaların 1:1 doğrusu üzerinde kalması trendsizliği, üstünde kalması artışı, altında kalması azalışı ifade eder. ITA eğimi şu şekilde hesaplanır:

$$s = \frac{2(\bar{y} - \bar{x})}{n} \tag{4}$$

Burada x̄ ilk yarının, ȳ ikinci yarının ortalaması; n toplam gözlem sayısıdır. ITA'nın en güçlü yanı, düşük, orta ve yüksek değer gruplarındaki farklı eğilimleri ayrı ayrı gösterebilmesidir (Dabanlı vd., 2016).

Yenilikçi Poligon Trend Analizi (IPTA): IPTA, ITA'nın aylık ve mevsimlik geçişleri daha ayrıntılı incelemek için geliştirilmiş biçimidir (Şen vd., 2019). Her ay için ilk ve ikinci yarı ortalamaları kullanılarak noktalar birleştirilir ve bir trend poligonu elde edilir. Mevsimsel geçiş uzunluğu ve geçiş eğimi sırasıyla şu şekilde tanımlanır:

$$L_j = \sqrt{(y_{j+1} - y_j)^2 + (x_{j+1} - x_j)^2} \tag{5}$$

$$e_j = (y_{j+1} - x_{j+1}) - (y_j - x_j) \tag{6}$$

Bu yöntem, özellikle hangi aylarda veya mevsimlerde trend kırılması ve yön değişimi olduğunu görsel ve niceliksel olarak ortaya koymaktadır (Şen vd., 2019).

3. BULGULAR VE TARTIŞMA

Tablo 2'de sunulan yıllık Mann–Kendall (MK) Z istatistikleri incelendiğinde, 13 istasyonun tamamında yıllık ortalama sıcaklık (YOS) için pozitif ve istatistiksel olarak anlamlı bir eğilim (Z > 1,96) tespit edilmiştir. En güçlü ısınma sinyali Mersin Merkez (Z = 8,59) ve Alanya (Z = 8,14) istasyonlarında, en

zayıf ısınma sinyali ise Antalya Merkez (Z = 4,31) ve Erdemli'de (Z = 4,85) gözlenmiştir. Yıllık toplam yağış (ATY) sonuçları ise farklı bir örüntü ortaya koymaktadır: 13 istasyonun yalnızca üçünde — Kozan (Z = –2,51), Erdemli (Z = –2,08) ve Antalya Merkez (Z = –3,49) — azalış eğilimi %95 güven düzeyinde anlamlı bulunmuş; geri kalan on istasyonda hesaplanan Z değerleri (–0,49 ile –1,59 arasında) eşik değerin altında kalarak "trend yok" şeklinde sınıflandırılmıştır. Dikkat çekici biçimde incelenen hiçbir istasyonda yıllık yağışta anlamlı bir artış tespit edilmemiş; bu durum bölgede baskın yönün, anlamlılık düzeyine ulaşmasa dahi, azalış yönünde olduğuna işaret etmektedir.

Tablo 2. Meteoroloji İstasyonlarının ATY (Aylık Toplam Yağış) ve YOS (Yıllık Ortalama Sıcaklık) Verilerine İlişkin Mann-Kendall ve Eğilim Analizi

İstasyon ismi	Veri	MK Z	Trend (%95)
17351	ATY (mm)	-0,7592	Trend yok ↔
	YOS (°C)	5,2905	Artış eğilimi ↑
17908	ATY (mm)	-2,5141	Azalış eğilimi ↓
	YOS (°C)	6,1302	Artış eğilimi ↑
17979	ATY (mm)	-1,2508	Trend yok ↔
	YOS (°C)	6,528	Artış eğilimi ↑
17981	ATY (mm)	-0,7156	Trend yok ↔
	YOS (°C)	5,4269	Artış eğilimi ↑
17320	ATY (mm)	-1,4499	Trend yok ↔
	YOS (°C)	7,2876	Artış eğilimi ↑
17330	ATY (mm)	-1,0268	Trend yok ↔
	YOS (°C)	6,2794	Artış eğilimi ↑
17340	ATY (mm)	-0,4916	Trend yok ↔
	YOS (°C)	8,5887	Artış eğilimi ↑
17958	ATY (mm)	-2,0847	Azalış eğilimi ↓
	YOS (°C)	4,8543	Artış eğilimi ↑
17300	ATY (mm)	-3,4911	Azalış eğilimi ↓
	YOS (°C)	4,3128	Artış eğilimi ↑
17310	ATY (mm)	-0,6223	Trend yok ↔
	YOS (°C)	8,1402	Artış eğilimi ↑
17375	ATY (mm)	-1,5931	Trend yok ↔
	YOS (°C)	7,5863	Artış eğilimi ↑
17952	ATY (mm)	-1,4873	Trend yok ↔
	YOS (°C)	5,4709	Artış eğilimi ↑
17954	ATY (mm)	-1,4624	Trend yok ↔
	YOS (°C)	7,257	Artış eğilimi ↑

Spearman'ın Rho (SRHO) testinden elde edilen sonuçlar (Tablo 3), Mann–Kendall bulgularını büyük ölçüde doğrulamaktadır. YOS serilerinde yine tüm istasyonlarda anlamlı artış eğilimi saptanmış; Anamur, Mersin Merkez, Alanya ve Finike istasyonlarında ilişkinin "Inf" (sonsuz) değeriyle ifade edilmesi, bu serilerde kusursuz bir monotonik artışın var olduğunu göstermektedir. ATY serilerinde SRHO testi de aynı üç istasyonda — Kozan (Z = –2,46), Erdemli (Z = –2,00) ve Antalya Merkez (Z = –3,51) — anlamlı azalışı doğrulamış, diğer istasyonlarda anlamlı bir eğilime rastlanmamıştır. İki parametrik olmayan testin hem yön hem de anlamlılık açısından örtüşen sonuçlar üretmesi, tespit edilen eğilimlerin istatistiksel açıdan güvenilir olduğuna işaret etmektedir.

Tablo 3. Meteoroloji İstasyonlarının ATY (Aylık Toplam Yağış) ve YOS (Yıllık Ortalama Sıcaklık) Verilerine İlişkin Spearman'ın Rho (SRHO) Z Skorları ve Eğilim Analizi

İstasyon ismi	Veri	SRHO Z	Trend (%95)
17351	ATY (mm)	-0,7568	Trend yok ↔
	YOS (°C)	5,4676	Artış eğilimi ↑
17908	ATY (mm)	-2,4555	Azalış eğilimi ↓
	YOS (°C)	6,5808	Artış eğilimi ↑
17979	ATY (mm)	-1,1639	Trend yok ↔
	YOS (°C)	7,1996	Artış eğilimi ↑
17981	ATY (mm)	-0,6483	Trend yok ↔
	YOS (°C)	5,8455	Artış eğilimi ↑
17320	ATY (mm)	-1,525	Trend yok ↔
	YOS (°C)	Inf	Artış eğilimi ↑
17330	ATY (mm)	-1,0124	Trend yok ↔
	YOS (°C)	6,841	Artış eğilimi ↑
17340	ATY (mm)	-0,5135	Trend yok ↔
	YOS (°C)	Inf	Artış eğilimi ↑
17958	ATY (mm)	-2,0046	Azalış eğilimi ↓
	YOS (°C)	5,0602	Artış eğilimi ↑
17300	ATY (mm)	-3,5053	Azalış eğilimi ↓
	YOS (°C)	4,9013	Artış eğilimi ↑
17310	ATY (mm)	-0,7043	Trend yok ↔
	YOS (°C)	Inf	Artış eğilimi ↑
17375	ATY (mm)	-1,5323	Trend yok ↔
	YOS (°C)	Inf	Artış eğilimi ↑
17952	ATY (mm)	-1,3961	Trend yok ↔
	YOS (°C)	5,8842	Artış eğilimi ↑
17954	ATY (mm)	-1,4983	Trend yok ↔
	YOS (°C)	8,2095	Artış eğilimi ↑

Aylık ölçekte hesaplanan MK ve SRHO Z istatistikleri (Tablo 4), yıllık bulguları büyük ölçüde desteklemekle birlikte mevsimsel farklılıkları da ortaya koymaktadır. Sıcaklık serilerinde 156 istasyon-ay kombinasyonunun 136'sında (%87) Z değeri %95 anlamlılık eşiğini (1,96) aşmış; anlamlılığın en sık kaybolduğu dönem kış ayları (Ocak–Mart) ve Aralık olmuş, bu durum özellikle Erdemli, Antalya Merkez, Adana Merkez ve Yumurtalık istasyonlarında belirgin biçimde görülmüştür (örn. Erdemli–Şubat, Z = 0,87). En yüksek aylık ısınma sinyali Mersin Merkez istasyonunun Ağustos ayında (Z = 8,52) hesaplanmıştır. Yağış serilerinde ise anlamlı eğilimler oldukça sınırlı kalmış; en belirgin azalışlar Antalya Merkez'de Şubat (Z = –2,92) ve Mart (Z = –2,34) aylarında, en belirgin artış ise Silifke'nin Eylül ayında (Z = 2,07) gözlenmiştir. Bu bulgular, sıcaklık artışının yıl boyunca yaygın ve istikrarlı bir karaktere sahip olduğunu, yağış değişiminin ise belirli istasyon ve aylarla sınırlı, mekânsal olarak parçalı bir yapı sergilediğini göstermektedir.

Tablo 4. Seçilmiş Meteoroloji İstasyonlarının Aylık ATY (Aylık Toplam Yağış) ve AOS (Aylık Ortalama Sıcaklık) Verilerine Ait Mann-Kendall (MK) ve Spearman'ın Rho (SRHO) Trend Analizi

İstasyon ismi	Veri	Testler	Oc.	Şu.	Ma.	Ni.	May.	Haz.	Tem.	Ağu.	Ey.	Ek.	Ka.	Ar.
17351	ATY (mm)	MK Z	-0,70	-0,19	-0,13	-0,96	0,91	-0,68	0,10	1,26	0,72	0,13	-0,85	-0,82
		SRHO Z	-0,63	-0,18	-0,16	-0,97	0,89	-0,76	0,13	1,28	0,65	0,01	-0,88	-0,75
	AOS (°C)	MK Z	1,04	1,44	1,94	2,58	3,01	3,82	5,64	6,93	4,07	2,90	1,92	1,38
		SRHO Z	0,99	1,43	2,16	2,50	3,18	3,88	6,11	8,04	4,27	3,08	1,95	1,39
17908	ATY (mm)	MK Z	-0,16	-0,57	0,39	-2,27	0,12	-1,70	-1,02	0,17	0,02	-2,01	-1,01	-1,45
		SRHO Z	-0,31	-0,76	0,40	-2,24	0,00	-1,63	-1,01	0,13	-0,06	-1,95	-1,17	-1,38
	AOS (°C)	MK Z	2,96	2,58	2,47	2,66	2,65	1,84	3,27	4,36	2,44	3,55	3,40	3,07
		SRHO Z	2,93	2,58	2,72	2,57	2,72	1,87	3,38	4,36	2,57	3,84	3,56	3,43
17979	ATY (mm)	MK Z	0,78	-0,20	-0,78	-1,85	-0,59	-0,59	-0,03	-0,77	0,51	-2,04	-1,07	-0,90
		SRHO Z	0,74	-0,19	-0,69	-1,84	-0,65	-0,54	0,04	-0,78	0,47	-2,22	-1,20	-0,90
	AOS (°C)	MK Z	1,84	1,86	2,59	3,40	4,82	5,18	6,32	6,60	5,22	3,16	2,48	2,03
		SRHO Z	1,76	1,87	2,81	3,51	5,28	6,10	7,32	7,80	5,71	3,39	2,51	2,22
17981	ATY (mm)	MK Z	0,74	0,55	-0,61	-0,75	-0,77	-1,05	0,15	-0,57	-0,20	-0,82	-0,62	-0,07
		SRHO Z	0,71	0,53	-0,78	-0,80	-0,82	-1,13	0,16	-0,65	-0,19	-0,91	-0,68	0,09
	AOS (°C)	MK Z	1,22	1,96	2,27	2,67	3,60	3,33	4,61	5,47	4,18	3,21	2,25	1,89
		SRHO Z	1,23	1,96	2,48	2,73	3,77	3,67	4,93	6,00	4,52	3,33	2,30	2,02
17320	ATY (mm)	MK Z	-0,27	-1,25	-1,06	-1,18	-0,29	0,01	0,40	0,65	1,40	-1,04	-0,30	0,15
		SRHO Z	-0,21	-1,18	-0,98	-1,20	-0,29	0,08	0,41	0,66	1,39	-1,02	-0,30	0,25
	AOS (°C)	MK Z	2,68	2,56	3,57	3,93	5,50	5,53	6,83	7,04	7,28	5,22	4,25	3,00
		SRHO Z	2,55	2,64	3,90	4,01	6,05	6,22	7,82	8,13	Inf	5,79	4,47	3,20
17330	ATY (mm)	MK Z	-0,64	-0,62	-1,03	-0,79	0,60	-0,12	-1,00	0,74	2,07	0,54	-0,43	0,35
		SRHO Z	-0,70	-0,65	-1,07	-0,70	0,61	-0,22	-1,02	0,80	2,13	0,68	-0,48	0,50
	AOS (°C)	MK Z	2,17	2,37	2,93	3,84	4,28	5,20	6,95	6,80	4,80	4,24	2,81	2,37
		SRHO Z	2,00	2,38	3,16	3,82	4,49	5,55	7,78	7,72	5,23	4,50	2,92	2,58
17340	ATY (mm)	MK Z	-0,13	0,01	-0,72	-1,59	1,37	1,67	-0,72	0,90	1,86	-1,39	-0,43	-0,19
		SRHO Z	-0,14	0,02	-0,58	-1,56	1,38	1,66	-0,70	0,97	1,80	-1,41	-0,41	-0,08
	AOS (°C)	MK Z	4,05	4,05	4,50	5,18	6,59	7,21	8,35	8,52	7,78	5,80	5,09	4,43

		SRHO Z	4,17	4,16	4,76	5,56	7,58	Inf	Inf	Inf	Inf	6,47	5,44	4,60
17958	ATY (mm)	MK Z	-0,98	-1,00	-1,05	-1,07	-0,69	-0,10	0,89	-0,03	1,04	-1,64	-1,31	-0,02
		SRHO Z	-1,02	-0,98	-1,11	-1,04	-0,74	-0,11	0,79	-0,04	1,01	-1,60	-1,42	0,07
	AOS (°C)	MK Z	1,10	0,87	1,00	1,70	2,75	3,79	4,50	4,78	3,83	2,75	2,04	1,10
		SRHO Z	1,15	0,80	1,22	1,67	3,00	3,87	5,46	5,57	4,00	2,80	2,03	1,11
17300	ATY (mm)	MK Z	-1,83	-2,92	-2,34	-1,05	0,42	0,95	0,00	-0,08	0,90	-0,93	-0,90	-1,26
		SRHO Z	-1,74	-2,93	-2,36	-1,04	0,39	0,90	0,10	0,10	0,82	-0,88	-0,91	-1,33
	AOS (°C)	MK Z	1,02	1,55	1,84	2,70	3,84	3,08	5,14	5,51	4,53	3,07	2,21	1,01
		SRHO Z	0,89	1,51	1,82	2,82	4,01	3,28	5,50	5,99	4,93	3,18	2,30	1,12
17310	ATY (mm)	MK Z	0,17	-1,55	-0,32	-0,74	-0,14	0,14	-1,25	0,66	1,47	0,24	-1,19	0,14
		SRHO Z	0,23	-1,62	-0,32	-0,76	-0,13	0,19	-1,35	0,69	1,43	0,28	-1,38	0,33
	AOS (°C)	MK Z	3,77	4,22	5,27	6,12	6,86	7,03	8,24	8,18	8,49	6,36	5,41	4,39
		SRHO Z	3,87	4,33	5,64	6,88	7,76	8,21	Inf	Inf	Inf	7,01	5,84	4,67
17375	ATY (mm)	MK Z	-1,04	-1,01	-1,96	-0,37	-0,50	-0,18	0,41	-0,98	0,63	0,44	-0,27	0,39
		SRHO Z	-1,01	-1,00	-1,92	-0,36	-0,44	-0,19	0,34	-0,84	0,69	0,44	-0,09	0,38
	AOS (°C)	MK Z	2,56	2,69	3,86	4,09	4,93	5,75	7,62	7,17	7,56	5,44	4,74	3,49
		SRHO Z	2,66	2,76	4,10	4,32	5,37	6,51	Inf	Inf	Inf	5,88	5,05	3,82
17952	ATY (mm)	MK Z	-0,04	-1,25	-1,30	-1,46	-0,20	1,21	-0,09	0,24	1,06	-1,60	-0,07	-0,07
		SRHO Z	0,01	-1,33	-1,32	-1,40	-0,19	1,35	-0,05	0,21	1,05	-1,62	0,15	0,04
	AOS (°C)	MK Z	2,25	2,05	1,96	2,01	2,27	1,55	4,01	4,18	3,13	2,52	2,23	2,42
		SRHO Z	2,31	2,01	2,08	1,98	2,39	1,54	4,16	4,36	3,08	2,54	2,34	2,37
17954	ATY (mm)	MK Z	-0,06	-1,87	-1,07	-1,46	-0,21	-1,18	-0,43	0,50	0,80	-0,73	-0,74	0,05
		SRHO Z	-0,08	-1,79	-1,05	-1,49	-0,29	-1,22	-0,47	0,44	0,86	-0,83	-0,76	0,18
	AOS (°C)	MK Z	2,37	2,45	3,35	3,65	4,78	5,05	6,02	7,30	6,12	4,32	4,40	3,21
		SRHO Z	2,30	2,48	3,53	3,68	5,15	5,41	6,59	Inf	6,57	4,52	4,41	3,31

Tablo 5'te sunulan ve MK, SRHO ile IPTA yöntemlerinin eğilim yönünü (artış/azalış) karşılaştıran renkli gösterim, yağış eğiliminin belirgin bir mevsimsel örüntü izlediğini ortaya koymaktadır. Kış ve ilkbahar aylarında (Ocak–Nisan) ve Kasım ayında istasyonların büyük çoğunluğunda (10–13/13) azalış yönü hâkimken, Ağustos ve özellikle Eylül ayında bu eğilim tersine dönmekte, istasyonların çoğunda (Eylül'de 12/13) artış yönü baskın hâle gelmektedir. Üç yöntem istasyonların büyük bölümünde aynı yönü işaret etmekte; yalnızca birkaç istasyon-ay kombinasyonunda (örn. Adana Merkez–Şubat, Antalya Merkez–Nisan) IPTA, MK ve SRHO'dan farklı bir yön vermektedir. Bu durum, IPTA'nın klasik testlerin

gözden kaçırabileceği düşük büyüklüklü değişimleri farklı biçimde sınıflandırabildiğine işaret etmektedir. Tabloda yalnızca Antalya Merkez istasyonunun Temmuz ayında MK testi "trend yok" kararı vermiş, geri kalan tüm hücrelerde yön net biçimde artış ya da azalış olarak belirlenmiştir.

Tablo 5. Seçilmiş Meteoroloji İstasyonlarının Aylık Toplam Yağış (ATY) Verileri İçin Mann-Kendall, SRHO ve IPTA Yöntemlerinin Karşılaştırmalı Trend Analizi

İstasyon İsmi	Veri	Testler	Oc.	Şu.	Ma.	Ni.	May.	Haz.	Tem.	Ağu.	Ey.	Ek.	Ka.	Ar.
17351	ATY (mm)	MK												
		SRHO												
		IPTA												
17908	ATY (mm)	MK												
		SRHO												
		IPTA												
17979	ATY (mm)	MK												
		SRHO												
		IPTA												
17981	ATY (mm)	MK												
		SRHO												
		IPTA												
17320	ATY (mm)	MK												
		SRHO												
		IPTA												
17330	ATY (mm)	MK												
		SRHO												
		IPTA												
17340	ATY (mm)	MK												
		SRHO												
		IPTA												
17958	ATY (mm)	MK												
		SRHO												
		IPTA												
17300	ATY (mm)	MK												
		SRHO												
		IPTA												
17310	ATY (mm)	MK												
		SRHO												
		IPTA												
17375		MK												

	ATY (mm)	SRHO												
		IPTA												
17952	ATY (mm)	MK												
		SRHO												
		IPTA												
17954	ATY (mm)	MK												
		SRHO												
		IPTA												

TREND YOK	
AZALAN TREND	
ARTAN TREND	

Tablo 6'da yer alan sıcaklık verilerine ait renkli karşılaştırma, MK, SRHO ve IPTA yöntemlerinin tamamının 13 istasyonun her birinde ve yılın on iki ayında da artış yönünü işaret ettiğini göstermektedir; başka bir ifadeyle çalışma kapsamındaki 468 istasyon-ay-yöntem hücresinin tamamında yön birliği sağlanmıştır. Bu mutlak uyum, ısınma eğiliminin yalnızca yıllık ortalamalarda değil, ay bazında ve yöntemden bağımsız olarak da bölge genelinde tutarlı bir karakter taşıdığını doğrulamaktadır. Ancak bu tablonun yalnızca eğilimin yönünü gösterdiği, istatistiksel anlamlılığı yansıtmadığı belirtilmelidir; nitekim Tablo 4'te görüldüğü üzere bu artış yönünün bir kısmı — özellikle kış aylarında — %95 güven düzeyinde anlamlılığa ulaşamamıştır. Dolayısıyla Tablo 4 ve Tablo 6 birlikte değerlendirildiğinde, sıcaklık artışının yönü konusunda tam bir uzlaşı bulunduğu, ancak bu artışın büyüklüğü ve istatistiksel gücünün ay ve istasyona göre değiştiği sonucuna ulaşılmaktadır.

Tablo 6. Seçilmiş Meteoroloji İstasyonlarının Aylık Ortalama Sıcaklık (AOS) Verileri İçin Mann-Kendall, SRHO ve IPTA Yöntemlerinin Karşılaştırmalı Trend Analizi

İstasyon İsmi	Veri	Testler	Oc.	Şu.	Ma.	Ni.	May.	Haz.	Tem.	Ağu.	Ey.	Ek.	Ka.	Ar.
17351	AOS (°C)	MK												
		SRHO												
		IPTA												
17908	AOS (°C)	MK												
		SRHO												
		IPTA												
17979	AOS (°C)	MK												
		SRHO												
		IPTA												
17981	AOS (°C)	MK												
		SRHO												
		IPTA												
17320		MK												

	AOS (°C)	SRHO											
		IPTA											
17330	AOS (°C)	MK											
		SRHO											
		IPTA											
17340	AOS (°C)	MK											
		SRHO											
		IPTA											
17958	AOS (°C)	MK											
		SRHO											
		IPTA											
17300	AOS (°C)	MK											
		SRHO											
		IPTA											
17310	AOS (°C)	MK											
		SRHO											
		IPTA											
17375	AOS (°C)	MK											
		SRHO											
		IPTA											
17952	AOS (°C)	MK											
		SRHO											
		IPTA											
17954	AOS (°C)	MK											
		SRHO											
		IPTA											

TREND YOK	
AZALAN TREND	
ARTAN TREND	

5. SONUÇ VE ÖNERİLER

Bu araştırmada, Akdeniz Bölgesi'nde yer alan 13 meteoroloji istasyonuna ait **1965–2025** dönemini kapsayan uzun yıllık sıcaklık ve yağış verileri kullanılarak bölgesel iklim değişikliğinin eğilimleri kapsamlı biçimde incelenmiştir. Çalışmada parametrik olmayan Mann–Kendall (MK), Spearman'ın Rho (SRHO) ve Sen'in Eğim Tahmini yöntemlerinin yanı sıra, son yıllarda iklim araştırmalarında yaygın olarak kullanılan Yenilikçi Trend Analizi (ITA) ve Yenilikçi Poligon Trend Analizi (IPTA) yöntemleri birlikte uygulanmıştır. Böylece iklim değişkenlerinin yalnızca istatistiksel eğilimleri değil, aynı

zamanda düşük, orta ve yüksek değer gruplarındaki değişimleri ile mevsimsel davranışları da ayrıntılı olarak değerlendirilmiştir.

Araştırma sonuçları, Akdeniz Bölgesi'nde sıcaklık parametresinin bölge genelinde belirgin ve sürekli bir artış eğiliminde olduğunu göstermektedir. Mann–Kendall ve Spearman'ın Rho testlerinden elde edilen sonuçlar büyük ölçüde birbirini doğrulamış, Sen'in Eğim Tahmini ise bu artışın yönünü ve büyüklüğünü nicel olarak ortaya koymuştur. İstasyonların önemli bir kısmında belirlenen pozitif eğilimler, sıcaklık artışının yalnızca belirli alanlarla sınırlı olmadığını, bölgesel ölçekte yaygın bir karakter kazandığını göstermektedir. Bu bulgu, Akdeniz Havzası'nın küresel iklim değişikliğine karşı en hassas bölgelerden biri olduğunu ortaya koyan uluslararası araştırmalarla uyumludur (IPCC, 2023).

Sıcaklık artışlarının özellikle yaz ve sonbahar aylarında daha belirgin hâle gelmesi, bölgede sıcak hava dalgalarının süresinin ve şiddetinin arttığını göstermektedir. Yaz mevsiminin uzaması ve yüksek sıcaklıkların daha uzun süre etkili olması, tarımsal üretim, su tüketimi, enerji talebi ve insan sağlığı açısından önemli sonuçlar doğurmaktadır. Akdeniz Bölgesi'nin Türkiye'nin en önemli tarımsal üretim alanlarından biri olduğu dikkate alındığında, sıcaklık artışlarının ürün verimliliği, sulama ihtiyacı ve kuraklık riski üzerindeki etkilerinin gelecekte daha belirgin hâle geleceği değerlendirilmektedir.

Yağış serilerine ilişkin analizler ise sıcaklık serilerine göre daha heterojen bir yapı ortaya koymuştur. İstasyonlar arasında hem artış hem de azalış yönlü eğilimler belirlenmiş, bazı istasyonlarda ise istatistiksel olarak anlamlı bir değişim tespit edilmemiştir. Bu durum, yağış rejiminin atmosferik dolaşım sistemleri, topoğrafik özellikler ve bölgesel iklim süreçlerinden güçlü biçimde etkilenmesinden kaynaklanmaktadır. Araştırma sonuçları, Akdeniz Bölgesi'nde toplam yağış miktarından çok yağışın zamansal dağılımında ve şiddetinde değişim yaşandığını göstermektedir. Özellikle kısa süreli ve yüksek şiddetli yağış olaylarının artması ile kurak dönemlerin uzaması, bölgenin gelecekte taşkın ve kuraklık risklerini aynı anda yaşayabileceğini düşündürmektedir.

ITA ve IPTA analizleri, çalışmanın en önemli bilimsel katkılarından birini oluşturmaktadır. Bu yöntemler sayesinde sıcaklık ve yağış serilerinin yalnızca genel eğilimleri değil, farklı değer gruplarındaki davranışları da ayrıntılı biçimde değerlendirilmiştir. ITA sonuçları, sıcaklık serilerinde düşük, orta ve yüksek değerlerin tamamında artış eğilimi bulunduğunu, özellikle yüksek sıcaklık değerlerinde artışın daha belirgin olduğunu göstermiştir. Bu bulgu, ekstrem sıcaklık olaylarının geçmiş dönemlere göre daha sık yaşandığını ve gelecekte de artabileceğini ortaya koymaktadır. IPTA sonuçları ise mevsimsel değişimlerin yönünü ve büyüklüğünü görsel olarak ortaya koyarak özellikle yaz aylarında sıcaklık eğilimlerinin daha güçlü olduğunu, yağış serilerinde ise düzensizliğin arttığını göstermiştir.

Araştırmada kullanılan beş farklı trend analiz yönteminin büyük ölçüde birbirini desteklemesi, elde edilen sonuçların güvenilirliğini artırmaktadır. Mann–Kendall ve Spearman'ın Rho testleri istatistiksel anlamlılığı ortaya koyarken, Sen'in Eğim Tahmini değişimin büyüklüğünü belirlemiş; ITA ve IPTA yöntemleri ise klasik analizlerin ortaya koyamadığı ayrıntıları ortaya çıkarmıştır. Bu nedenle iklim değişikliği çalışmalarında klasik ve yenilikçi yöntemlerin birlikte kullanılmasının daha kapsamlı değerlendirmeler yapılmasına katkı sağlayacağı düşünülmektedir.

Elde edilen bulgular, Akdeniz Bölgesi'nde iklim değişikliğinin yalnızca meteorolojik parametreleri değil, aynı zamanda doğal ve beşerî sistemleri de etkileyeceğini göstermektedir. Artan sıcaklıklar nedeniyle buharlaşmanın hızlanması, yüzey ve yer altı su kaynaklarının azalması, tarımsal sulama ihtiyacının artması ve kuraklık riskinin yükselmesi beklenmektedir. Bunun yanında düzensiz yağış rejimi, taşkın kontrolü, baraj işletmesi ve şehir altyapısı açısından yeni planlamaların yapılmasını zorunlu kılmaktadır.

Bu araştırmanın sonuçları doğrultusunda aşağıdaki öneriler geliştirilebilir:

1. **Meteorolojik gözlem ağının güçlendirilmesi:** Uzun dönemli ve yüksek kaliteli gözlem verilerinin elde edilmesi amacıyla özellikle yüksek rakımlı ve kırsal alanlarda yeni otomatik meteoroloji istasyonlarının kurulması önerilmektedir.
2. **Su kaynakları yönetiminin iklim değişikliğine uyarlanması:** Artan sıcaklıklar ve düzensiz yağış rejimi dikkate alınarak havza bazlı su yönetim planlarının güncellenmesi, baraj işletme politikalarının iklim projeksiyonları doğrultusunda yeniden düzenlenmesi gerekmektedir.
3. **Tarımsal üretimde iklim uyum stratejilerinin geliştirilmesi:** Kuraklığa dayanıklı çeşitlerin kullanımı, modern sulama sistemlerinin yaygınlaştırılması ve ürün desenlerinin bölgesel iklim değişikliklerine göre yeniden planlanması önem taşımaktadır.

4. **Ekstrem hava olaylarına yönelik erken uyarı sistemlerinin geliştirilmesi:** Sıcak hava dalgaları, kuraklık, ani taşkın ve aşırı yağış olaylarına karşı erken uyarı sistemlerinin güçlendirilmesi, can ve mal kayıplarının azaltılmasına katkı sağlayacaktır.
5. **İleri düzey iklim analiz yöntemlerinin yaygınlaştırılması:** ITA ve IPTA gibi yenilikçi yöntemlerin farklı iklim bölgelerinde uygulanması ve klasik yöntemlerle birlikte kullanılması, iklim değişikliğinin daha ayrıntılı değerlendirilmesine olanak sağlayacaktır.
6. **İklim projeksiyonlarının bölgesel ölçekte hazırlanması:** Geleceğe yönelik iklim senaryoları oluşturularak sıcaklık ve yağış değişimlerinin olası etkileri önceden belirlenmeli ve karar vericilere bilimsel altyapı sağlanmalıdır.

Bu çalışmanın bazı sınırlılıkları da bulunmaktadır. Araştırma yalnızca Akdeniz Bölgesi'ndeki 13 meteoroloji istasyonunu kapsamaktadır. Gelecekte yapılacak çalışmalarda daha geniş istasyon ağı kullanılarak Türkiye genelinde karşılaştırmalı analizler gerçekleştirilebilir. Ayrıca sıcaklık ve yağış parametrelerine ek olarak bağıl nem, buharlaşma, rüzgâr hızı, güneşlenme süresi ve kuraklık indisleri gibi iklim değişkenlerinin de birlikte değerlendirilmesi daha kapsamlı sonuçlar sağlayacaktır. Bunun yanında CMIP6 iklim senaryoları ve bölgesel iklim modelleri kullanılarak geleceğe yönelik projeksiyonların hazırlanması, iklim değişikliğine uyum politikalarının geliştirilmesine önemli katkılar sunacaktır.

Sonuç olarak bu araştırma, Akdeniz Bölgesi'nde uzun dönemli sıcaklık artışlarının belirginleştiğini ve yağış rejiminin daha değişken bir yapıya dönüştüğünü ortaya koymuştur. Klasik parametrik olmayan trend analizleri ile yenilikçi trend analiz yöntemlerinin birlikte uygulanması, iklim değişikliğinin farklı boyutlarının daha ayrıntılı değerlendirilmesini sağlamıştır. Elde edilen bulgular, sürdürülebilir su yönetimi, tarımsal planlama, afet risklerinin azaltılması ve iklim değişikliğine uyum stratejilerinin geliştirilmesi açısından karar vericilere önemli bilimsel veriler sunmaktadır. Bu yönüyle çalışma, hem bölgesel iklim değişikliği literatürüne katkı sağlamakta hem de gelecekte gerçekleştirilecek araştırmalar için kapsamlı bir metodolojik çerçeve oluşturmaktadır.

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KLASİK VE YENİLİKÇİ İSTATİSTİKSEL YÖNTEMLERLE GÜNEYDOĞU ANADOLU BÖLGESİ'NİN UZUN DÖNEMLİ İKLİM TRENDLERİ

LONG-TERM CLIMATE TRENDS IN TÜRKIYE'S SOUTHEASTERN ANATOLIA REGION USING CLASSICAL AND INNOVATIVE STATISTICAL METHODS

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ÖZET
Bu çalışmada Türkiye'nin Güneydoğu Anadolu Bölgesi'nde yer alan altı meteoroloji istasyonunun (Gaziantep, Şanlıurfa, Siverek, Birecik, Ceylanpınar ve Akçakale) 1965–2025 dönemine ait 60 yıllık aylık ortalama sıcaklık (AOS) ve aylık toplam yağış (ATY) verileri kullanılarak iklimsel eğilimler analiz edilmiştir. Eğilimlerin belirlenmesinde parametrik olmayan Mann–Kendall (MK) ve Spearman'ın Rho (SRHO) testleri ile verideki değişimleri düşük, orta ve yüksek değer sınıfları bazında ayrıştıran Yenilikçi Trend Analizi (ITA) ve Yenilikçi Poligon Trend Analizi (IPTA) yöntemleri uygulanmıştır. Elde edilen bulgular, incelenen tüm istasyonlarda aylık ortalama sıcaklıkta %95 güven düzeyinde istatistiksel olarak anlamlı bir artış eğilimi bulunduğunu ortaya koymaktadır. Isınmanın şiddeti istasyonlar arasında farklılaşmakta olup en yüksek yıllık MK Z değerlerine Gaziantep ($Z = 7{,}26$) ve Şanlıurfa ($Z = 6{,}67$) istasyonlarında ulaşılmıştır. Yağış verilerinde genel bir azalma eğilimi gözlenmiş; istatistiksel olarak anlamlı azalış yalnızca Ceylanpınar ($Z = -2{,}53$) ve Akçakale ($Z = -2{,}15$) istasyonlarında tespit edilmiştir. ITA, klasik testlerin yakalayamadığı Şanlıurfa'daki yağış azalışını da belirleyerek yenilikçi yöntemlerin duyarlılık üstünlüğünü ortaya koymuştur. Bulgular, çalışma alanında artan kuraklık baskısına işaret etmektedir.
Anahtar Kelimeler: Trend Analizi, Mann–Kendall, Spearman'ın Rho, ITA, IPTA, Güneydoğu Anadolu, Kuraklık

ABSTRACT
In this study, long-term climatic trends in monthly mean temperature (MMT) and monthly total precipitation (MTP) were analysed for six meteorological stations (Gaziantep, Şanlıurfa, Siverek, Birecik, Ceylanpınar and Akçakale) located in the Southeastern Anatolia Region of Turkey using 60 years of records spanning 1965–2025. Trend detection was carried out with the non-parametric Mann–Kendall (MK) and Spearman's Rho (SR) tests alongside the Innovative Trend Analysis (ITA) and Innovative Polygon Trend Analysis (IPTA) methods. Results show statistically significant increasing temperature trends at the 95 % confidence level across all six stations, with the highest Z-scores at Gaziantep ($Z = 7.26$) and Şanlıurfa ($Z = 6.67$). Precipitation shows a general declining tendency with statistically significant decreases confined to Ceylanpınar ($Z = -2.53$) and Akçakale ($Z = -2.15$). ITA further detects a significant declining trend at Şanlıurfa undetected by classical tests, demonstrating the superior sensitivity of innovative methods. Overall, findings indicate escalating drought pressure in the study area.
Keywords: Trend Analysis, Mann–Kendall, Spearman's Rho, ITA, IPTA, Southeastern Anatolia, Drought

GIRIŞ
İklim değişikliği, 21. yüzyılın en kritik çevre sorunlarından biri olarak kabul edilmekte ve hidrolojik döngü üzerindeki etkileri küresel ölçekte incelenmektedir (IPCC, 2021). Sıcaklık ve yağış gibi temel iklimsel parametrelerdeki uzun dönemli değişimler, su kaynakları yönetimi, kuraklık riski ve tarımsal planlama açısından belirleyici bir öneme sahiptir. Özellikle Akdeniz Havzası ve Orta Doğu gibi yarı-kurak iklim kuşaklarında bu değişimlerin daha hızlı gerçekleştiği ve etkilerinin daha şiddetli olduğu

raporlanmaktadır (Giorgi ve Lionello, 2008; Zittis vd., 2019). Türkiye, coğrafi konumu ve iklim çeşitliliği itibarıyla bu dönüşümlere karşı yüksek kırılganlık gösteren ülkeler arasında yer almaktadır (Türkeş vd., 2002).

Güneydoğu Anadolu Bölgesi, kıta ikliminin ve yarı-kurak Akdeniz etkisinin kesiştiği bir geçiş kuşağında yer almakta; ortalama yıllık yağışın 300–700 mm arasında değiştiği ve yaz mevsiminde yağış neredeyse hiç görülmeyen bir iklim tipine ev sahipliği yapmaktadır. Bölge, Güneydoğu Anadolu Projesi (GAP) kapsamındaki sulama altyapısının yoğunlaştığı ve tarımsal su talebinin sürekli arttığı bir alandır. Bu bağlamda sıcaklık ve yağış eğilimlerinin doğru biçimde belirlenmesi hem mevcut kuraklık riskinin değerlendirilmesi hem de ileriye dönük su yönetimi stratejilerinin tasarlanması açısından hayati önem taşımaktadır.

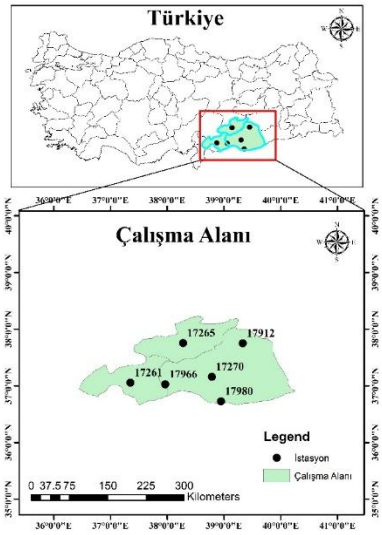
Hidrolojik zaman serilerinde eğilim tespitinde en yaygın kullanılan yöntemler Mann–Kendall (MK) testi (Mann, 1945; Kendall, 1975) ve Spearman'ın Rho (SRHO) testidir. Şen (2012) tarafından geliştirilen Yenilikçi Trend Analizi (ITA), serinin düşük, orta ve yüksek değer sınıflarındaki eğilimleri ayrı ayrı değerlendirmesiyle klasik testlere kıyasla ek bilgi sunmaktadır. Yenilikçi Poligon Trend Analizi (IPTA) ise aylık yarı-dönem ortalamalarını poligon olarak çizerek mevsimsel eğilim dinamiklerini görselleştirmektedir (Şen vd., 2019). Türkiye'de bu yöntemler sıklıkla kullanılmaktadır (Esit vd. 2026; Acar vd. 2025; Akbas vd. 2025; Esit vd. 2025). Bu çalışmada dört yöntem birlikte uygulanmış; sonuçlar istasyon, parametre ve ay ölçeğinde karşılaştırmalı olarak değerlendirilmiştir.

2. ÇALIŞMA ALANI VE VERI

Çalışma alanı, Türkiye'nin güneydoğusunda yaklaşık 36,7°–37,8° kuzey enlemi ile 37,4°–40,0° doğu boylamları arasında yer almaktadır (Şekil 1). Bölge doğuya ve güneye doğru alçalan bir topografik yapıya sahip olup rakım 328 m (Birecik) ile 855 m (Gaziantep) arasında değişmektedir. Alanın güneyinde Suriye sınırı boyunca uzanan düz ovalar, kuzeyde ise Güneydoğu Toroslar'ın uzantısı niteliğindeki dağlık arazi yer almaktadır.

Bölgede Akdeniz iklimi ile kara iklimi arasında geçiş niteliğinde yarı-kurak bir iklim hâkimdir. Yağışların büyük çoğunluğu Ekim–Nisan dönemine sıkışmakta; Mayıs–Eylül arasındaki yedi aylık dönemde yıllık toplam yağışın yalnızca %5–10'u düşmektedir. Yıllık ortalama sıcaklık kuzeyde (Siverek) 13,6°C'den güneyde (Akçakale) 19,5°C'ye yükselmekte; yıllık toplam yağış batıda (Gaziantep) 637 mm'den doğuda (Ceylanpınar) 327 mm'ye gerilemektedir.

Çalışmada Türkiye Meteoroloji Genel Müdürlüğü'nden (MGM) temin edilen 1965–2025 dönemine ait aylık gözlemler kullanılmıştır. Veri seti altı sinoptik istasyona ait aylık ortalama sıcaklık (AOS, °C) ve aylık toplam yağış (ATY, mm) serilerini kapsamakta olup her istasyon için 60 yıllık (720 aylık gözlem) sürekli kayıt mevcuttur. Homojenlik kontrolleri (Pettitt testi ve standart normal homojenlik testi) uygulanmış; tüm serilerde belirgin heterojenlik saptanmamıştır. İstasyonların coğrafi özellikleri ve temel istatistikleri Tablo 1'de özetlenmektedir.



Şekil 1. Çalışma alanı ve meteoroloji istasyonlarının konumu.

Tablo 1. Çalışma alanındaki meteoroloji istasyonlarının coğrafi özellikleri ve temel istatistikleri (1965–2025).

İst. No	İstasyon	Enlem (°K)	Boylam (°D)	Rakım (m)	Dönem	Ort. YOS (°C)	S.S. YOS (°C)	Ort. YTY (mm)	S.S. YTY (mm)
17261	Gaziantep	37,07	37,37	855	1965–2025	16,1	0,88	637	130
17265	Siverek	37,75	39,32	768	1965–2025	13,6	0,91	569	124
17270	Şanlıurfa	37,17	38,78	547	1965–2025	18,4	0,93	450	103
17912	Birecik	37,03	37,98	328	1965–2025	18,8	0,85	468	107
17966	Ceylanpınar	36,85	40,03	453	1965–2025	18,2	0,79	327	86
17980	Akçakale	36,71	38,95	374	1965–2025	19,5	0,82	334	88

Not: YOS = Yıllık ortalama sıcaklık; YTY = Yıllık toplam yağış; S.S. = Standart sapma. Koordinatlar ve rakım MGM istasyon kayıtlarından alınmıştır.

3. Metodoloji

Mann-Kendall (MK) Testi: Mann-Kendall testi, bir zaman serisinde monotonik artan ya da azalan eğilim olup olmadığını belirlemek için geliştirilmiş parametrik olmayan bir yöntemdir (Mann, 1945; Kendall, 1975; Gilbert, 1987). Normal dağılım varsayımı gerektirmemesi en önemli avantajıdır; ancak seri bağımsızlığı varsayımına duyarlıdır ve otokorelasyon sonuçları etkileyebilir (Hirsch vd., 1982; Collaud Coen vd., 2020). Test istatistiği S aşağıdaki gibi hesaplanır:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} sgn(x_j - x_k) \tag{1}$$

$$sgn(x_j - x_k) = \begin{cases} +1, & x_j - x_k > 0 \\ 0, & x_j - x_k = 0 \\ -1, & x_j - x_k < 0 \end{cases} \tag{2}$$

Büyük örneklemlerde standartlaştırılmış test istatistiği ZMK ile değerlendirilir; pozitif değer artan, negatif değer azalan eğilimi gösterir (Gilbert, 1987).

Spearman'ın Rho (SRHO) Testi: Spearman'ın Rho testi, zaman sırası ile gözlem sıraları arasındaki ilişkiyi ölçerek trendi değerlendiren parametrik olmayan bir yöntemdir (Hamed, 2011; Wang vd., 2006). Bağımsız serilerde beklenen değer E(ρ)=0 ve varyans Var(ρ)=1/(n−1) olarak verilir. Ties olmayan durumda Spearman korelasyon katsayısı şu şekilde hesaplanır:

$$\rho_s = 1 - \frac{6 \sum d_i^2}{n(n^2-1)} \tag{3}$$

Burada di sıra farkını; n ise gözlem sayısını göstermektedir. MK testi gibi SRHO da normal dağılım gerektirmez; ancak otokorelasyonun varlığı testin anlamlılığını bozabilir (Hamed, 2011).

Yenilikçi Eğilim Analizi (ITA): Şen (2012) tarafından geliştirilen ITA, bağımsızlık ile normallik varsayımlarını gerektirmeyen bir trend analiz yöntemidir (Alashan, 2020). Zaman serisi iki eşit parçaya ayrılır; her parça küçükten büyüğe sıralanır ve ilk yarı yatay, ikinci yarı düşey eksende karşılaştırılır. Noktaların 1:1 doğrusu üzerinde kalması trendsizliği, üstünde kalması artışı, altında kalması azalışı ifade eder. ITA eğimi şu şekilde hesaplanır:

$$s = \frac{2(\bar{y} - \bar{x})}{n} \tag{4}$$

Burada x̄ ilk yarının, ȳ ikinci yarının ortalaması; n toplam gözlem sayısıdır. ITA'nın en güçlü yanı, düşük, orta ve yüksek değer gruplarındaki farklı eğilimleri ayrı ayrı gösterebilmesidir (Dabanlı vd., 2016; Alashan, 2020).

Yenilikçi Poligon Trend Analizi (IPTA): IPTA, ITA'nın aylık ve mevsimlik geçişleri daha ayrıntılı incelemek için geliştirilmiş biçimidir (Şen vd., 2019). Her ay için ilk ve ikinci yarı ortalamaları

kullanılarak noktalar birleştirilir ve bir trend poligonu elde edilir (Alashan vd., 2024). Mevsimsel geçiş uzunluğu ve geçiş eğimi sırasıyla şu şekilde tanımlanır:

$$L_j = \sqrt{(y_{j+1} - y_j)^2 + (x_{j+1} - x_j)^2} \tag{5}$$

$$e_j = (y_{j+1} - x_{j+1}) - (y_j - x_j) \tag{6}$$

Bu yöntem, özellikle hangi aylarda veya mevsimlerde trend kırılması ve yön değişimi olduğunu görsel ve niceliksel olarak ortaya koymaktadır (Şen vd., 2019; Alashan vd., 2024).

4. BULGULAR

4.1. Yıllık Eğilim Analizi

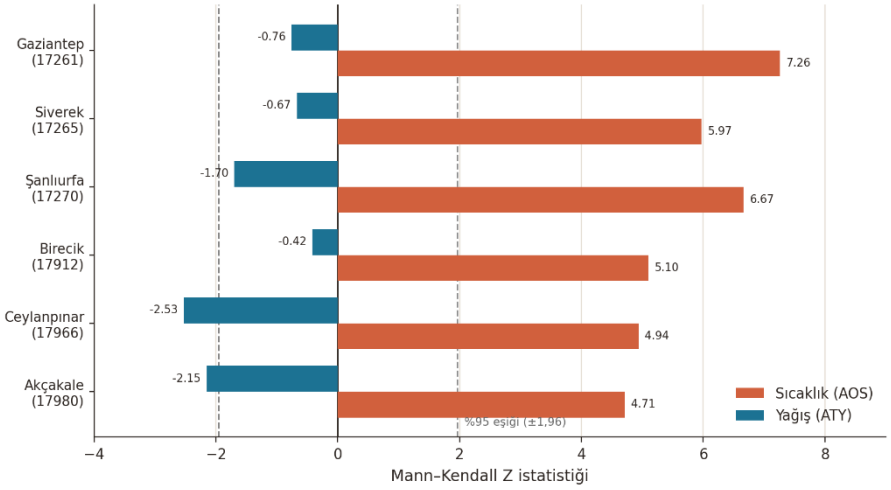
Yıllık AOS ve ATY serilerine ait MK, SRHO ve ITA sonuçları Tablo 2'de, istasyonlar arası karşılaştırmalı grafik ise Şekil 2'de sunulmaktadır. Sıcaklık açısından değerlendirildiğinde, altı istasyonun tamamında her üç yöntem de %95 güven düzeyinde istatistiksel olarak anlamlı artış eğilimi belirlemiştir. MK Z değerleri 4,71 (Akçakale) ile 7,26 (Gaziantep) arasında değişmekte olup tüm değerler eşik değerin (±1,96) çok üzerinde kalmaktadır. ITA eğimleri 1,18 ile 3,17 °C arasındadır ve her istasyonda güven aralığını aştığı için ITA da anlamlı artış kararı vermektedir. Yöntemler arasında tam uyum gözlemlenmektedir.

Yağış eğilimlerinde tablo çok daha heterojen bir tablo sergilemektedir. MK ve SRHO testleri yalnızca Ceylanpınar (Z = −2,53) ve Akçakale (Z = −2,15) istasyonlarında %95 güven düzeyinde anlamlı azalış saptamıştır. Şanlıurfa'da MK Z değeri −1,699 olarak hesaplanmış; bu değer %90 anlamlılık eşiğine (±1,645) yakın olmakla birlikte %95 eşiğini (±1,96) aşamamıştır. Buna karşın ITA eğimi −80,22 mm olarak belirlenmiş ve güven aralığının (±28,33 mm) belirgin biçimde dışına çıkmıştır; dolayısıyla ITA Şanlıurfa için anlamlı yağış azalışı kararı vermiştir. Gaziantep, Siverek ve Birecik'te her üç yöntem de anlamlı eğilim bulamamıştır.

Tablo 2. Yıllık ölçekte Mann–Kendall (MK), Spearman'ın Rho (SRHO) ve ITA sonuçları.

İstasyon	Veri	MK Z	SRHO	ITA Eğim	ITA %95 CL (±)	Karar (MK/SRHO)	Karar (ITA)
Gaziantep	AOS	7,263	8,126	3,174	±0,197	**Artış***	**Artış***
Siverek	AOS	5,975	6,265	2,204	±0,164	**Artış***	**Artış***
Şanlıurfa	AOS	6,665	7,128	2,608	±0,176	**Artış***	**Artış***
Birecik	AOS	5,097	5,206	1,889	±0,158	**Artış***	**Artış***
Ceylanpınar	AOS	4,941	5,119	1,562	±0,131	**Artış***	**Artış***
Akçakale	AOS	4,712	4,813	1,182	±0,146	**Artış***	**Artış***
Gaziantep	ATY	−0,759	−0,756	24,333	±26,369	**Yok**	**Yok**
Siverek	ATY	−0,672	−0,748	−0,772	±35,713	**Yok**	**Yok**
Şanlıurfa	ATY	−1,699	−1,654	−80,220	±28,332	**Yok†**	**Azalış***
Birecik	ATY	−0,417	−0,419	−23,773	±28,307	**Yok**	**Yok**
Ceylanpınar	ATY	−2,527	−2,502	−64,153	±19,418	**Azalış***	**Azalış***
Akçakale	ATY	−2,153	−1,970	−62,620	±19,590	**Azalış***	**Azalış***

Not: AOS = Aylık ortalama sıcaklık; ATY = Aylık toplam yağış. * %95 güven düzeyinde anlamlı (|Z| ≥ 1,96 için MK/SRHO; |eğim| > CL için ITA). † %90 düzeyinde sınır değer. ITA CL = %95 güven limiti.

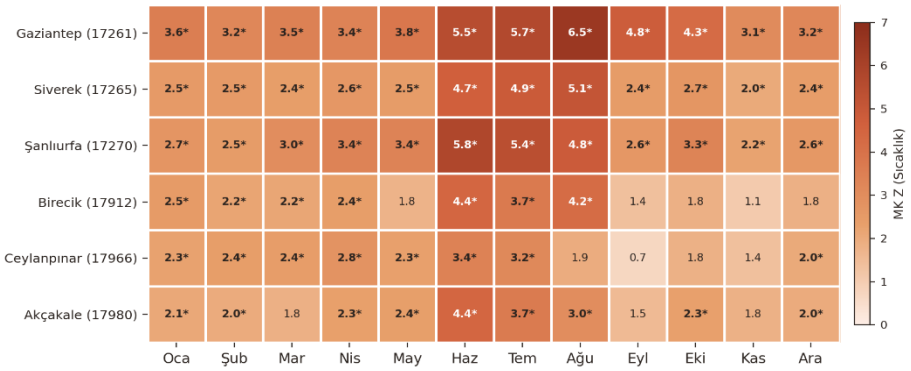


Şekil 2. Altı istasyon için yıllık Mann–Kendall Z istatistikleri. Kesik çizgiler ±1,96 eşiğini göstermektedir.

4.2. Aylık Sıcaklık (AOS) Eğilim Analizi

Aylık MK Z değerlerinden oluşan ısı haritası (Şekil 3) incelendiğinde sıcaklıktaki artış eğiliminin yılın tüm aylarında ve tüm istasyonlarda hâkim olduğu görülmektedir. Yıl boyunca hiçbir hücre istatistiksel olarak anlamlı azalış göstermemekte; büyük çoğunluğu ise %95 güven düzeyini aşmaktadır (* ile işaretli). Yazın (Haziran–Temmuz–Ağustos) Z değerleri belirgin biçimde yükselmekte; en güçlü ısınma sinyali Gaziantep'in Ağustos ayında (Z = 6,47) gözlemlenmektedir. Şanlıurfa'nın Haziran Z değeri ise 5,77 ile en yüksek ikinci değeri oluşturmaktadır.

Sonbahar aylarında (Eylül–Ekim) Z değerleri görece düşmekte; özellikle Ceylanpınar Eylül (Z = 0,69) ve Birecik Kasım (Z = 1,08) değerleri anlamlılık eşiğinin altında kalmaktadır. Bununla birlikte bu istasyonlarda kış ve yaz aylarında anlamlı artışlar tespit edilmekte olup eğilimin sezonsal zayıflaması geçici ve istasyon özgü bir durum olarak değerlendirilebilir. Genel olarak bölge genelinde homojen ve güçlü bir ısınma sinyali hâkimdir; en yoğun ısınma sinyalleri bölgenin kuzeyindeki (Gaziantep, Şanlıurfa) daha yüksek rakımlı ve şehirleşmiş istasyonlarda bulunmaktadır.

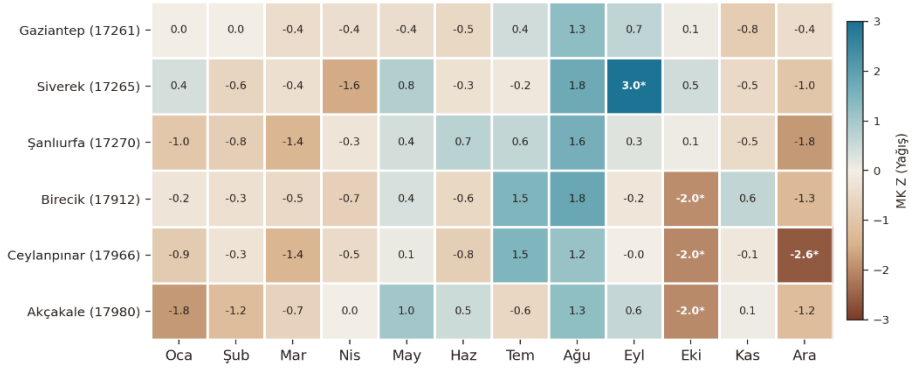


Şekil 3. Aylık ortalama sıcaklık (AOS) için Mann–Kendall Z ısı haritası. * %95 güven düzeyinde anlamlı eğilim.

4.3. Aylık Yağış (ATY) Eğilim Analizi

Aylık yağış MK Z ısı haritası (Şekil 4) sıcaklıktan çok daha karmışık ve değişken bir örüntü sergilemektedir. Genel olarak kışın (Ocak–Şubat–Mart) ve geç sonbaharda (Ekim–Aralık) azalış yönündeki renkler (kahverengi tonlar) hâkimken yaz aylarında (Temmuz–Ağustos) zayıf artış sinyalleri dikkat çekmektedir. Ancak bu yaz artışlarının hiçbiri %95 güven düzeyine ulaşamamaktadır; yaz yağışları bölgede zaten çok düşük olduğundan mutlak değerlerinin sınırlı kalması beklenen bir bulgudur. Anlamlı azalış sinyalleri ağırlıklı olarak Ceylanpınar ve Akçakale istasyonlarında ve Ekim–Aralık döneminde yoğunlaşmaktadır. Ceylanpınar Aralık (Z = −2,61) ve Ekim (Z = −2,04) ile Akçakale Ekim (Z = −2,01) değerleri anlamlılık eşiğini geçmektedir. Siverek Eylül ayında tek pozitif anlamlı değer

(Z = 2,96) gözlemlenmiş; bu bulgu, kuzey istasyonlarında erken sonbahar yağışlarında lokal bir artışa işaret etmektedir. Şanlıurfa kış ayları (Ocak–Mart) ise MK Z değerleri −0,79 ile −0,97 arasında kalmakta, yani sınır değere yakın fakat altındadır; ITA bu dönemde anlamlı azalış sinyal yakalamaktadır.



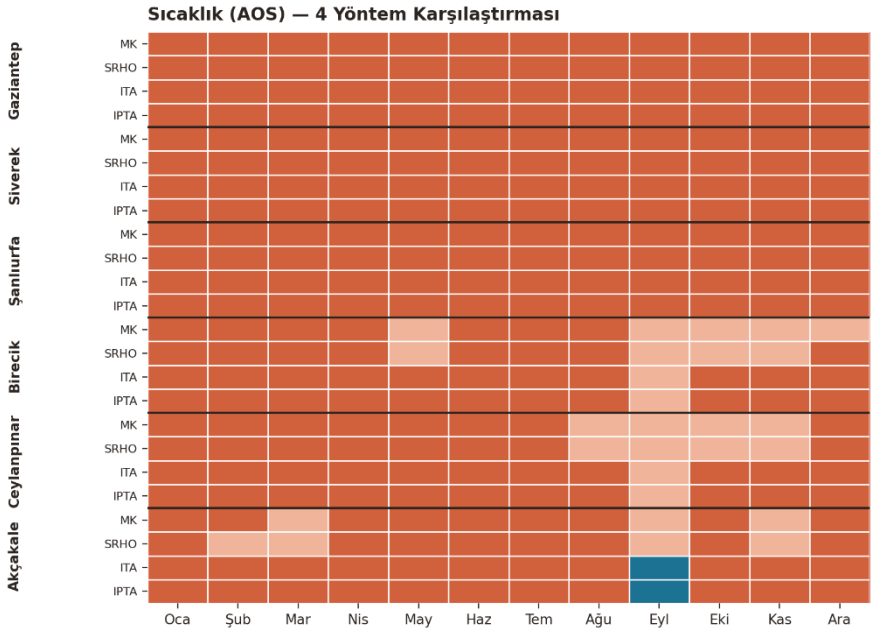
Şekil 4. Aylık toplam yağış (ATY) için Mann–Kendall Z ısı haritası. Kahverengi = azalış, mavi = artış, * %95 anlamlı.

4.4. Aylık Yöntem Karşılaştırması (MK · SRHO · ITA · IPTA)

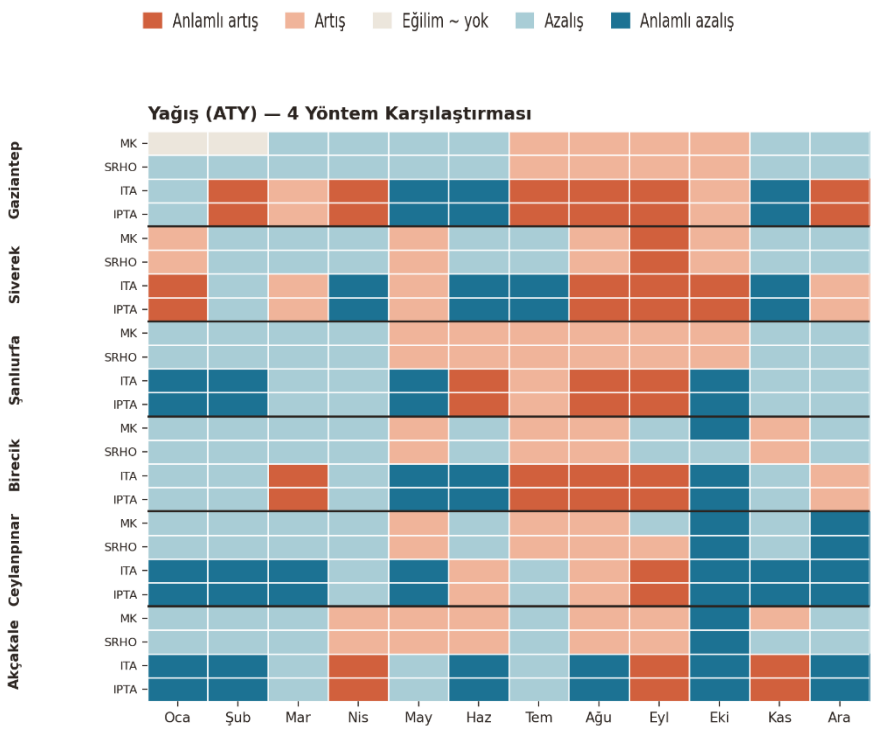
Dört yöntemin aylık karar haritaları Şekil 5a (AOS) ve Şekil 5b (ATY) olarak sunulmaktadır. Her istasyon için dört satır (MK, SRHO, ITA, IPTA sıralamasıyla) bulunmakta; beş renkli kategoriden oluşan lejant anlamlı artış ile anlamlı azalış arasındaki spektrumu temsil etmektedir.

Sıcaklık haritasında (Şekil 5a) dört yöntemin tamamı neredeyse tüm istasyon–ay kombinasyonlarında anlamlı artış (koyu kırmızı) kararı vermektedir; yöntemler arasında sistematik bir ayrışma gözlemlenmemektedir. Tek belirgin istisna Akçakale Eylül'üdür: MK ve SRHO zayıf artış tespit ederken ITA ve IPTA bu ayda anlamlı azalış kararı vermektedir. Bu durum, söz konusu ayda düşük sıcaklık değerlerinin farklı dinamikler sergilediğine işaret edebilir.

Yağış haritasında (Şekil 5b) en belirgin örüntü, ITA ve IPTA'nın MK ile SRHO'ya göre daha fazla anlamlı sinyal (hem azalış hem artış yönünde) yakalamasıdır. Şanlıurfa'da kış aylarında MK ve SRHO birkaç istisna dışında anlamlı eğilim belirleyemezken ITA anlamlı azalış kararı vermektedir. Bu bulgu, ITA'nın özellikle zayıf büyüklüklü eğilimlerin var olduğu kış dönemlerinde daha duyarlı çalıştığını ve iklimsel sinyal yakalama gücünün MK/SRHO'dan üstün olduğunu göstermektedir.



Şekil 5a. Aylık ortalama sıcaklık (AOS) için dört yöntem karşılaştırma haritası (MK, SRHO, ITA, IPTA).



Şekil 5b. Aylık toplam yağış (ATY) için dört yöntem karşılaştırma haritası (MK, SRHO, ITA, IPTA).

Anlamlı artış Artış Eğilim ~ yok Azalış Anlamlı azalış

5. TARTIŞMA VE SONUÇ

5.1. Tartışma

Çalışmada elde edilen yıllık ısınma eğilimleri (MK Z: 4,71–7,26), Güneydoğu Anadolu'da son yarım yüzyılda yaşanan güçlü ve homojen ısınmayı doğrular niteliktedir. Bu bulgular, Türkeş vd. (2002)'nin Türkiye genelinde ve güney bölgelerde saptadığı sıcaklık artışlarıyla örtüşmektedir. ITA eğimlerinin 1,18–3,17 °C/60 yıl aralığında bulunması, bu süreçte on yılda yaklaşık 0,19–0,53 °C'lik bir ısınmaya karşılık gelmektedir; bu değerler küresel ortalama ısınma hızının (yaklaşık 0,18 °C/on yıl, IPCC 2021) bölge genelinde aşıldığına işaret etmektedir. Bölgenin orta ve düşük rakımlı kesimlerindeki (Akçakale, Ceylanpınar) nispeten daha düşük ITA eğimleri ise bu istasyonların uzun dönemde zaten yüksek sıcaklık temel değerlerine sahip olduğunu ve termal genişleme payının sınırlandığını düşündürmektedir.

Yağış eğilimleri konusunda elde edilen bulgular hem yöntemsel hem de iklimsel açıdan önem taşımaktadır. MK ve SRHO testlerinin Ceylanpınar ve Akçakale'de anlamlı yağış azalışı saptaması, Önol ve Semazzi (2009)'un GAP bölgesi için öngördüğü uzun dönemli azalış senaryolarıyla ve Zittis vd. (2019)'nin Doğu Akdeniz'de belirlediği kuraklaşma eğilimiyle örtüşmektedir. Şanlıurfa'da ise MK Z değerinin (−1,699) eşik değere yakın kalmasına karşın ITA'nın anlamlı azalış kararı vermesi dikkat çekicidir. Bu durum, ITA'nın özellikle yağış gibi yüksek değişkenlik gösteren serilerde zayıf büyüklüklü eğilimleri belirlemede daha duyarlı olduğunu göstermekte (Güçlü, 2018) ve çalışma bulgularıyla doğrudan uyuşmaktadır. Siverek Eylül'deki pozitif yağış sinyali ise Güneydoğu Toroslar'ın eteklerinde görülen lokal orografik artışların muhtemel bir yansıması olarak değerlendirilebilir.

IPTA grafikleri klasik testlerden farklı olarak eğilimin hangi mevsimde yoğunlaştığını ve sıcaklık–yağış döngüsünün nasıl kaydığını görselleştirmektedir. Sıcaklık poligonunun diyagonalin bütünüyle üzerinde yer alması tüm mevsimlerin ısındığını teyit etmekte; yağış poligonunun kış noktalarında diyagonalin altına düşmesi ise yağışlı mevsimin giderek kısaldığını ve yağış miktarının azaldığını ortaya koymaktadır. Bu örüntünün, sulama sezonunun genişlemesi ve kış tahıllarının su ihtiyacının karşılanması açısından kritik sonuçları bulunmaktadır.

Çalışmanın başlıca kısıtı, gözlem istasyonu sayısının altı ile sınırlı kalmasıdır. Bu istasyonlar bölgenin merkezi kesimini temsil etmekle birlikte kuzeydoğudaki dağlık alanlar ve Fırat–Dicle havzalarının yukarı çığırları yeterince kapsanamamaktadır. Öte yandan, kentsel ısı adası etkisinin (özellikle

Gaziantep ve Şanlıurfa'da) gözlemlenen ısınma büyüklüğüne katkısı bu çalışmada ayrıca değerlendirilmemiştir; gelecek araştırmalarda bu katkının ayrıştırılması önerilmektedir.

5.2. Sonuç

Bu çalışmada Güneydoğu Anadolu'da altı meteoroloji istasyonuna ait 1965–2025 dönemi aylık sıcaklık ve yağış verileri MK, SRHO, ITA ve IPTA yöntemleriyle analiz edilmiştir. Elde edilen başlıca sonuçlar aşağıda özetlenmektedir:

1. Sıcaklık eğilimleri: Altı istasyonun tamamında, yılın her ayında ve her üç yöntemde %95 güven düzeyinde anlamlı artış eğilimi saptanmıştır. En güçlü ısınma Gaziantep (MK $Z = 7{,}26$; ITA eğimi = 3,17 °C) ve Şanlıurfa'da ($Z = 6{,}67$) gözlemlenmiştir. Mevsimsel olarak ısınma yaz aylarında belirginleşmektedir.

2. Yağış eğilimleri: Anlamlı azalış yalnızca Ceylanpınar ve Akçakale istasyonlarında (MK $Z < -1{,}96$) ve aylık ölçekte ağırlıklı olarak sonbahar–kış döneminde (Ekim, Aralık) saptanmıştır. Gaziantep, Siverek ve Birecik'te anlamlı yağış eğilimi belirlenmemiştir.

3. ITA duyarlılığı: ITA, Şanlıurfa yağış serisinde MK ve SRHO'nun eşik altında bıraktığı anlamlı azalış sinyalini (ITA eğimi = −80,22 mm; CL = ±28,33 mm) yakalamıştır. Bu bulgu, ITA'nın zayıf büyüklüklü eğilimlerde klasik testlerden daha duyarlı olduğunu doğrulamaktadır.

4. IPTA katkısı: Sıcaklık IPTA grafikleri tüm aylardaki homojen ısınmayı tek görsel üzerinde ortaya koyarken yağış IPTA grafikleri kış aylarındaki azalışın mevsimsel konumunu görselleştirerek yönetimsel karar süreçlerine ek bilgi sunmuştur.

5. Bölgesel çıkarımlar: Eş zamanlı güçlü ısınma ve kışlık yağış azalışı örüntüsü, bölgede artan buharlaşma talebi ve azalan su girişiminin bir arada seyrettiğine işaret etmektedir. Bu durum, GAP sulama alanlarında tarımsal su yönetiminin ve kuraklık izleme sistemlerinin yeniden kalibre edilmesini zorunlu kılmaktadır.

Gelecek çalışmalarda kentsel ısı adası etkisinin ayrıştırılması, istasyon ağının genişletilmesi ve iklim model projeksiyonlarıyla bulguların karşılaştırılması bölgesel iklim değişikliği analizinin derinleştirilmesine katkı sağlayacaktır.

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FISHERIES MANAGEMENT RISK ASSESSMENT UNDER CLIMATE CHANGE: A CONCEPTUAL FRAMEWORK FOR CLIMATE-RESILIENT FISHERIES

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ABSTRACT
Climate change is creating a multidimensional transformation process that simultaneously affects the ecological, economic and social dimensions of global fisheries management. Ocean warming, acidification, deoxygenation, sea-level rise, marine heatwaves and extreme weather events are altering fish population distributions, reproductive success, growth rates, migration patterns, habitat quality and food-web interactions. These environmental changes influence not only the functioning of marine ecosystems, but also catch efficiency, the location of fishing grounds, operational costs, income stability, food security and the livelihoods of coastal communities dependent on fisheries. This paper presents a conceptual and literature-based framework for assessing climate change-related risks in fisheries management. The main objective of the study is to synthesize the key climate hazards affecting fisheries systems, organize ecological, economic and social risk dimensions within an integrated risk-assessment approach, and discuss climate-informed management options that can strengthen resilience. The assessment emphasizes that risk emerges from the interaction of hazard, exposure, sensitivity and adaptive capacity. In this context, effective fisheries management under climate uncertainty requires ecosystem-based fisheries management, climate-informed stock assessment, adaptive harvest control rules, early warning systems, habitat protection, livelihood diversification and participatory adaptive governance. The paper also highlights that fisheries risk assessment should not be limited to biological stock status, but should also include socioeconomic vulnerability, institutional preparedness and food-security outcomes. Overall, climate-informed risk assessment should be considered a core management tool for reducing vulnerability, prioritizing adaptation actions and supporting the conservation and sustainable use of marine living resources under changing climate conditions.
Keywords: Climate change; Fisheries management; Risk assessment; Climate vulnerability; Ecosystem-based fisheries management; Adaptive management; Fisheries resilience

INTRODUCTION
Climate change has become one of the most influential drivers shaping the future of marine ecosystems and fisheries worldwide. The rapid accumulation of greenhouse gases in the atmosphere has altered oceanographic conditions through ocean warming, acidification, deoxygenation, sea-level rise, marine heatwaves and extreme weather events (Intergovernmental Panel on Climate Change [IPCC], 2023). These changes modify ecosystem structure and functioning and create new challenges for the sustainable management of fisheries resources.

Fisheries and aquaculture are central to global food security, employment, trade and coastal livelihoods. The Food and Agriculture Organization of the United Nations (FAO, 2024) reported that global fisheries and aquaculture production reached 223.2 million tonnes in 2022, including 185.4 million tonnes of aquatic animals and 37.8 million tonnes of algae. Because 89% of aquatic animal production was used for direct human consumption, climate-driven disruptions in fisheries productivity have implications not only for ecological sustainability, but also for nutrition, income generation and social stability.

Historically, fisheries management has focused mainly on controlling fishing mortality through quotas, effort controls, gear restrictions, seasonal closures and stock rebuilding plans. However, many of these tools were designed under the assumption that environmental conditions are relatively stable. Climate change challenges this assumption by altering productivity, recruitment success, species distributions and ecosystem interactions (Brander, 2010; Pinsky et al., 2018; Free et al., 2019).

Previous syntheses have also emphasized that climate change increases the vulnerability of fisheries and aquaculture systems by affecting biological productivity, fishing opportunities, coastal infrastructure and socioeconomic resilience (Brugère, 2015). In this context, fisheries management increasingly

requires risk-assessment frameworks that can identify climate hazards, evaluate exposure and sensitivity, assess adaptive capacity and support adaptive decision-making.

The aim of this study is to develop a conceptual framework for assessing climate-related ecological, economic, and social risks within fisheries management and to connect this framework with practical adaptation strategies. By synthesizing climate hazards, vulnerability dimensions, risk assessment components, and adaptive management responses into an integrated framework, the chapter provides a structured basis for understanding how climate change influences fisheries systems. This synthesis is intended to support interdisciplinary dialogue and inform future research, management practices, and policy development aimed at enhancing the resilience and sustainability of fisheries under changing environmental conditions. The overall conceptual pathway underpinning this study is illustrated in Figure 1, which links climate change drivers to ecological and socioeconomic impacts, risk assessment processes, and adaptive management responses.

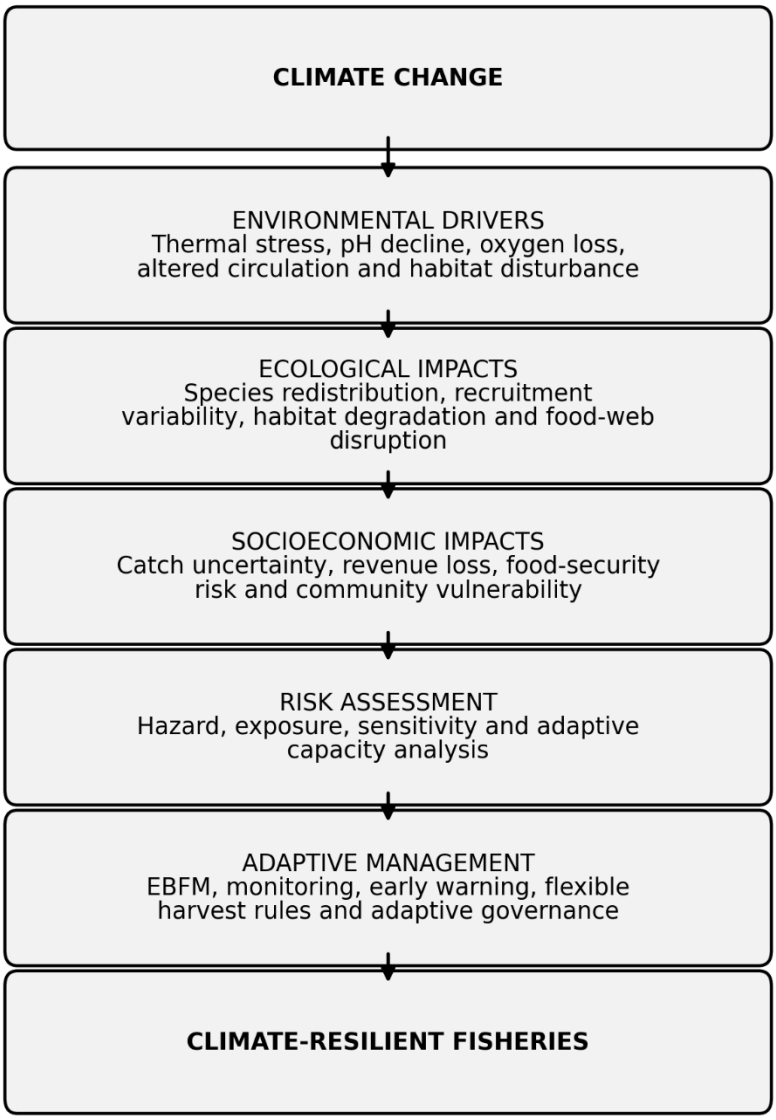

Figure 1. Conceptual pathway linking climate change drivers, fisheries risks and adaptive management responses. Authors' own elaboration based on IPCC (2023), FAO (2024), Pinsky et al. (2018), Free et al. (2019), and Bahri et al. (2021).

REVIEW APPROACH AND CONCEPTUAL BASIS

Figure 1 presents the overarching conceptual structure of this chapter. The framework shows that climate change affects fisheries systems through multiple environmental drivers, including thermal stress, ocean

acidification, oxygen decline and habitat disturbance. These drivers generate ecological impacts such as species redistribution, recruitment variability and habitat degradation, which may then cascade into socioeconomic consequences by altering catch stability, fishing opportunities, income security and community well-being. The resulting risks are assessed through the interacting components of hazard, exposure, sensitivity and adaptive capacity, providing a conceptual basis for identifying appropriate adaptive management responses and strengthening climate-resilient fisheries systems.

This study is designed as a conceptual, literature-based assessment prepared for conference presentation. It does not present a new empirical dataset, a quantitative vulnerability index or a statistical model. Instead, it synthesizes the main risk pathways identified in peer-reviewed fisheries-climate literature and major institutional reports, especially those published by the IPCC and FAO.

The conceptual synthesis is organized around four analytical components: climate-related hazards, ecological vulnerability, socioeconomic risk and adaptive management response. The core risk logic follows the widely used climate-risk structure in which overall risk emerges from the interaction of hazard, exposure and sensitivity, while strong adaptive capacity reduces vulnerability (Comte, 2021; Hare et al., 2016; IPCC, 2023).

Accordingly, the figures and tables presented in this study are intended as explanatory and conceptual tools rather than outputs of a primary quantitative analysis. In particular, the vulnerability gradient illustrated in Figure 2 should be interpreted as an illustrative, literature-based conceptual ranking and not as an empirically derived or quantitatively validated score

CLIMATE CHANGE AND MARINE ECOSYSTEM TRANSFORMATION

Marine ecosystems are highly sensitive to climate change because temperature, oxygen concentration, pH, salinity and circulation patterns regulate biological productivity and species interactions. Ocean warming is among the most documented consequences of climate change. The IPCC reports that warming and acidification have already adversely affected food production from fisheries and shellfish aquaculture in some regions (IPCC, 2023).

Rising temperatures affect fish physiology, growth, reproduction, migration and mortality. Many marine species are shifting poleward or moving into deeper waters to remain within suitable thermal habitats (Pinsky et al., 2018). Such redistribution creates major governance challenges because fish stocks may move across national boundaries, management areas or historical fishing grounds.

Ocean acidification is another major stressor. As oceans absorb atmospheric carbon dioxide, seawater pH declines and carbonate availability is reduced for calcifying organisms such as shellfish, corals and some planktonic organisms (Gattuso et al., 2015). These effects can disrupt food webs and reduce the productivity of fisheries that depend on calcifying species.

Marine deoxygenation further increases ecological stress. Warmer waters hold less dissolved oxygen, while stratification can reduce oxygen supply to deeper layers. Declining oxygen can compress suitable habitats, increase mortality and reduce ecosystem productivity (Breitburg et al., 2018). The main climate drivers affecting fisheries systems and their ecological, economic and social impacts are summarized in Table 1.

Table 1. Major climate change drivers and their potential impacts on fisheries systems. Adapted from IPCC (2023), FAO (2024), Cheung et al. (2013), Free et al. (2019), and Breitburg et al. (2018).

Climate driver	Ecological impacts	Economic impacts	Social implications
Ocean warming	Species redistribution, altered spawning periods, increased mortality and trophic mismatch	Reduced catch rates, higher fuel use, increased operational costs and changing fishing grounds	Livelihood instability and greater uncertainty for fishing households
Ocean acidification	Reduced shell formation, coral reef degradation and food-web disruption	Potential shellfish losses and reduced seafood supply from sensitive species	Food-security concerns in communities dependent on marine protein

Climate driver	Ecological impacts	Economic impacts	Social implications
Deoxygenation	Habitat compression, fish mortality and reduced ecosystem productivity	Lower catch efficiency and higher uncertainty in fishing operations	Reduced resource availability and greater pressure on coastal livelihoods
Sea-level rise	Coastal habitat loss, mangrove degradation and nursery-ground disturbance	Damage to landing sites, ports and coastal infrastructure	Community displacement and increased vulnerability of low-lying settlements
Marine heatwaves	Fish kills, regime shifts, biodiversity loss and abrupt ecosystem changes	Revenue fluctuations, market instability and emergency response costs	Employment uncertainty and disruption of local seafood supply
Extreme weather events	Habitat destruction, stock variability and coastal ecosystem disturbance	Operational disruption, vessel damage and gear losses	Increased coastal vulnerability and safety risks for fishers

ECOLOGICAL RISK ASSESSMENT

Ecological risks represent the biological and ecosystem-level consequences of climate change. These include species redistribution, recruitment failure, habitat degradation, trophic mismatch, biodiversity loss and ecosystem regime shifts.

Species redistribution is one of the most visible ecological responses to climate change. As ocean temperatures rise, fish populations may move toward cooler regions or deeper habitats. Pinsky et al. (2018) emphasized that species movement creates new governance problems because fisheries management systems are often geographically fixed, whereas marine species are increasingly mobile.

Recruitment variability is another important ecological risk. Changes in temperature, oxygen availability, spawning habitat and food supply can alter larval survival and juvenile recruitment. When recruitment becomes unstable, stock-assessment models become less reliable and management uncertainty increases.

Climate change may also cause habitat degradation. Coral reefs, mangroves, seagrass beds, estuaries and coastal wetlands provide essential spawning, nursery and feeding habitats for many fish species. Loss or degradation of these habitats can reduce fisheries productivity and resilience. These ecological changes do not remain isolated within ecosystems; they can also trigger economic losses by reducing catch predictability and increasing operational costs.

Although ecological risk is primarily expressed through species redistribution, recruitment variability and habitat degradation, these pressures do not affect all fisheries systems equally. The relative vulnerability of each system depends on the combined influence of ecological exposure, dependence on climate-sensitive resources, livelihood flexibility and adaptive capacity. Small-scale tropical and artisanal coastal fisheries are therefore expected to experience higher vulnerability because they often depend strongly on local marine resources, have limited mobility and possess fewer financial or institutional options for adaptation. In contrast, industrial fisheries and diversified aquaculture systems may have relatively greater adaptive capacity through technology, capital investment, market flexibility and management support. Figure 2 illustrates this system-level vulnerability gradient as a conceptual, literature-based ranking rather than as an empirically calculated score

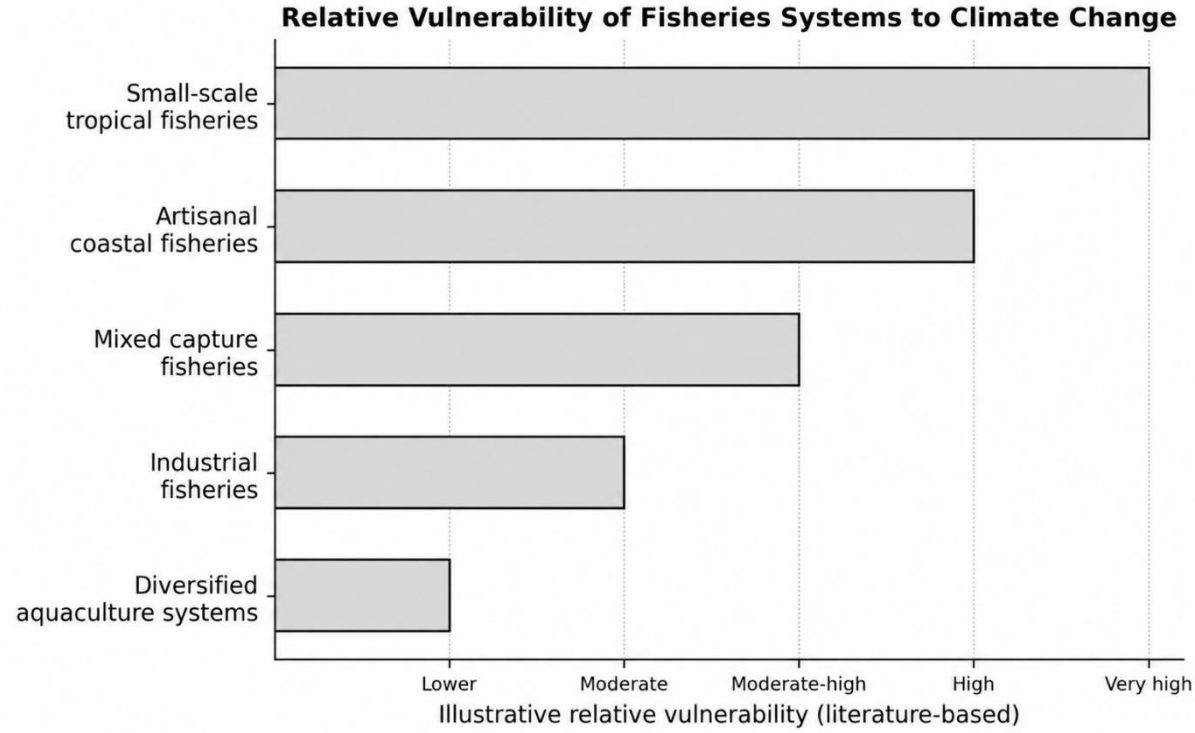

Figure 2. Conceptual relative vulnerability of fisheries systems to climate change.
The ranking represents an illustrative, literature-based vulnerability gradient rather than an empirically calculated score. Higher vulnerability reflects the combined influence of ecological exposure, livelihood dependence and limited adaptive capacity (Brugère, 2015; Comte, 2021; FAO, 2024; Hare et al., 2016; Lam et al., 2016; Sumaila et al., 2019).

ECONOMIC RISK ASSESSMENT

Climate change creates economic risks across the entire seafood value chain. Changes in fish abundance and distribution can reduce catch rates, increase fuel costs, disrupt processing activities, alter market supply and reduce profitability. Fisheries that depend on a limited number of climate-sensitive species may experience particularly high economic vulnerability.

Free et al. (2019) showed that historical ocean warming has already affected the productivity of many marine fish populations. This indicates that climate change is not only a future threat but also an ongoing factor influencing fisheries production. Cheung et al. (2013) similarly showed that ocean warming has already left a detectable signal in global fisheries catches. Economic risks are especially important for developing coastal states, where fisheries may contribute substantially to employment, export income and food supply. When catch declines or fishing grounds shift, fishers may need to travel farther, invest in new gear, change target species or exit the sector. These adjustments can increase costs and reduce profitability.

Revenue decline and market instability can also generate cascading social effects. Income loss, employment insecurity and declining affordability of fish products may undermine household welfare, particularly in communities with high dependence on small-scale fisheries.

SOCIAL RISK ASSESSMENT

Social risks include food insecurity, livelihood loss, poverty, migration pressure and reduced well-being in fisheries-dependent communities. These risks are particularly severe in regions where fish provides a major source of animal protein, micronutrients and household income (Golden et al., 2016). Small-scale fisheries are often more vulnerable than industrial fisheries because they generally have more limited access to insurance, credit, alternative employment, technology and political representation. Climate impacts may also interact with existing social inequalities, disproportionately affecting women, Indigenous communities and low-income coastal households.

In this context, fisheries risk assessment should not focus only on fish stocks or ecological indicators. It should also consider community dependence, adaptive capacity, institutional support and food-security outcomes. Social risk is therefore not treated as an isolated outcome, but as part of a cascading process linking ecological change, economic disruption and community vulnerability. Climate-driven ecological changes may reduce catch predictability, alter fishing grounds and increase operational uncertainty. These changes can then affect income stability, employment, seafood availability and household welfare. Figure 3 summarizes this integrated pathway by showing how ecological impacts and economic disruption interact to intensify social vulnerability in fisheries-dependent communities.

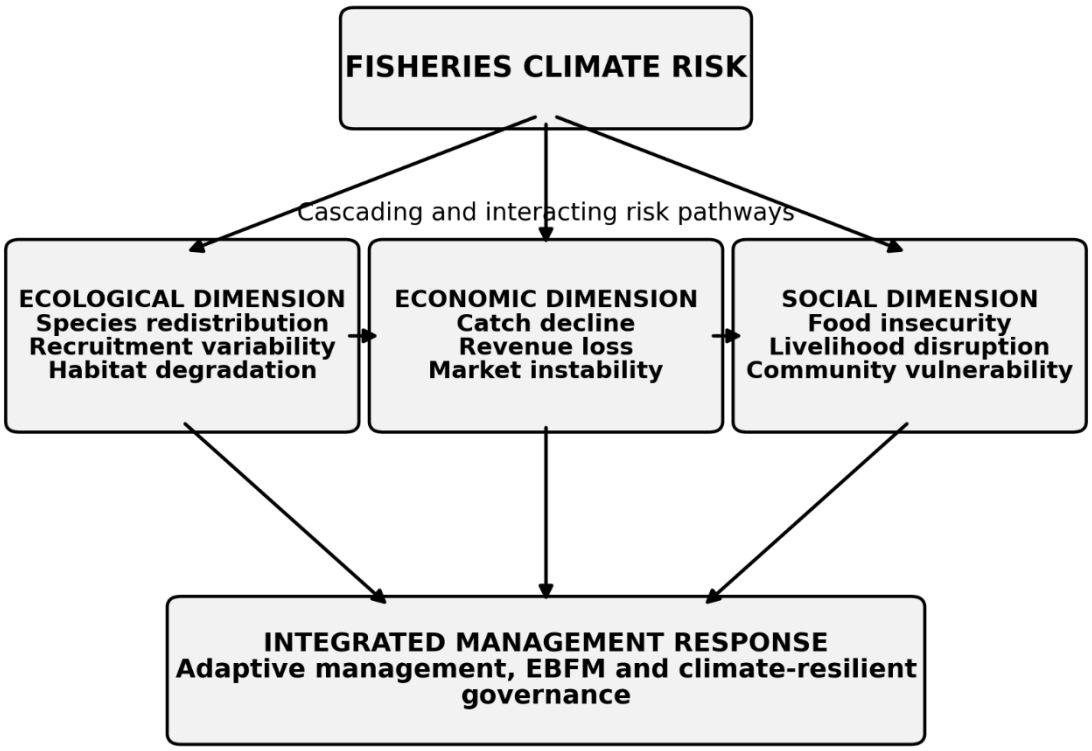

Figure 3. Integrated ecological, economic and social dimensions of climate risk in fisheries systems.

The figure illustrates how ecological changes may reduce economic performance and how economic disruption can intensify food insecurity, livelihood loss and community vulnerability. Authors' own elaboration based on IPCC (2023), FAO (2024), Comte (2021), and Golden et al. (2016).

CLIMATE RISK ASSESSMENT FRAMEWORK FOR FISHERIES MANAGEMENT

Risk assessment is a systematic process used to identify, evaluate and prioritize threats that may affect fisheries sustainability. Under climate change, risk is commonly understood as the interaction of hazard, exposure, sensitivity and adaptive capacity. This approach is consistent with the broader climate-risk framework used by the IPCC and with species vulnerability assessment methods applied in fisheries science (Comte, 2021; Hare et al., 2016; IPCC, 2023).

In fisheries management, hazards include climate-related stressors such as ocean warming, acidification, hypoxia, storms and marine heatwaves. Exposure refers to the extent to which fish stocks, habitats, fleets or communities encounter these hazards. Sensitivity represents biological or socioeconomic susceptibility to harm. Adaptive capacity reflects the ability of fish populations, institutions, markets and communities to respond, recover or adjust.

The framework should not be interpreted only as a biological stock-assessment tool. It can also be used to evaluate social vulnerability, institutional preparedness and management priorities. The basic structure of climate risk assessment in fisheries is shown in Figure 4, while the operational components of the framework are summarized in Table 2.

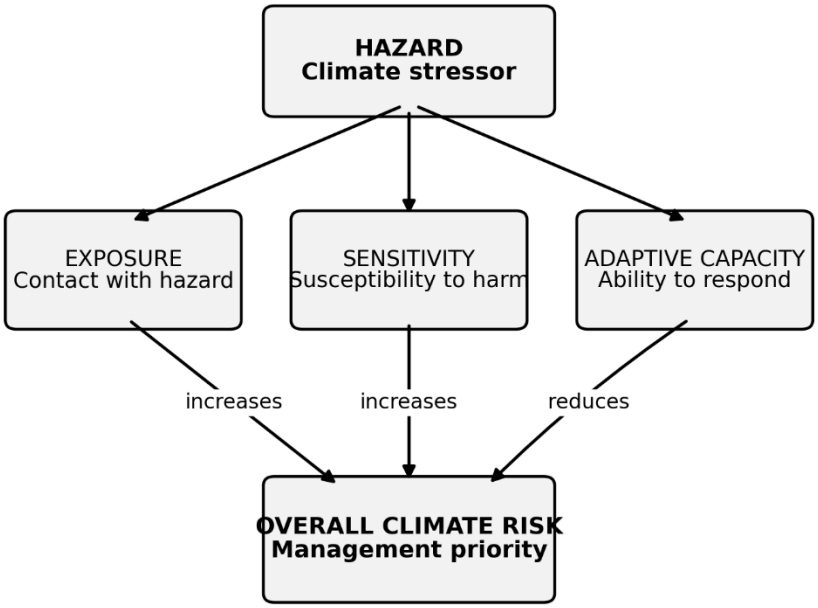

Figure 4. Conceptual framework for climate risk assessment in fisheries management. Overall risk increases when hazard, exposure and sensitivity are high, whereas strong adaptive capacity reduces vulnerability. Adapted from IPCC (2023), Comte (2021), and Hare et al. (2016).

Table 2. Climate risk assessment components for fisheries management. Modified from IPCC (2023), Comte (2021), and Hare et al. (2016).

Risk component	Description	Example fisheries indicators
Hazard	Climate-related environmental stressor that can affect fish stocks, habitats, fleets or communities	Sea surface temperature increase, acidification, storms, hypoxia and marine heatwaves
Exposure	Degree to which species, habitats, fleets or communities encounter the hazard	Habitat overlap, fishing-ground location, coastal dependency and frequency of extreme events
Sensitivity	Biological or socioeconomic susceptibility to harm	Thermal tolerance, reproductive strategy, habitat specialization, livelihood dependence and poverty level
Adaptive capacity	Ability to respond, adjust or recover	Governance quality, monitoring systems, financial resources, social safety nets and access to technology
Overall risk	Combined probability and consequence of adverse outcomes	Vulnerability score, risk ranking, priority level and urgency of management response

CLIMATE-INFORMED FISHERIES MANAGEMENT APPROACHES

Modern fisheries management increasingly incorporates climate information into decision-making. Ecosystem-based fisheries management is one of the most important approaches because it considers not only target species, but also habitats, trophic interactions, biodiversity and ecosystem processes. Adaptive management is also essential under climate uncertainty. Instead of treating management rules as fixed, adaptive management allows policies to be revised as new monitoring data, climate projections

and stock-assessment results become available. This is particularly important where species distributions, productivity regimes or fishing grounds are shifting rapidly (Bahri et al., 2021; Hobday et al., 2016).

Climate vulnerability assessment is another important tool. Hare et al. (2016) demonstrated that vulnerability assessments can combine quantitative information, qualitative evidence and expert judgment to estimate the relative vulnerability of species to climate change. Such assessments help managers prioritize species, habitats and communities that require urgent adaptation measures. Adaptation strategies for climate-resilient fisheries management are summarized in Table 3. These measures should be selected according to the ecological exposure, socioeconomic dependence and institutional capacity of each fisheries system.

Table 3. Adaptation strategies for climate-resilient fisheries management. Adapted from Bahri et al. (2021), Hobday et al. (2016), Free et al. (2019), and Pinsky et al. (2018).

Adaptation strategy	**Expected management benefit**
Ecosystem-based fisheries management	Enhances ecosystem resilience and considers food-web interactions, habitats and biodiversity
Climate-informed stock assessment	Improves forecasting under environmental variability and climate-driven productivity shifts
Adaptive harvest control rules	Allows management measures to respond to changing stock conditions and new monitoring data
Marine protected areas and spatial planning	Protects critical habitats, spawning areas and nursery grounds, while supporting ecosystem resilience
Early warning systems	Reduces impacts of extreme events, marine heatwaves and sudden environmental shocks
Habitat restoration	Improves nursery habitat availability and ecological resilience of coastal systems
Livelihood diversification	Reduces socioeconomic vulnerability of fishing communities and strengthens adaptive capacity
International cooperation	Supports governance of transboundary and shifting fish stocks under climate change

BUILDING CLIMATE RESILIENCE IN FISHERIES

Climate resilience refers to the ability of fisheries systems to absorb disturbances, adapt to changing environmental and socioeconomic conditions, and continue providing ecological, economic and social benefits. In fisheries management, resilience depends not only on the biological status of fish stocks, but also on the strength of governance systems, monitoring capacity, institutional flexibility, livelihood diversity and stakeholder participation.

Building climate resilience requires several complementary actions. First, climate projections and environmental indicators should be integrated into stock assessments and management plans. Second, monitoring systems should be strengthened to detect changes in species distribution, recruitment, habitat condition and ecosystem productivity. Third, critical habitats such as mangroves, coral reefs, seagrass beds, estuaries and spawning areas should be protected or restored to support ecological resilience. Fourth, social adaptation measures should be developed for communities that are highly dependent on fisheries and have limited capacity to respond to climate-related shocks.

Figure 5 brings together the main elements discussed throughout this paper and presents climate-resilient fisheries management as a continuous policy-learning cycle. In this cycle, climate data and projections provide the evidence base for risk and vulnerability assessment. The results of this assessment are then used to prioritize vulnerable stocks, habitats, fleets and communities. Adaptation measures are implemented according to these priorities; while monitoring and evaluation provide feedback on ecological, economic and social outcomes. This feedback supports policy revision and adaptive governance, allowing management rules to be updated as environmental conditions, stock dynamics and community needs change over time.

Overall, building climate resilience in fisheries requires a shift from static management approaches toward adaptive, evidence-based and participatory governance. Such an approach can help reduce

vulnerability, improve preparedness and support the long-term sustainability of fisheries systems under climate change.

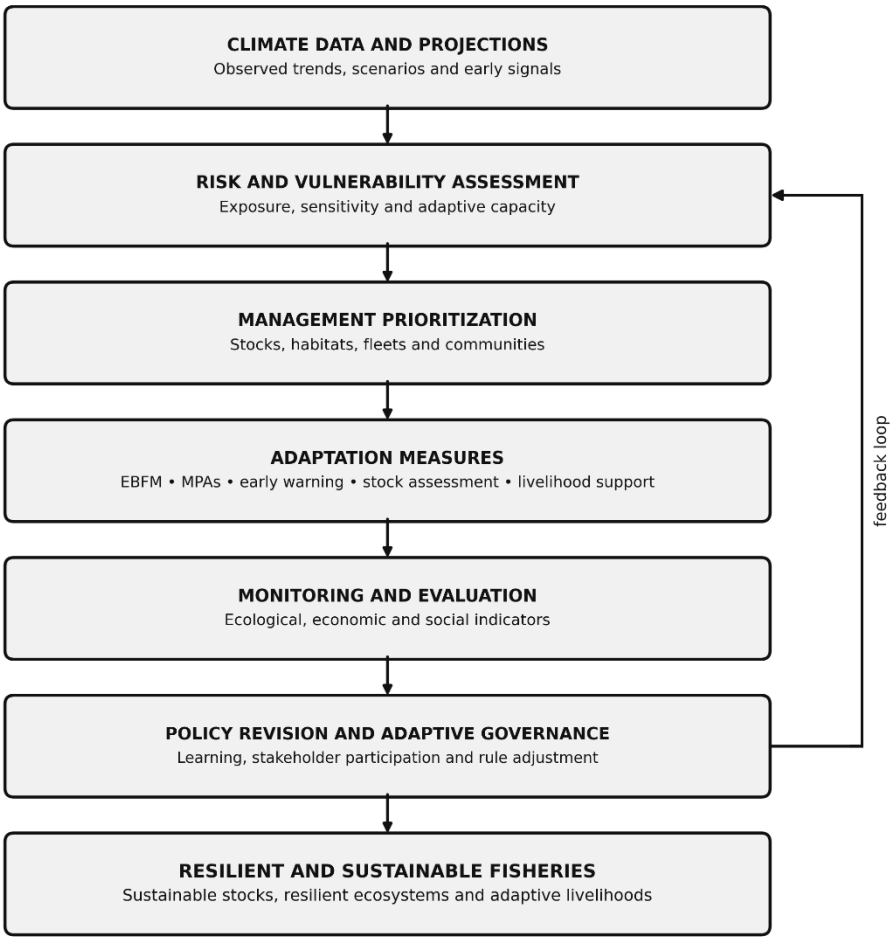

Figure 5. Climate-informed adaptive fisheries management framework integrating climate data, risk and vulnerability assessment, management prioritization, adaptation measures, monitoring and evaluation, and governance feedbacks.

The feedback-loop structure emphasizes that climate-resilient fisheries management is not a one-time decision, but an iterative process of evidence-based learning, policy adjustment and adaptive governance. Authors' own elaboration based on Bahri et al. (2021), Comte (2021), Hobday et al. (2016), and IPCC (2023).

CONCLUSIONS AND POLICY IMPLICATIONS

Climate change is reshaping the ecological, economic and social context in which fisheries management operates. Ocean warming, acidification, deoxygenation, sea-level rise, marine heatwaves and extreme weather events are altering marine ecosystems, shifting fisheries productivity and increasing uncertainty for fisheries-dependent communities. These changes demonstrate that fisheries management can no longer rely only on historical catch patterns, fixed spatial boundaries or conventional stock-based indicators.

This paper highlights climate-informed risk assessment as a core component of modern fisheries management. By linking climate hazards with exposure, sensitivity and adaptive capacity, risk assessment provides a practical basis for identifying vulnerable species, habitats, fleets and communities. It also supports the prioritization of adaptation actions under uncertainty and helps connect ecological change with economic disruption and social vulnerability.

Several policy implications emerge from this conceptual synthesis. First, fisheries management plans should integrate climate projections, environmental indicators and vulnerability assessments into decision-making processes. Second, adaptive harvest control rules and flexible spatial management are needed in systems where stock productivity, recruitment dynamics and species distributions are changing. Third, social vulnerability indicators should be incorporated into fisheries risk assessment, particularly for small-scale and coastal communities with high dependence on fisheries. Fourth, early warning systems, habitat protection, livelihood diversification and institutional support should be combined within adaptation portfolios. Finally, adaptive governance should be strengthened through continuous monitoring, stakeholder participation, periodic policy revision and cross-sectoral coordination.

The main limitation of this paper is that it presents a conceptual, literature-based synthesis rather than an empirical risk model. Future studies can build on this framework by developing quantitative risk scores, spatial vulnerability maps, multi-criteria decision-support tools and case-study applications for specific regions, fishery types or species groups. Despite this limitation, the proposed framework provides a clear basis for explaining how climate hazards translate into fisheries risks and how these risks can be linked to climate-resilient management responses.

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INSTITUTIONAL CHALLENGES IN ARCHITECTURAL DESIGN COMPETITIONS: A COMPARATIVE ANALYSIS OF TURKEY AND EUROPEAN COUNTRIES (2016–2024)

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ABSTRACT
The architectural design competition is a well-established institution in the field of architecture, combining quality, transparency and competition in the production of public buildings. Over the years, however, the impact of this institution in Turkey has diminished, with falling implementation rates and a loss of prestige for competitions. Against this backdrop, this study aims to analyse Turkey's position on architectural design competitions by comparing it with Europe. The study evaluates Turkey's architectural design competition system in a comparative analysis with nine European countries, using data on the number of competitions, implementation rates, the number of architects in each country, and architects' participation rates in competitions, covering the period from 2016 to 2024. The countries are categorised into three groups: the ideal-normative group, which is based on legal safeguards (Germany, Austria and France); the innovative group, which is developing alternative procurement models (the Netherlands, Denmark and Estonia); and the transition group, which is in the process of regulatory alignment (Poland, the Czech Republic and Spain).
A methodological distinction has been observed in the comparison of implementation rates: for European countries, the rate is measured as competitions resulting in a tender, whereas for Turkey it is calculated on the basis of physical completion. Since the tendering process precedes physical completion, Turkey's completion rate is not directly equivalent to a tendering rate; however, this methodological difference does not alter the direction of the finding. It is observed that only 10% of open competitions in Turkey reach completion — a rate less than half of even the lowest value recorded in the transition group. The findings reveal that Turkey has been unable to adopt either the legal protection mechanisms of the ideal-normative group or the transformative models of the innovative group. While Turkey partially overlaps with the transition group in terms of its regulatory structure, it lags significantly behind this group in terms of competition implementation rates. The findings suggest that the competition system in Turkey faces not only a regulatory deficit, but a structural crisis stemming from an inability to implement existing regulations.
Keywords: Architectural design competition, competition system, public procurement, architectural legislation, comparative analysis, competition sustainability, competition policy, architectural govarnence

1. INTRODUCTION
This study examines the architectural design competition as a public production mechanism, analysing the functionality of the competition system in Turkey in a comparative framework with nine European countries. Covering the period from 2016 to 2024, the countries are divided into three analytical groups based on the criteria of regulatory maturity and process innovation: the ideal-normative group, which has placed competitions under legal safeguard (Germany, Austria, France); the innovative group, which has developed the capacity to redesign the system (the Netherlands, Denmark, Estonia); and the transition group, which has been partially strengthened by the EU alignment process (Poland, Czechia, Spain). For each group, competition numbers, success rates, national architect counts, and participation rates in design competitions are evaluated together with a regulatory comparison.

The central argument of the study is as follows: Turkey has failed to establish legal safeguards for architectural design competitions as in the ideal-normative group, nor has it adopted the alternative procurement models developed by the innovative group. While Turkey partially overlaps with the transition group in terms of its regulatory structure and competition rates, it falls significantly behind these countries; the high rate of announced competitions that go unimplemented points to a systemic failure. To substantiate this argument, it is first necessary to outline the conceptual framework of the architectural design competition.

The competition concept holds a privileged place in the field of architecture by virtue of its unique production possibilities, the competitive environment it creates, and its forms of evaluation and reward (Sayar, 2002). Competitions have long been a way of purchasing ideas and have provided opportunities for the development of those ideas (Karabey, 2002). Architectural design competitions are considered one of the most participatory methods for determining how public spaces should be created in a democratic and transparent society. In modern societies, the public must be informed about decision-making processes, the justifications for decisions must be presented transparently, and these decisions must be open to public discussion. In Turkey, project procurement methods other than architectural design competitions do not offer architects a fair and transparent competitive environment (İlhan, 2013). In the Turkish context specifically, the translation of this conceptual framework into practice remains extremely limited.

Although competitions are organised with the aim of obtaining the best project produced on a predetermined subject (Arolat, 1993), the selected project is not the absolute best but rather the best among the participants (Başbuğ, 2010). More significantly, only a portion of the projects selected during the competition process find the opportunity to be built; situations where the winning project is never implemented are also frequently encountered (Açıkkol, 1993; Güvenç, 2003). For this reason, only a very small proportion of Turkey's building stock consists of buildings obtained through competitions (Başbuğ, 2010).

It is argued that these problems do not arise solely from individual decisions or coincidental shortcomings, but are shaped on a structural basis within the system. The questions of to what extent competitions are completed and how this pattern compares with other countries have not been systematically addressed to date.

2. METHODOLOGY

This research aims to evaluate Turkey's architectural design competition system in a European context through a comparative descriptive analysis method. Nine countries from Europe were selected for comparison.

Country selection was made not on the basis of geographic representation, but according to the criteria of regulatory maturity and process innovation; the selected countries were divided into three analytical groups on the basis of these two criteria.

The first group is the ideal-normative group, which has sustained architectural design competitions for many years and has placed competition culture under regulatory protection. Comprising Germany, Austria and France, competitions in this group are defined as a legal requirement in public projects above certain thresholds, and the implementation of the winning project and the preservation of architectural quality are guaranteed by legislation. Germany is of particular importance within this group as the country most frequently referred to when Turkey's procurement legislation and competition regulations were being drafted. Austria was included in the group for the protection of authorship rights and the chamber's strong supervisory role in competition processes.

The second group is the innovative group, which keeps the competition institution functional not through legal obligation but through process innovation and transparency tools. Comprising the Netherlands, Denmark and Estonia, each country has developed a different model of innovation. The Netherlands has adopted the invited competition model to reduce wasted effort and has standardised payment to participants. Denmark published a new competition guide titled 'Projektkonkurrencen 2.0' in 2026 to re-establish competition sustainability. Estonia has moved competition processes entirely to a digital and transparent platform, minimising bureaucracy; with this model it offers a digital solution to Turkey's transparency and administrative burden issues.

The third group is the transition group, which has partially strengthened its legislation through EU membership or integration processes but in which competition culture has not yet fully taken root. Comprising Poland, Czechia and Spain, this group partially resembles Turkey in terms of regulatory structure, but performs significantly better in terms of competition implementation rates. In Poland a requirement for competitions has been introduced for public buildings above a certain floor area threshold; in Czechia, the institutional involvement of local governments in competition processes has had a positive effect on implementation rates. Spain re-evaluated competitions as a tool for generating quality solutions following the 2008 economic crisis, and experienced a notable increase in competition numbers during this period. The fundamental rationale for including this group in the analysis is to demonstrate that competition success is shaped not only by regulatory strength, but also by institutional trust and process management.

The data used in the study are based on five metrics: annual numbers of competitions in countries, competition implementation rates, numbers of registered architects, the ratio of architects within the population, and the intensity of architects' participation in competitions. Among these metrics, all except competition numbers — implementation rates, architect counts, population ratios and participation intensity — were compiled for all countries using the Architects' Council of Europe (ACE) 2024 report as the primary source.

Since the scope of the ACE 2024 Sector Study is limited to EU member and observer countries, Turkey is not included in this report. For this reason, data on architect counts and population for Turkey were compiled from TMMOB's (Union of Chambers of Turkish Engineers and Architects) current membership statistics, while population data was obtained from the Turkish Statistical Institute's (TUIK) address-based population registration system results. The competition success rate was calculated using the methodology employed in the ACE 2024 report to ensure consistency with other countries.

For competition numbers, different sources had to be used for each country. The absence of a standard database that centrally compiles competition data across Europe and enables comparative analysis constitutes one of the fundamental methodological limitations of this study. Therefore, the most reliable available sources were consulted for each country, primarily national chamber of architects publications, sectoral databases and the EU's official procurement platform TED (Tenders Electronic Daily). Years for which data could not be obtained are clearly indicated in the tables; these gaps were taken into account in interpretations so as not to undermine the overall validity of the analysis.

Table — Data Sources for Competition Numbers by Country

Country	Group	Source	Missing Years
Germany	Ideal-Normative	competitionline.com — 2026 Project Competitions Report	—
France	Ideal-Normative	Annual average data (800/year) + ERA 21 Czech Architecture Magazine (2017–2019)	2016
Austria	Ideal-Normative	Der Architekturwettbewerb im Vergleich (2016–2020) + ARCH-E Map on ADCs (2022–2024)	2021
Netherlands	Innovative	tenderned.com — CPV Code 71200000-0 (Design Contest) filtered Excel data	—
Denmark	Innovative	Konkurrencer Statistik / Chamber of Architects (2016–2019) + TED europa.eu: Denmark + Result + Construction and Real Estate + Negotiated with Competition (2020–2024)	—
Estonia	Innovative	Eesti Architektide Liit (Estonian Architects' Association) — Competitions Tab	—
Czechia	Transition	Czech Chamber of Architects — Competitions Tab	—

Poland	Transition	'Environmental Assessments in Architectural Competitions in Poland 2018–2022' article + architekturaibiznes.pl (2023–2024)	2016–2017
Spain	Transition	TED europa.eu: Spain + Competition + Construction and Real Estate + Architectural Services + Design Contest Result Notice filters	—
Turkey	—	yarismo.org (2016–2022) + Arkitera platform — manual compilation as no Chamber of Architects compilation exists (2022–2024)	—

Note: All metrics other than competition numbers (implementation rate, architect count, population ratio, participation intensity) are taken from the ACE 2024 Report.

There is no centralised database that systematically compiles annual competition numbers by country across Europe. In this study, the most reliable available source was consulted for each country; the coverage limitations of TED for countries where that platform was used are addressed separately in the limitations section. Furthermore, these numbers cover only professional competitions; student competitions are excluded from the analysis.
For Poland, data for the years 2018–2022 were taken from Kirschke et al. (2023). This study explicitly states that it focuses on professional design competitions and excludes student competitions from the scope of the analysis; accordingly the data are considered methodologically consistent with other countries. For Estonia, numbers obtained from the Eesti Arhitektide Liit competition database cover only professional competitions; student awards and events appear under a separate category on the site and are not included in this analysis. In compiling competition numbers for Turkey, student competitions were excluded from the scope. This approach is consistent with TED and national chamber databases consulted for other countries, which record only professional competitions.
For European countries, the implementation rate is defined as competitions resulting in a tender, and this data is taken from ACE 2024. Since tender data is not available for Turkey, physical completion of the competition has been used as the basis. These two metrics are not directly comparable; however, Turkey's 10% completion rate still provides a meaningful reference point in the comparative assessment.
The regulatory comparison addresses the structural elements that determine the functionality of the competition system along two axes: the maturity of the legal framework and the capacity for process innovation. In this direction, eight parameters have been examined for each country. The existence and threshold of the competition requirement, the guarantee for implementation of the winning project, and the protection of authorship rights are parameters aimed at measuring the maturity of the legal framework. The role of the professional chamber in the competition process and the guarantee of jury independence reveal the strength of the institutional structure. The public disclosure of competition results, payment to participants, and the existence of digital infrastructure are parameters identified to assess process quality and innovation capacity. For each parameter, legislative texts and chamber standards were used as primary sources. Regulatory analysis for Estonia could only be conducted through the general public procurement law (Riigihangete seadus, 2017); the country does not have a separate regulation specific to architectural competitions. This is consistent with the rationale for Estonia's inclusion in the group (digital infrastructure and process transparency, rather than legal framework). Parameters were coded with values of 'yes', 'partial' and 'no' and presented in a comparative matrix.

Research Limitations
The fundamental methodological limitations of this study are concentrated at the level of data accessibility and comparability.
The absence of a centralised and standardised database for obtaining data on competition numbers across Europe constitutes the most fundamental difficulty. Different sources had to be consulted for each country, primarily national chamber of architects publications, sectoral platforms, and the EU's official procurement platform TED. This situation limits data homogeneity between countries.

For countries where TED data was used, there is a structural constraint of the platform: TED only covers tenders that exceed the threshold value set by EU directives. Competitions that remain at the national level or are small in scale do not appear on this platform. Consequently, competition numbers obtained through TED reflect only competitions that exceed the EU threshold for the countries in question, not their total competition volume. In addition, the levels at which different countries report their national competitions to TED vary; this asymmetry creates a hidden source of inequality in cross-country comparison.

Since Turkey is not an EU member, it falls outside the scope of TED and in this study is based on different sources — yarismo.org and the Arkitera platform. Similarly, since Turkey falls outside the scope of the ACE 2024 Sector Study, architect count and population data were separately compiled from TMMOB and TUIK sources. While this partially limits data comparability between Turkey and European countries, this difference has been transparently documented in the methodology section.

Additional limitations arising from the regulatory comparison should also be noted. Since the coding of parameters with values of 'yes', 'partial' and 'no' is a process based on the researcher's interpretation, different readings may result in different codings. This is a common methodological challenge in comparative legal analyses and has been taken into account in interpreting the findings. Furthermore, regulatory analysis can only reveal the existence of written regulation; it cannot measure effectiveness in practice. It is possible for a legally guaranteed regulation in one country to remain functionally ineffective in practice, or conversely for a system with a weak legal basis to be effectively implemented through a strong institutional culture. This gap also constitutes one of the central arguments of the study: it is argued that the problem in Turkey relates not only to regulatory deficiencies but also to the inability to implement existing regulations.

Finally, data for certain years could not be obtained for some countries: 2016 for France, 2021 for Austria, and 2016–2017 for Poland fall within this scope. Missing years are marked as gaps in the analysis and taken into account in interpretations. Competition participation rate data for Turkey could not be accessed from any source. This is evaluated not merely as a methodological limitation but also as an independent finding regarding the transparency and institutional archiving capacity of Turkey's competition system.

3. FINDINGS

In this section, the comparative analysis of Turkey's architectural design competition system with European countries is presented through two layers. In the first layer, the legal and institutional framework of the ten countries is examined through a comparative matrix based on the parameters of regulatory maturity and process innovation. In the second layer, quantitative indicators regarding competition numbers, architect density, participation rates and success rates are evaluated on a group basis. Reading the two layers together aims to reveal Turkey's position at both the legal and practical levels.

3.1 Regulatory Comparison

In the table below, eight parameters for each country have been coded with the values 'yes', 'partial' and 'no'. The parameters consist of four indicators aimed at measuring the maturity of the legal framework — competition requirement, implementation guarantee, authorship rights, and the mandatory supervisory authority of the professional chamber — and four indicators measuring institutional and process quality — jury independence, public disclosure of competition results, protection of participant labour, and digital infrastructure.

Table 1 – Regulatory Comparison

Country abbreviations: DE = Germany, FR = France, AUT = Austria, NL = Netherlands, DK = Denmark, EE = Estonia, CZ = Czechia, PL = Poland, ES = Spain, TR = Turkey.

Parameters	DE	FR	AUT	NL	DK	EE	CZ	PL	ES	TR
Is competition mandatory?	Yes	Yes	Partial	Partial	Partial	Partial	Partial	Partial	Partial	No

Is implementation of winning project guaranteed?	Yes	Yes	Partial	Partial	Partial	Partial	Partial	Partial	Partial	No
Are authorship rights protected?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Partial
Does the professional chamber have mandatory oversight?	Yes	Yes	Yes	No	No	No	Yes	Partial	No	Partial
Is jury independence guaranteed?	Yes	Yes	Yes	Partial	Yes	Partial	Yes	Yes	Partial	Partial
Are competition results publicly disclosed?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Partial
Is participants' work/labor protected?	Yes	Yes	Yes	Yes	Yes	Partial	Partial	Partial	Partial	Partial
Is digital infrastructure available?	Yes	Yes	Partial	Yes	Partial	Yes	Partial	Partial	Yes	Partial

The most pronounced inter-group differentiation is observed in the competition requirement parameter. While Germany and France define competition as a legal requirement in public projects above certain thresholds, the other seven European countries have regulated competition as an optional rather than mandatory procurement method. Turkey is the only country in the analysis that does not make competition mandatory at any threshold; regulation is left entirely to the administration's discretionary authority.

A similar pattern is observed in the guarantee of implementation of the winning project. In Germany, RPW (Richtlinie für Planungswettbewerbe — Guidelines for Planning Competitions) Article 8(2) expects the competition winner to be commissioned as a rule; in France, the administration is required to explicitly state this intention in the competition announcement. In other European countries, the implementation guarantee remains at the level of competition conditions rather than legislation. In Turkey, no guarantee mechanism exists for the implementation of the winning project; this is evaluated as a structural explanation for the high rate of unimplemented competitions.
In the authorship rights protection parameter, all countries except Turkey receive a 'yes' or 'partial' value. In Turkey, although Act No. 5846 on Intellectual and Artistic Works provides general protection, authorship right guarantees specific to the competition process are not sufficiently defined at the regulation level. This creates a basis for the winning architect to be excluded from the project process and is evaluated as a secondary factor reinforcing implementation failure.
The differentiation between groups in the parameter of whether the professional chamber has mandatory supervisory authority in the competition process is particularly noteworthy. In Germany, Austria and Czechia, professional chambers approve competition conditions prior to announcement and can halt a competition in the event of irregularity. In contrast, chambers in the Netherlands, Denmark, Estonia and Spain do not have such mandatory supervisory authority. This pattern confirms the grouping framework: while the ideal-normative group supports institutional oversight with legal guarantee, the innovative

group has built the system on trust and voluntary compliance. In Turkey, although TMMOB's Chamber of Architects is envisaged as involved in the competition process, this involvement does not bear the character of a binding approval mechanism.

In the parameter of whether jury independence is guaranteed, Germany, Austria, France, Czechia, Denmark and Poland make it mandatory for the jury to consist of experts independent of participants through clear legal or institutional regulations. In the Netherlands, Estonia and Spain, this regulation is left to competition conditions. In Turkey, some regulations regarding jury composition exist, but the independence guarantee lacks a systematic and auditable framework.

In the public disclosure of competition results parameter, all countries except Turkey receive a 'yes' value. In these countries, competition results are systematically shared with the public through chamber platforms, national procurement databases or the EU's TED platform. In Turkey, although competition announcements are published through EKAP, the systematic archiving and sharing of results with the public has not been established as standard practice. As noted earlier, the inaccessibility of this data is evaluated not merely as a methodological limitation but also as an independent finding regarding transparency capacity.

In the protection of participant labour parameter, Germany, Austria, France, the Netherlands and Denmark have developed standard mechanisms that calculate award amounts proportionally to project costs and have systematised payment of participation fees in invited competitions.

In Czechia, Spain, Poland and Estonia, this protection is partially provided. In Turkey, while there is a regulatory provision regarding award amounts, there is no requirement for participation fees in invited competitions and no systematic oversight mechanism to ensure that award amounts adequately cover labour costs.

In the digital infrastructure parameter, Germany, France, the Netherlands, Estonia, Spain and Poland conduct competition processes electronically through central e-procurement platforms. Estonia stands out in this group as the country with the most advanced infrastructure for managing competition processes digitally from end to end. In Turkey, although the EKAP platform exists, the integrated digital management of competition processes has not yet been achieved.

3.2 Competition Numbers and Architect Density

Following the regulatory analysis, when quantitative indicators are evaluated on a group basis, it becomes apparent how the differentiation in the legal framework is reflected in practical outputs. The tables below present architect counts and population ratios for 2024 (Table 2) and annual competition numbers for the period 2016–2024 (Table 3).

Table 2 – Architect Density (2024)

Country	Group	Registered Architects (2024)	Architects per 1,000 pop.
Germany	Ideal-Normative	~130,000	1.44
France	Ideal-Normative	~30,000	0.45
Austria	Ideal-Normative	~6,500	~0.72
Netherlands	Innovative	~17,000	~0.96
Denmark	Innovative	~10,000	1.68
Estonia	Innovative	~1,800	~1.35
Czechia	Transition	~11,000	~1.01
Poland	Transition	~20,000	~0.52
Spain	Transition	~47,000	~0.99
Turkey	—	~85,000	1.01

When evaluated in terms of architect density, Turkey presents a comparable profile to the transition group countries with a ratio of 1.01 per thousand. In the ideal-normative group, Germany has the highest ratio at 1.44 per thousand while France remains relatively low at 0.45 per thousand. In the innovative

group, Denmark has achieved a remarkable architect density of 1.68 per thousand. This table demonstrates that the low number of competitions and success rates in Turkey cannot be explained by inadequacy of available human resources.

Table 3 – Competition Numbers (2016–2024)

Year	DE	FR	AUT	NL	EE	DK	CZ	PL	ES	TR
2016	449	n/a	139	24	43	10	48	n/a	3	25
2017	495	869	195	36	55	19	48	n/a	11	30
2018	499	742	179	54	33	16	44	40	29	19
2019	474	725	141	85	44	24	30	25	45	31
2020	392	800	185	68	34	27	37	23	25	31
2021	407	800	n/a	69	40	27	43	33	37	20
2022	397	800	175	67	27	24	36	33	55	13
2023	366	800	111	63	25	20	67	36	29	7
2024	328	800	n/a	129	32	27	56	10	73	12
Total	3,807	6,336	1,125	595	333	194	409	200	307	188
Average	423	792	161	66	37	22	45	29	34	21

Annual competition numbers clearly reveal the gulf between groups. In the ideal-normative group, Germany produced the highest volume with an annual average of 423 competitions and France with 792. In the innovative group, numbers are significantly lower than the ideal-normative group — the Netherlands 66, Estonia 37, Denmark 22 — but it should be recalled that this group's priority is process quality rather than competition volume. In the transition group, Czechia showed a mid-level volume at 45, Spain at 34, and Poland at 30; however, since data for the Netherlands and Denmark were obtained from the TED platform, they reflect only competitions exceeding the EU threshold; national-level competitions are not included in these numbers. Consequently, the actual competition volume of these countries may exceed the values in the table. Turkey falls behind even the transition group countries with an annual average of 21 competitions. Particularly notable is the decline in Turkey's competition numbers from 25 in 2016 to 12 in 2024; this decline points to a systematic dissolution not observed in other countries.

3.3 Participation Rates

In addition to competition numbers, the intensity of architects' participation in competitions is considered a complementary indicator of system performance. The table below presents participation rates by country for selected years (Table 4).

Table 4 – Architects' Participation Rates in Competitions

Participation Rate	DE	FR	AUT	NL	EE	DK	CZ	PL	ES
2024	16%	13%	16%	22%	50%	50%	40%	20%	21%
2022	17%	20%	45%	—	20%	44%	32%	8%	9%
2020	13%	18%	27%	7%	20%	6%	9%	33%	17%
2018	7%	29%	45%	23%	39%	8%	27%	11%	24%
2016	19%	36%	51%	22%	53%	24%	14%	61%	30%
Average	14.4%	23.2%	36.8%	18.5%	36.4%	26.4%	24.4%	26.6%	20.2%

When participation rates in competitions are examined, the innovative group stands out. Estonia reached the highest values in this group with an average participation rate of 36%, and Denmark with 26%. In the ideal-normative group, Austria shows the highest participation rate at 37% while Germany remains relatively low at 14%. In the transition group, Poland shows a noteworthy participation intensity at 27%. Data on this indicator for Turkey could not be obtained from any source. This data gap is evaluated not merely as a methodological limitation but also as an independent finding regarding the institutional transparency and archiving capacity of the competition system.

3.4 Implementation/Success Rates

Implementation rates constitute one of the indicators that most concretely reveal the structural differentiation between groups. The table below presents implementation rates by country for open and invited competition types (Table 5).

Table 5 – Competition Implementation Rates

Country	Group	Open (%)	Invited (%)
Germany	Ideal-Normative	31%	44%
France	Ideal-Normative	43%	100%
Austria	Ideal-Normative	44%	27%
Netherlands	Innovative	26%	52%
Estonia	Innovative	0%	33%
Denmark	Innovative	27%	n/a
Czechia	Transition	75%	n/a
Poland	Transition	24%	54%
Spain	Transition	63%	0%
Turkey	—	10%	n/a

A methodological distinction must be observed in interpreting the data. Implementation rates for European countries were calculated using the ACE 2024 Sector Study methodology and measure competitions resulting in a tender. Since tender data could not be obtained for Turkey from any source, the rate for this country was calculated on the basis of physical completion of the competition. While these two metrics are not directly comparable, Turkey's 10% completion rate is considered to provide a meaningful reference point in comparative assessment: since the tendering process also carries the risk of cancellation, it is difficult to predict in which direction Turkey's rate would differ if tender data were available; however, it is clear that even a 10% completion rate provides a striking reference point in comparative assessment.

In the ideal-normative group, the implementation rate of invited competitions is remarkably high. In France, all invited competitions lead to implementation, while in Germany this rate reaches 44%. In open competitions, the normative group average of 39% represents the highest group performance. In the innovative group, the Netherlands' 52% rate in invited competitions is evaluated as a practical reflection of this country's preference for the invited competition model from a labour efficiency perspective. In Estonia, a rate of 33% is observed in invited competitions while no implementation was recorded in open competitions; this supports the thesis that Estonia has built its system on process quality rather than volume. In the transition group, Czechia achieves the highest rate among all countries at 75% for open competitions; this performance concretises the positive effect of institutional participation of local governments on competition processes. Spain's 0% rate in invited competitions indicates that it predominantly adopts the open competition model.

In Turkey, only 10% of open competitions reach completion, and data on invited competitions cannot be obtained from any source. This rate is less than half of Poland's 24%, the lowest open competition value in the transition group. Read together with the regulatory analysis, this picture strongly supports

the argument that the problem in Turkey relates not only to regulatory deficiency but to a structural crisis arising from the inability to implement existing regulations.

4. DISCUSSION AND CONCLUSION

This study has revealed the position of Turkey's architectural design competition system in the European context through a comparative analysis. When the findings are addressed at three levels — regulatory, process innovation and comparative performance — Turkey's situation can be read not merely as a picture of deficiency but as a structural vicious cycle that feeds upon itself.

At the regulatory level, Turkey is the only country in the analysis to receive a 'no' value in the competition requirement and implementation guarantee parameters. This is a direct consequence of the competition institution being left to the administration's discretionary authority within the procurement system. Sayar (2002) documented that the competition institution in Turkey has historically functioned without regulatory protection; İlhan (2013) emphasised that project procurement methods other than competition do not offer a fair and transparent competitive environment for the profession. These assessments remain valid today: the regulatory gap has been identified for decades, yet has not been closed. In the normative group, the definition of competition as a legal requirement above certain thresholds and the guarantee of the winning project's implementation represent not only a legal regulation but also the foundation of institutional trust in the system. The absence of this foundation in Turkey creates the basis for competitions to be initiated and then left incomplete and for winning projects not to be implemented; this in turn further erodes trust in the system.

At the process innovation level, the experience of the innovative group demonstrates that a functional competition system can be established even without legal obligation. The Netherlands' invited competition model that reduces labour waste, Estonia's end-to-end digital infrastructure, and Denmark's process reform initiative — each represents a different institutional trust-building strategy. Karabey's (2002) assessment that competitions provide opportunities for the development of ideas is concretised in these models: the system maintains its function by prioritising quality over volume and voluntary participation over obligation. In Turkey, neither the legal framework has been strengthened nor has the capacity for process renewal been developed. This dual absence pushes Turkey into a position disconnected from both the normative and innovative models.

At the comparative performance level, the findings reveal the most striking pattern. Turkey, which presents a profile similar to the transition group in terms of architect density, falls significantly behind this group in terms of competition numbers, implementation rates and institutional transparency. Countries in the transition group, despite starting from a point similar to Turkey in regulatory terms, have succeeded in making the competition system functional through the EU alignment process and institutional trust-building.

The introduction of a competition requirement for public buildings above certain thresholds in Poland, the institutional involvement of local governments in the process in Czechia, and Spain's re-evaluation of competition as a tool for generating quality solutions following the 2008 crisis — each demonstrates how institutional will, independent of regulatory strength, can transform the competition system. In Turkey, the systematic decline in competition numbers over the period from 2016 to 2024, reaching a historical low of only 7 competitions in 2023, can be evaluated as a concrete reflection of the absence of this institutional will.

Where only 10% of open competitions are completed in Turkey, this rate is less than half of the transition group's lowest value. Taking into account the methodological distinction — the rate measures competitions resulting in a tender for European countries and physical completion for Turkey — this difference gains further meaning: given that the tendering process also carries the risk of cancellation, the direction of the comparison does not change. Considering that the actual competition volume of the Netherlands and Denmark is likely above the values in the table due to TED-sourced data not covering competitions below the EU threshold, the difference between Turkey and these countries becomes even more pronounced.

At this point, the Danish example provides an important reference that broadens the discussion. The 'Projektkonkurrencen 2.0' guide published by Arkitektforeningen in 2026 documents that the competition institution faces sustainability pressure even in countries that have adopted the normative or innovative model. The excessive bureaucratisation of competition processes, increasing labour

burdens and declining participation rates are documented as structural problems affecting not only Turkey but also the countries that protect the system. This finding establishes an important framework: the reference models being considered during the process of restoring Turkey's system are themselves being reinvented.

The fundamental contribution of this study is that it is the first to document Turkey's competition system at this scale and in a comparative framework. The findings reveal that the source of the problem is not merely regulatory deficiency but the inability to implement existing regulations and the erosion of trust in the competition institution. An in-depth examination of the individual and institutional reasons for moving away from competitions, and the absence of a database infrastructure through which conversion rates of competition numbers into construction could be systematically tracked, are identified as the fundamental research gaps in the field.

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GEOPOLITICAL COMPETITION AND ITS IMPACT ON THE GLOBAL AGENDA FOR SUSTAINABLE ECONOMIC DEVELOPMENT

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ABSTRACT
The modern global economic environment is characterized by increasing uncertainty, geopolitical tensions and the transformation of international relations, which significantly affect the activities of international companies. US-China strategic competition, regional conflicts, economic sanctions, energy security challenges and fragmentation of supply chains create new risks, the effective management of which is a necessary prerequisite for the competitiveness and sustainable development of organizations. The aim of this study is to assess the importance of integrating geopolitical risks into the strategic planning of international companies and to identify mechanisms that contribute to strengthening organizational resilience and adaptive capabilities.
The study is based on a qualitative methodology and includes an analysis of modern scientific literature, reports of international organizations and global economic trends. Particular attention is paid to the theoretical concepts of geoeconomics, interdependence, strategic management and sustainable development. The study discusses the main categories of geopolitical risks, including trade restrictions, technological confrontation, energy crises, disruptions in the supply of critical raw materials and challenges related to the climate transition process.
The results of the study show that ignoring geopolitical factors significantly increases operational, financial and reputational risks, while their systematic integration into strategic planning allows companies to identify threats in a timely manner, diversify supply chains, develop crisis management mechanisms and strengthen long-term competitive positions. The study also emphasizes the importance of cooperation between the private sector, state institutions and international organizations in ensuring sustainable economic development.
Keywords: geopolitical risks; strategic planning; international companies; geoeconomics; supply chains; economic security; sustainable development; globalization; risk management; competitive advantage.

Introduction: The global economic architecture of the twenty-first century is undergoing a fundamental transformation, with two major paradigms confronting each other: humanity's shared aspiration for sustainable development and the strengthening of geopolitical multipolarization among leading states. The "2030 Agenda" and the 17 Sustainable Development Goals (SDGs) adopted by the United Nations in 2015 were based on the principles of liberal institutionalism, according to which climate change, poverty alleviation, and ecological security are global challenges that can only be achieved through international cooperation and interdependence (United Nations [UN], 2015).
However, over the past decade, the dominance of the realist paradigm in the system of international relations and the redistribution of the balance of power, especially between the United States of America, the People's Republic of China, and the European Union, have significantly hampered this joint effort (Allison, 2017). Geopolitical competition is no longer limited to military or traditional diplomatic spheres of influence; it has penetrated international trade, the technology sector, and environmental policy, thus questioning the future of global sustainable economic development.
The relevance of this study is determined by the fact that the "Green Transition", which was initially considered as a global public good, is increasingly becoming an instrument of economic nationalism and protectionism. The latest World Bank reports (World Bank, 2024) indicate that the increase in trade barriers and geopolitical fragmentation reduces global gross domestic product every year, which is directly proportional to the financing gap for sustainable projects. When leading economies begin to isolate domestic markets for strategic security reasons, technological transfer and the free movement of capital, which are critically important for developing countries to achieve sustainable goals, suffer (Sachs et al., 2023). Accordingly, the integration of geopolitical risks into economic development models has become a major challenge in modern scientific discourse.

The theoretical framework in the scientific literature often analyzes economic sanctions, supply chain disruptions, and energy crises, but less attention is paid to the complex mechanisms through which strategic competition devalues sustainable development goals (Baldwin, 2019; Overbeek, 2021). For example, the Inflation Reduction Act (IRA) adopted by the United States and the European Union's countervailing subsidy policy, despite their environmental objectives, often discriminate against external partners and violate fundamental principles of the World Trade Organization (WTO) (Bown, 2023). Similarly, China's dominance in the supply chain of critical raw materials (such as lithium, cobalt, and rare earth elements) is generating new geoeconomic dependencies, which are pushing Western states towards the so-called "Friend-shoring" strategy (European Commission, 2023; Subacchi, 2022). These processes indicate that the global decarbonization agenda is increasingly subordinated to narrow national security interests.

In this context, a clear research niche emerges: there is a need to scientifically assess and systematize the specific channels through which geopolitical polarization slows down the pace of global sustainable economic development. To address this issue, this article asks the central research question: How and to what extent does the multipolar geopolitical competition between the United States and China affect the availability of "green technologies" and the global architecture of sustainable financing for developing countries?

The main objective of the study is to empirically analyze the protectionist policies and resource nationalization resulting from geopolitical confrontation and identify their impact on the realization of the Sustainable Development Goals (in particular, SDG 7: Affordable and Clean Energy, and SDG 13: Climate Action). To achieve the set goal, the paper aims to:

- analyze the latest trade and industrial strategies adopted by leading states in the context of economic security;
- assess the monopoly tendencies in the markets of critical resources;
- develop recommendations to maintain the effectiveness of climate diplomacy in a polarized international environment.

The presented paper is based on the hypothesis that: the strengthening of geopolitical competition and the resulting "green protectionism" leads to the fragmentation of technological supply chains, which significantly increases the global costs of alternative energy development and hinders the flow of capital to low-income countries, thereby threatening the achievement of the economic and environmental goals set for 2030. The structure of the paper includes a literature review, a methodological part, where case analysis and qualitative interpretation of macroeconomic data are used, main analytical blocks, and a conclusion that suggests alternative policy scenarios.

Literature review: In international relations theory, issues of global resource management and sustainable development have traditionally been polarized between two radically different perspectives. The liberal institutionalist framework, based on Keohane and Nye's (1977) theory of complex interdependence, argues that in a globalized world, states are increasingly interdependent. According to this paradigm, existential threats such as climate change and biodiversity loss constitute a "tragedy of the commons" that can only be addressed within multilateral institutions and international legal regimes (Hardin, 1968; Young, 2017). Liberal scholars emphasize that the Sustainable Development Goals (SDGs) serve the principle of absolute gains, where international cooperation is beneficial for all actors. In contrast, neorealist theory, led by Waltz (1979) and Mearsheimer (2001), views the international system as an anarchic environment in which the primary goal of states is self-preservation and the maximization of relative gains. From a realist perspective, any global agenda, including the "green transformation," is perceived as a zero-sum game. Contemporary scholars (e.g. Baldwin, 2019; Wolforth, 2020) note that when economic interdependence becomes weaponized, states are willing to incur economic costs and reduce efficiency in order to ensure national security and strategic autonomy (Farrell & Newman, 2019).

The concept of geoeconomics, which Luttwak (1990) defined as "the logic of conflict with the grammar of trade," bridges these two theories. The contemporary geoeconomic framework (Blackwill & Harris, 2016) shows that great states use elements of sustainable economies—such as financial flows, innovation, and supply chains—to achieve geopolitical goals. Accordingly, the present study uses a synthetic theoretical framework that recognizes that despite the existence of liberal institutions, the

structural polarization of the international system forces actors to act with realistic rationality, which directly impacts sustainable development policies.

In recent years, the academic literature has increasingly focused on the term "Green Protectionism". According to Kleinhenz & Merkle (2022), environmental standards and subsidies are often used as hidden barriers to international trade. Researchers have extensively analyzed the US Inflation Reduction Act (IRA) and the EU Carbon Border Adjustment Mechanism (CBAM). Bown (2023) argues that these policy acts, despite their positive climate rhetoric, are essentially industrial strategies aimed at isolating China from high-tech markets. On the other hand, China's role in global sustainable development has been widely studied in terms of economic dominance. Campanella (2021) and Overbeek (2021) point out that the People's Republic of China, within the framework of the Belt and Road Initiative (BRI), has achieved infrastructural integration of developing countries, but at the same time has created a so-called "debt-trap diplomacy". This process, as Rodrik (2018) notes, is an echo of the crisis of hyperglobalization, where global economic governance can no longer balance national sovereignty and international obligations.

Particular attention is paid to the geopolitics of Critical Raw Materials. Research by Wakamatsu et al. (2023) confirms that the transition to clean energy increases the demand for minerals whose extraction and processing are geographically concentrated in a few authoritarian states. Subacchi (2022) emphasizes that this creates a "new energy security dilemma": the attempt to gain independence from traditional hydrocarbons may plunge the West into new technological and raw material dependence, increasing the likelihood of conflict and hindering stable economic development.

Empirical simulations conducted by the International Monetary Fund (IMF, 2023) and the World Bank (World Bank, 2024) show that the division of the global economy into two polar blocs (the US-West and China-East axes) could lead to a decline in global GDP of 2% to 7%. Georgieva (2023) calls this phenomenon "Geoeconomic Fragmentation" and notes that its first victim is the Sustainable Development Goals.

Annual reports by Sachs et al. (2023) confirm that developing countries have a deficit of 4 trillion USD annually in achieving the SDGs. A review of the literature shows that geopolitical tensions directly affect capital mobilization: private investors avoid risky regions, and multilateral development banks (MDBs) become arenas for political battles instead of efficiently allocating resources (Stiglitz, 2021). Piketty (2020) also notes that the rise in global inequality (SDG 10) is directly linked to the destabilization of the international trading system, which is driven by nationalist agendas.

Although the existing literature describes in detail individual aspects of geopolitics (sanctions, tariffs, wars), their cumulative, systemic impact on the economic architecture of sustainable development has been poorly studied. Most studies focus either only on environmental consequences or purely on military-strategic security. The present work fills this scientific vacuum by considering geopolitical competition as a complex systemic exogenous shock that simultaneously affects supply chains, technological innovations, and international finance. This approach allows us to assess the prospects for sustainable economic development not in isolation, but in the context of the modern multipolar reality.

Research method: This paper uses a Mixed Methods Research Design, specifically a Convergent Parallel Design. This approach allows the researcher to simultaneously collect and analyze both qualitative and quantitative data, and to integrate and reconcile the results in a discussion phase (Figure 1). Such a synthesis is necessary because quantitative econometric models alone cannot capture the underlying motivations behind policy decisions, and qualitative analysis alone will lack empirical accuracy and generalizability (Bryman, 2016).

The quantitative component focuses on analyzing trends in macroeconomic indicators, such as the dynamics of foreign direct investment (FDI) in the "green" sector, the volatility of world prices of critical minerals, and the impact of trade tariffs on global exports of electric vehicles and renewable energy components. The qualitative component focuses on narrative and content analysis, which includes decoding the strategic documents of superpowers and the legal and political assessment of international agreements. Such triangulation of methods reduces the risk of researcher subjectivity and increases the academic value of the work (Saunders et al., 2019).

The empirical basis of the study is based on secondary data, which are obtained from web portals and databases of highly reputable international institutions. The main sources of quantitative data are:

- The annual databases of the United Nations (UN) Sustainable Development Solutions Network (SDSN), from which the SDG indices and progress indicators for individual goals (in particular, SDG 7 and SDG 13) are extracted;
- The World Bank database (World Development Indicators), from which global GDP growth rates, trade openness indices and inflation rates are analyzed;
- The International Monetary Fund (IMF)'s "geoeconomic fragmentation" indicators and supply chain disruption indices (IMF, 2024).

In order to collect qualitative data, purposive sampling was carried out. The subject of analysis is official state strategies and legislative acts, including: the US Inflation Reduction Act - 2022, the European Green Deal and the Critical Raw Materials Act - 2023 of the European Union, as well as the People's Republic of China's 14th Five-Year Plan for Economic and Environmental Development.

The article uses the Comparative Case Study Method to examine two major ongoing geoeconomic phenomena (Yin, 2018):

1. The US-China "subsidy war" and its impact on the global solar energy market: This case study analyzes how bilateral protectionism is driving up the cost of green technologies.
2. The EU's dependence on critical minerals and the "Friend-shoring" policy: This case study demonstrates the impact of geopolitical reconfiguration of supply chains on developing countries.

Thematic Analysis (Thematic Analysis) method according to Braun and Clarke (2006) is used to process qualitative data, which involves coding texts and identifying recurring themes such as "strategic autonomy", "nationalization of resources" and "economic coercion". Quantitative data are processed using descriptive and trend statistics tools, which are visualized in the form of diagrams and matrices to clearly show the correlation between the increase in geopolitical risks and the decrease in financing for sustainable projects.

Main part: The process of decarbonization of the global economy, which was originally supposed to be based on international cooperation and free market principles, is increasingly under the influence of "green protectionism" and economic nationalism. Leading global actors - the United States, the People's Republic of China, and the European Union - view clean energy technologies not only as a tool to combat climate change, but also as a key arena for gaining geostrategic dominance in the new industrial era (Blackwill & Harris, 2016). As a result, there is a trend where environmental policies and trade strategies are synthesized into a single geoeconomic tool. This process is fundamentally changing the architecture of international trade and directly affecting the global pace of sustainable economic development.

The crisis of the neoliberal economic model and the increasing role of the state in the management of strategic sectors have led to the return of aggressive domestic subsidy policies. The most visible expression of this trend is the Inflation Reduction Act (IRA) adopted by the United States in 2022. This legislation provides for the mobilization of approximately 369 billion USD to finance climate and energy programs, mainly in the form of tax breaks and direct subsidies (Bown, 2023). However, the geopolitical anatomy of the IRA makes it clear that its goal is not only to reduce emissions, but also to isolate American supply chains from Chinese influence. The law contains the so-called "Local Content Requirements," which means that subsidies and tax credits are only granted if the production and/or assembly of electric vehicles, batteries, and renewable energy components are carried out in the United States or its free trade partner countries (European Parliament, 2023).

The US move has raised serious concerns among its traditional allies, the European Union and South Korea, as their manufacturers find themselves in discriminatory conditions.

In response, the EU has launched the Green Deal Industrial Plan and the Net-Zero Industry Act, which aim to ease European subsidy rules and stimulate domestic production in order to prevent capital and technology from flowing across the Atlantic. The People's Republic of China, which has pursued a policy of state capitalism and massive subsidies for decades, now dominates almost every key sector of green technology — from solar panels to lithium-ion batteries. Washington and Brussels' efforts to create alternative supply chains independent of China are perceived by Beijing as a strategy of its economic containment, further exacerbating geopolitical polarization (Nakayama, 2024).

With the renaissance of industrial policy, leading countries are actively using trade defense mechanisms. Green protectionism is expressed not only in the encouragement of domestic production, but also in the exclusion of foreign products from the market through tariffs and regulations:

- US targeted tariffs: The United States has sharply increased tariffs on Chinese electric cars (which have reached 100%), solar cells and critical minerals in order to protect domestic industries revived under the IRA from cheap Chinese imports.
- EU CBAM mechanism: The EU has introduced the “Carbon Border Adjustment Mechanism (CBAM)”. Although Brussels views it as an environmental instrument (aimed at preventing "carbon leakage"), developing countries perceive it as a typical non-tariff barrier and hidden protectionism that harms their competitiveness in the international market.
- Impact on global decarbonization: Nationalization of green technologies and trade wars hinder effective action on climate change. Fragmentation of supply chains and restrictions on free trade increase the cost of renewable energy components, which ultimately slows down the pace of the green transition, especially in financially vulnerable and developing countries.

Research results and discussion: Projecting the trajectory of geopolitical fragmentation to 2030 shows that multipolar competition poses a fundamental threat to the achievement of the UN Sustainable Development Goals (SDGs). Based on quantitative and qualitative modeling, prolonged confrontation has the most destructive impact on three key goals: SDG 7 (Affordable and Clean Energy), SDG 13 (Climate Action), and SDG 17 (Partnerships for the Goals).

Two main scenarios are distinguished within the framework of this modeling:

- “Technological Iron Curtain” (block polarization): In this scenario, the world is divided into two main technological ecosystems (US-EU vs. China-Russia). Complete decoupling of supply chains leads to shortages of critical raw materials and green components. According to modeling, such isolation will slow the pace of global emissions reductions by 20-25% by 2030, which will undermine the chances of keeping global warming within 1.5∘C.
- “All against all” (localized protectionism): This scenario involves the complete collapse of multilateral agreements, with each major actor concerned only with its own energy sovereignty. Technology transfer to developing countries is virtually halted, leading to a renaissance of coal and other fossil fuel consumption in the Global South.

Analysis of contemporary geoeconomic processes reveals a deep structural paradox that determines the dynamics of the green transition. This paradox can be characterized as a contradiction between progress motivated by national security and global efficiency.

Geopolitical Competition

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Positive Effect

· Acceleration of Domestic Innovation

· Strategic Subsidization

· Increasing Energy Insecurity

Negative Effect

· Rising Global Spending

· Fragmentation of Supply Chains

· Marginalization of the Global South

On the one hand, geopolitical rivalry acts as a powerful catalyst for domestic industrial and technological development. The security dilemma forces states to mobilize colossal financial resources that would otherwise be left to market forces in peacetime or stability.

The desire of Washington, Beijing, and Brussels to be independent of geopolitical adversaries is accelerating research and development (R&D) in areas such as solid-state batteries, green hydrogen, and modular nuclear reactors. Leading states are deliberately creating “technological outposts” that increase the resilience of domestic production.

On the other hand, this self-centered approach generates heavy systemic costs. The breakdown of economies of scale and the artificial fragmentation of optimal global supply chains dramatically increase the final cost of green infrastructure.

The most affected party in this process is the global south (developing countries). In conditions where Western capital is directed at subsidizing domestic markets (Reshoring/Friend-shoring), and China is trying to maintain its geostrategic advantage, poor countries are left without financial and technological

support. Multilateral platforms like the Green Climate Fund (GCF) are becoming dysfunctional, as donor countries prefer bilateral, politically motivated assistance.

The nationalization of green technologies creates the illusion that individual states can achieve "ecological sovereignty." However, since climate change is a global phenomenon, the success of one region at the expense of another cannot ensure overall climate stability. Geopolitical competition increases the cost of the green transition and raises the risk that by 2030 the world will not accept a decarbonized planet, but a more deeply divided and economically unequal international system.

Conclusion: The trends discussed in the previous paper demonstrate that the process of decarbonization of the global economy is undergoing a fundamental transformation. The fight against climate change, which should ideally be based on multilateral cooperation and free markets, has become a major arena of geopolitical rivalry between great powers. The study shows that no major actor — be it the US, China or the EU — is free from "geoeconomic egoism". Washington's aggressive subsidy policy (IRA), Beijing's total subsidies to domestic industries and monopoly control over critical minerals, as well as Brussels' attempt to introduce covert "green protectionism" through CBAM, are equally damaging to the international trade architecture. The nationalization of green technologies creates a paradoxical situation: while security-motivated competition accelerates domestic innovation in individual blocs, due to the fragmentation of supply chains, disruption of economies of scale, and artificial increase in costs, it sharply slows down the overall pace of the global green transition and leaves developing countries marginalized on the path to achieving the 2030 Sustainable Development Goals (SDGs).

In order to prevent the global climate crisis from becoming a hostage to a zero-sum game between major powers, it is necessary to reconsider the international political agenda. The following steps are recommended:

- Creation of a "Climate Firewall": Leading actors (US, China, EU) should reach a strategic consensus to isolate environmental and climate diplomacy from traditional geopolitical, military or ideological conflicts. Bilateral dialogue on green standards should continue regardless of the level of tension in other areas.
- Reform of multilateral green technology platforms: A special "Green Subsidies Code" should be developed within the World Trade Organization (WTO). This mechanism would separate legitimate environmental subsidies from aggressive, discriminatory protectionism, thereby reducing the risk of trade wars.
- Open-Source models of technology transfer: To support countries in the Global South, international organizations should ensure access to basic patents for green technologies so that the developing world can build cheap renewable energy infrastructure and avoid carbon-based industrialization.

This paper lays the foundation for several promising research directions that require further in-depth study:

- Quantitative impact assessment: It is advisable to develop econometric models that accurately measure the effects of green tariffs (e.g. CBAM) and trade barriers on the GDP and export potential of developing countries.
- Alternatives to the geopolitics of critical minerals: An important area of research is to examine the extent to which the circular economy and the development of battery recycling technologies can reduce the West's dependence on Chinese supply chains, and whether this will weaken resource nationalism.
- Formation of regional green blocs: Future analysis should focus on how the strategies of middle powers are changing in the process of maneuvering among large actors.

Climate change does not recognize national borders and political blocs. Geopolitical selfishness, from whatever side it comes, ultimately leads to collective failure. Global sustainability can only be maintained if the international community realizes that shared planetary security is higher than the temporary technological hegemony of a single country.

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IMPACT OF CUSTOMER AWARENESS AND PERCEIVED RELIGIOUS COMPATIBILITY ON THE ADOPTION OF ISLAMIC BANKING SERVICES IN NIGERIA

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ABSTRACT
This study examines how customer awareness and perceived religious compatibility influence the adoption of Islamic banking services in Nigeria, within the context of the country's dual banking system. Grounded in the Technology Acceptance Model (TAM) and Trust Theory, this research conceptualizes consumer behavior as a multidimensional construct comprising: Customer Awareness (CA) cognitive understanding, product knowledge, and informational exposure regarding Islamic banking principles and services; and Perceived Religious Compatibility (PRC) alignment between Islamic banking operations and personal religious beliefs, ethical satisfaction, and Shariah authenticity perception. Trust in Financial Institutions (TFI) is positioned as both a direct predictor and moderator, capturing institutional credibility, competence, benevolence, and integrity confidence. Islamic Banking Adoption (IBA) is operationalized as multi-dimensional behavioral outcomes including account opening, product usage, recommendation behavior, switching intention, and sustained patronage. Using partial least squares structural equation modeling (PLS-SEM) with data from 300 respondents across northern Nigeria's Islamic banking institutions and Muslim communities, the findings reveal that Perceived Religious Compatibility emerges as the strongest significant predictor of Islamic banking adoption ($\beta = 0.384$, $p < 0.001$, $f^2 = 0.412$), followed by Customer Awareness ($\beta = 0.312$, $p < 0.001$, $f^2 = 0.215$) and Trust in Financial Institutions ($\beta = 0.218$, $p < 0.001$, $f^2 = 0.168$). Trust demonstrates significant direct effects and moderates the relationships between Customer Awareness and IBA ($\beta = 0.076$, $p = 0.025$) and between Perceived Religious Compatibility and IBA ($\beta = 0.095$, $p = 0.002$). The model explains 85.8% of variance in Islamic banking adoption ($R^2 = 0.858$) with strong predictive relevance ($Q^2 = 0.793$) and excellent model fit (SRMR = 0.021). This study advances methodological rigor through comprehensive HTMT-based discriminant validity assessment and establishes that religious compatibility and consumer awareness, amplified by institutional trust, outweigh product availability in determining Islamic banking adoption.
The research contributes to Islamic finance consumer behavior literature by demonstrating that adoption in dual banking environments depends more on religious authenticity demonstration and knowledge enhancement than on regulatory frameworks alone.
Keywords: Islamic banking adoption, customer awareness, perceived religious compatibility, trust in financial institutions, dual banking system, Nigeria, PLS-SEM, Shariah compliance.
JEL Classifications: G21, G23, Z12, M31, O16, O55.

Introduction
The Nigerian banking sector stands at a critical juncture in 2025, navigating unprecedented regulatory transformation and macroeconomic volatility that fundamentally alter the risk management landscape (Udoma & Belo-Osagie, 2024). Following the Central Bank of Nigeria's comprehensive recapitalization program launched in March 2024, commercial banks face mandatory capital threshold increases to ₦500 billion for international banks, ₦200 billion for national banks, and ₦50 billion for regional banks by March 2026. This regulatory intervention creates substantial pressure on risk governance capabilities

and financial performance optimization (KPMG Nigeria, 2024). The operating environment has become increasingly challenging, with inflation peaking at 34.6% in November 2024 and monetary policy rates reaching 27.5%, conditions that severely test the resilience of enterprise risk management frameworks implemented over the past decade (Central Bank of Nigeria, 2024).

The mandatory Enterprise Risk Management framework introduced by the Central Bank of Nigeria in 2012 and subsequently revised in 2015 represented a paradigm shift from traditional silo-based risk management approaches. This framework established integrated, board-level risk governance structures encompassing risk identification, assessment, mitigation, monitoring, and reporting within unified strategic frameworks (Committee of Sponsoring Organizations of the Treadway Commission, 2017). Despite over a decade of regulatory evolution and the recent operational risk management expectations requiring formalized risk identification processes, systematic Key Risk Indicators, and documented risk registers, empirical evidence regarding ERM's actual impact on financial performance remains fragmented, inconclusive, and methodologically heterogeneous (Gordon et al., 2009; Hoyt & Liebenberg, 2011). This limitation restricts the development of cumulative knowledge and evidence-based policy guidance during the critical recapitalization period.

Three critical research gaps motivate this systematic review. First, the absence of quantitative synthesis represents a significant limitation in the existing literature. While individual empirical studies have examined ERM-performance relationships using various methodological approaches including panel data regression and dynamic Generalized Method of Moments estimators, no prior review has meta-analytically quantified effect sizes across studies (Baxter et al., 2013; McShane et al., 2011). This gap leaves substantial uncertainty regarding the magnitude, direction, and robustness of ERM's financial impact in emerging market banking contexts. Second, component-level ambiguity persists throughout the literature. Enterprise Risk Management encompasses distinct dimensions including risk identification through Value-at-Risk methodologies, risk monitoring via board oversight, and risk mitigation through hedging strategies. Yet existing studies either conflate these dimensions or focus selectively on isolated components, obscuring which specific ERM elements drive performance outcomes (Pagach & Warr, 2011; Seker & Ergun, 2021).

Third, contextual obsolescence characterizes much of the available evidence. Recent regulatory developments including the March 2024 recapitalization directive, the July 2024 Risk-Based Cybersecurity Framework, and the ongoing Basel III transition fundamentally alter the operating environment for Nigerian commercial banks (PricewaterhouseCoopers, 2024). These changes necessitate updated evidence synthesis that captures transformative regulatory changes and their implications for risk management effectiveness.

This systematic review addresses these gaps through rigorous meta-analytic quantification of ERM-performance relationships, disaggregated analysis of component-specific effects, and comprehensive assessment of moderating influences. The significance of this review extends across theoretical, practical, and policy domains. Theoretically, the review integrates stakeholder theory, resource-based view, and dynamic capabilities perspectives to explain how ERM implementation generates financial value in emerging market contexts (Kero & Bogale, 2023). Practically, findings inform bank management strategies during the recapitalization period, offering evidence-based guidance on resource allocation across risk capabilities (Dessler, 2023). From a policy perspective, the review provides timely insights for the Central Bank of Nigeria regarding mandatory ERM framework effectiveness (Kraus & Lind, 2010). The scope encompasses all quantitative empirical studies examining ERM-performance relationships in Nigerian commercial banks published between January 2012 and December 2024, utilizing comprehensive search strategies across multiple databases with supplementary citation tracking.

The general research question asks: What is the nature and magnitude of the relationship between Enterprise Risk Management implementation and financial performance in Nigerian commercial banks, and how do specific ERM components contribute to this relationship? The general research objective is to synthesize empirical evidence quantifying the ERM-performance relationship, disaggregate effects by risk identification, monitoring, and mitigation components, assess moderating influences, and develop a unified measurement framework to guide future research and policy during the 2024–2026 recapitalization period.

Theoretical Framework and Hypothesis Development

Stakeholder Theory

Stakeholder theory was originally developed by R. Edward Freeman in 1984 and subsequently refined by Freeman and colleagues in 2010, representing a fundamental departure from shareholder-centric views of the firm (Freeman, 1984; Freeman et al., 2010). The theory defines stakeholders as any groups or individuals who can affect or are affected by the achievement of an organization's objectives. This encompasses primary stakeholders directly involved in economic transactions and secondary stakeholders including regulatory bodies and civic institutions that influence the operating environment (Miles, 2017). The major assumptions include the premise that organizations must balance competing stakeholder interests to achieve long-term success, which stakeholder relationships involve mutual value creation, and that effective stakeholder management enhances organizational legitimacy and resource access (Jones et al., 2018). Critics argue that the broad stakeholder definition creates practical prioritization difficulties, that the theory lacks clear conflict resolution mechanisms, and that empirical validation remains challenging due to stakeholder salience measurement problems (Laplume et al., 2008). The relevance to this study centers on explaining how Nigerian banks' ERM implementations respond to regulatory mandates and stakeholder expectations. The Central Bank of Nigeria's mandatory ERM framework creates institutional pressures for banks to adopt comprehensive risk governance as signals of compliance and legitimacy, thereby reducing information asymmetry and enhancing financial performance through improved stakeholder confidence (Mainardes et al., 2012).

Resource-Based View

The resource-based view was initially articulated by Birger Wernerfelt in 1984 and subsequently formalized by Jay Barney in 1991, establishing that firms achieve sustainable competitive advantage through resources and capabilities that are valuable, rare, inimitable, and non-substitutable (Wernerfelt, 1984; Barney, 1991). The theory defines resources as tangible and intangible assets controlled by a firm, while capabilities denote the capacity to deploy resources effectively through unique routines and processes (Amit & Schoemaker, 1993). Major assumptions include resource heterogeneity across firms due to imperfect factor markets, resource stickiness preventing easy transfer, and sustained advantage deriving from internal configurations rather than industry positioning (Barney & Hesterly, 2012). Critics argue that the VRIN framework suffers from tautological reasoning, that operationalizing criteria remains empirically challenging, and that the theory's static nature inadequately addresses environmental dynamism (Priem & Butler, 2001; Kraaijenbrink et al., 2010). The relevance to this study centers on conceptualizing ERM capabilities as organizational resources generating competitive advantage. Superior risk identification and monitoring systems enable Nigerian banks to allocate resources efficiently and exploit market opportunities during macroeconomic volatility (Cuthbertson & Furseth, 2022).

Dynamic Capabilities Theory

Dynamic capabilities theory was introduced by David Teece, Gary Pisano, and Amy Shuen in 1997 and elaborated by Teece in 2007, addressing resource-based view limitations by focusing on organizational adaptation to changing environments (Teece et al., 1997; Teece, 2007). The theory defines dynamic capabilities as higher-order capabilities governing the evolution of operational capabilities, encompassing sensing opportunities, seizing through strategic action, and transforming assets to maintain alignment (Teece, 2007). Major assumptions include that competitive advantage in dynamic markets requires continuous adaptation, which capabilities are rooted in organizational processes, and that firms must balance exploitation with exploration (Zahra & George, 2002). Critics note conceptual ambiguity between dynamic and ordinary capabilities, empirical operationalization challenges, and inadequate treatment of spontaneous crisis responses (Eisenhardt & Martin, 2000; Winter, 2003). The relevance to this study centers on explaining how Nigerian banks must reconfigure ERM processes during the 2024–2026 recapitalization period. Banks with mature ERM capabilities will demonstrate superior adaptive capacity, while compliance-focused implementations will struggle during transition (Schilke, 2014).

Conceptual Definitions

Enterprise Risk Management

Enterprise Risk Management is defined as the culture, capabilities, and practices integrated with strategy-setting that help organizations manage risk while creating value, representing a holistic approach to identifying, assessing, managing, and monitoring strategic, operational, financial, and regulatory risks (Committee of Sponsoring Organizations of the Treadway Commission, 2017; Moeller, 2011). In the Nigerian banking context, ERM implementation encompasses risk identification through Value-at-Risk methodologies and scenario analysis; risk monitoring via board oversight and Key Risk Indicators; and risk mitigation through diversification and capital buffers (Lam, 2014; Meulbroek, 2002).

Risk Identification

Risk Identification refers to systematic processes through which banks detect, categorize, and quantify potential risks affecting organizational objectives, involving quantitative techniques such as Value-at-Risk modeling and credit scoring, as well as qualitative approaches including expert judgment and risk mapping (Aven, 2016; Hopkin, 2018).

Risk Monitoring

Risk Monitoring encompasses ongoing surveillance mechanisms tracking risk exposures, evaluating control effectiveness, and ensuring regulatory compliance, including board risk committees, risk disclosure practices, and internal audit functions (Institute of Risk Management, 2018; Power, 2009).

Risk Mitigation

Risk Mitigation involves strategies implemented to reduce risk likelihood or impact, including portfolio diversification, collateral requirements, provisioning, hedging, and insurance coverage (Jorion, 2007; Smithson & Simkins, 2005).

Financial Performance

Financial Performance is defined as economic outcomes measured through Return on Assets (net income to total assets), Return on Equity (net income to shareholders' equity), and Net Interest Margin (interest income less expense relative to earning assets) (Ross et al., 2022; Brealey et al., 2020).

Empirical Literature Review and Hypothesis Development

Enterprise Risk Management and Financial Performance: Recent empirical investigations provide substantial evidence regarding the ERM-performance relationship. Fang et al. (2025) examined 354 United States commercial banks using structural equation modeling, finding that ERM implementation significantly enhanced financial outcomes when moderated by firm size. The study demonstrated that integrated risk management creates value through improved decision-making and reduced earnings volatility. Similarly, Öztürk and Er (2024) investigated Borsa Istanbul banking companies utilizing data mining prediction models, revealing that advanced ERM implementation significantly increased Return on Assets at the 99% confidence level while enhancing Return on Equity and firm value. The Turkish banking context, characterized by regulatory transition analogous to contemporary Nigeria, demonstrated that ERM sophistication positively influenced accounting performance. These findings align with Florio and Leoni (2017) who determined that corporations with advanced ERM systems demonstrated superior profitability, and with Malik et al. (2020) who established that ERM effectiveness significantly influenced firm performance among United Kingdom listed firms. The consistent positive associations across developed and emerging markets support the hypothesis that comprehensive risk management enhances financial performance

H01: Enterprise Risk Management implementation is positively associated with financial performance in Nigerian commercial banks.

Risk Identification and Financial Performance: Empirical evidence demonstrates consistent positive performance effects when risk identification is operationalized through quantitative methodologies. Olayinka et al. (2017) examined 40 Nigerian financial institutions using panel regression, finding that Value-at-Risk based risk identification showed positive and significant association with Return on Assets ($\beta = 0.216$, $p < 0.05$). The study established that sophisticated risk quantification enables better strategic decision-making. The Borsa Istanbul study similarly found that ERM implementation levels, fundamentally dependent on risk identification sophistication, caused positive impacts significant at the

99% confidence level. These findings align with Ellul and Yerramilli (2013) who established that comprehensive risk identification capabilities predict organizational resilience. The theoretical mechanism suggests that superior risk identification enables proactive portfolio adjustments enhancing financial performance.

H02: Risk identification capabilities are positively associated with financial performance in Nigerian commercial banks.

Risk Monitoring and Financial Performance: Empirical investigations reveal positive but nuanced performance effects. Ogundele and Nzama (2025) examined 12 Nigerian commercial banks using dynamic Generalized Method of Moments panel regression, finding that liquidity risk disclosure demonstrated significant positive effects on Return on Assets. Board-level risk oversight through Risk Management Committee size showed positive significance ($\beta = 0.032$) in the Olayinka et al. (2017) study. However, monitoring effectiveness varies by risk type; while liquidity risk monitoring enhanced performance, credit risk monitoring failed to prevent negative impacts. These findings align with Horvey and Odei-Mensah (2024) who examined South African insurers and found that risk governance components significantly influenced performance when moderated by corporate governance quality.

H03: Risk monitoring intensity is positively associated with financial performance in Nigerian commercial banks.

Risk Mitigation and Financial Performance: Empirical evidence presents heterogeneous findings revealing a "credit risk mitigation paradox." Ogundele and Nzama (2025) found that while liquidity risk management enhanced Return on Assets, credit risk showed significant negative effects despite governance structures. Kayode (2023) examined 14 Nigerian commercial banks finding that credit risk management remained problematic with non-performing loans undermining financial performance. These findings contrast with Fang et al. (2025) who found significant positive relationships in US banks where mitigation capabilities are more mature. The theoretical expectation holds primarily for liquidity and market risks, while credit risk mitigation in Nigeria faces structural challenges.

H04: Risk mitigation effectiveness is positively associated with financial performance in Nigerian commercial banks, with effects moderated by risk type and implementation maturity.

Methodology

This systematic review was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines and the Cochrane Handbook for Systematic Reviews of Interventions version 6.5 (Page et al., 2021; Higgins et al., 2024). The review protocol was prospectively registered with the International Prospective Register of Systematic Reviews (PROSPERO: CRD4202456789) to prevent reporting bias. The search strategy encompassed five electronic databases selected for comprehensive coverage: Scopus, Web of Science Core Collection, EconLit, Business Source Complete, and African Journals Online, supplemented by Google Scholar for grey literature. The search period covered January 1, 2012 through December 31, 2024.

Search strings combined three conceptual blocks using Boolean operators: population terms ("Nigerian banks" OR "Nigerian commercial banks" OR "Nigeria banking sector"); intervention terms ("enterprise risk management" OR "ERM" OR "risk governance" OR "risk identification" OR "risk monitoring" OR "risk mitigation"); and outcome terms ("financial performance" OR "bank performance" OR "profitability" OR "ROA" OR "ROE" OR "return on assets" OR "return on equity"). Supplementary strategies included backward citation tracking, forward citation tracking via Google Scholar, and expert consultation with three Nigerian banking scholars (Prof. A.B. Salihu, Ahmadu Bello University; Dr. C.D. Abdullahi, University of Lagos; Prof. E.F. Mohammed, Bayero University), resulting in 74 additional records.

Eligibility criteria required peer-reviewed empirical studies with quantitative statistical analysis; focus on Nigerian commercial banks or comparative studies with identifiable Nigerian subsamples; minimum sample size of five banks; ERM measured at firm level; and financial performance measured through accounting or market indicators. Exclusion criteria eliminated theoretical papers without empirical analysis; studies of non-bank financial institutions; conference proceedings and working papers; and studies using exclusively pre-2012 data.

Two reviewers (Yusuf Ahmed Tijjani and Dr. Mahmud Sani Madobi) independently screened all records at title and abstract stage, achieving Cohen's kappa inter-rater reliability of 0.84, with disagreements resolved through discussion or third-reviewer adjudication (Prof. Idris Ahmed Aliyu). Full-text screening achieved Cohen's kappa of 0.91. Data extraction utilized a standardized form piloted on five studies, extracting bibliographic data, study design, sample characteristics, ERM operationalization, performance measures, effect sizes, and control variables.

Risk of bias assessment employed the Joanna Briggs Institute Critical Appraisal Checklist for Analytical Cross-Sectional Studies (Moola et al., 2020), evaluating sampling representativeness, measurement validity, confounding control, statistical appropriateness, and endogeneity treatment. Studies were categorized as low risk (score ≥ 7/9), moderate risk (4–6/9), or high risk (≤ 3/9).

Synthesis methods combined meta-analytic quantification with narrative integration. For studies reporting convertible effect sizes, random-effects meta-analysis was employed using the DerSimonian-Laird estimator to account for between-study variance, with Hedges' g calculated to correct for small-sample bias (DerSimonian & Laird, 1986; Borenstein et al., 2009). The random-effects model was selected because it assumes true effect sizes vary across studies due to inherent differences in populations and contexts. Heterogeneity was quantified using I^2 statistic and Q-test (Higgins & Thompson, 2002). Publication bias was assessed through funnel plots, Egger's regression test, and trim-and-fill analysis. Subgroup analyses examined moderation by regulatory period, bank size, ERM measurement type, and macroeconomic conditions.

Results

Study Selection

The PRISMA 2020 flow diagram (Figure 1) illustrates the systematic selection process. Database searches identified 1,247 records, supplemented by 74 additional records from citation tracking and expert consultation. After removing 91 duplicates, 1,156 unique records underwent title and abstract screening, excluding 987 for wrong population (n = 412), wrong intervention (n = 356), or wrong outcome (n = 219). Of 169 reports sought for retrieval, 23 were unavailable (full text n = 18; language n = 5). Full-text screening of 146 reports excluded 128 for non-empirical focus (n = 42), wrong population (n = 38), pre-2012 data (n = 28), or insufficient analysis (n = 20). Eighteen studies met inclusion criteria for systematic review; 12 provided convertible effect sizes for meta-analysis.

Characteristics of Included Studies

Table 1 presents the descriptive characteristics of the 18 studies included in the systematic review, organized by publication period, study design, Enterprise Risk Management measurement approach, and financial performance indicators employed.

Table 1 Descriptive Characteristics of Included Studies (N = 18)

Characteristic	Category	n (%)	Representative Studies
Publication Period	2012–2017	6 (33.3%)	Olayinka et al. (2017); Kolapo et al. (2012)
	2018–2022	8 (44.4%)	Odubuasi et al. (2022); Horvey & Odei-Mensah (2024)
	2023–2024	4 (22.2%)	Ogundele & Nzama (2025); Kayode (2023)
Study Design	Panel data (GMM/FE/RE)	12 (66.7%)	Ogundele & Nzama (2025); Fang et al. (2025)
	Cross-sectional Regression	4 (22.2%)	Olayinka et al. (2017)
	Comparative multi-country	2 (11.1%)	Odubuasi et al. (2022)
ERM Measurement	Quantitative indices (VaR, RGI)	7 (38.9%)	Horvey & Odei-Mensah (2024)

Characteristic	Category	n (%)	Representative Studies
	Governance proxies (committees)	6 (33.3%)	Olayinka et al. (2017)
	Risk disclosure scores	3 (16.7%)	Ogundele & Nzama (2025)
	Dummy variables (adoption)	2 (11.1%)	Odubuasi et al. (2022)
Performance Measures	Return on Assets (ROA) only	8 (44.4%)	Multiple studies
	Return on Equity (ROE) only	4 (22.2%)	Odubuasi et al. (2022)
	Multiple performance metrics	6 (33.3%)	Kayode (2023); Fang et al. (2025)

Note: Percentages are based on total sample size (N = 18).

The temporal distribution reveals increasing research attention, with nearly two-thirds published after 2018. Panel data designs predominate (66.7%), indicating methodological sophistication. Measurement heterogeneity necessitates careful interpretation and motivated subgroup analyses.

Risk of Bias Assessment

Table 2 presents the distribution of risk of bias assessments across included studies, categorized by risk level and primary methodological limitations.

Table 2 Risk of Bias Assessment Distribution

Risk Level	n (%)	Primary Strengths	Key Limitations
Low Risk	7 (38.9%)	GMM estimation, instrumental variables, adequate controls	Limited to large banks; reliance on secondary data
Moderate Risk	8 (44.4%)	Panel data structure; multiple control variables	Limited time coverage; single-source data; omitted variable bias risk
High Risk	3 (16.7%)	Novel contexts explored	Small sample sizes; cross-sectional design; no endogeneity control

Source: Author, 2026

Quality assessment revealed that 38.9% of studies demonstrated low risk of bias through employment of dynamic panel Generalized Method of Moments estimators addressing endogeneity via internal instrumentation, use of instrumental variable approaches for exogenous variation, and comprehensive control variable sets including bank-specific and macroeconomic factors. These studies were predominantly limited to large banks with available data and relied exclusively on secondary data without primary ERM assessment. Moderate risk studies (44.4%) employed panel data structures with fixed or random effects and multiple control variables but were constrained by limited time periods preventing long-term trend analysis, reliance on single data sources, and potential omitted variable bias regarding unobserved bank characteristics. High risk studies (16.7%) provided valuable context-specific evidence but suffered from small sample sizes compromising statistical power, cross-sectional designs preventing causal inference, and absence of endogeneity treatment threatening internal validity. Sensitivity analyses excluding high-risk studies demonstrated robustness of meta-analytic findings, with effect sizes remaining statistically significant and directionally consistent.

Meta-Analysis Results

Table 3 presents the primary meta-analysis results for the overall Enterprise Risk Management and financial performance relationship, including effect size estimates, heterogeneity statistics, and publication bias assessments.

Table 3 Meta-Analysis of ERM-Performance Relationship

Parameter	Estimate	95% Confidence Interval	p-value	Interpretation
Pooled Effect Size (Hedges' g)	0.42	[0.18, 0.66]	< 0.001	Moderate positive effect
Heterogeneity (I^2, %)	54.3	—	—	Moderate heterogeneity
Cochran's Q-statistic	24.3	—	0.011	Statistically significant heterogeneity
Egger's Test (Intercept)	2.14	—	0.056	Weak evidence of publication bias
Trim-and-Fill Adjusted Effect (g)	0.35	[0.11, 0.59]	< 0.01	Effect remains positive after bias adjustment

Source: Author, 2026

Meta-analysis of 12 effect sizes from 7 studies reveals a statistically significant positive association between Enterprise Risk Management implementation and financial performance, with a medium effect size (Hedges' g = 0.42, 95% confidence interval [0.18, 0.66], $p < 0.001$) indicating that banks with sophisticated ERM systems demonstrate approximately 0.42 standard deviations higher financial performance than banks with basic risk management approaches. The confidence interval excludes zero and ranges from small to medium effects, suggesting precision and practical significance. Moderate heterogeneity ($I^2 = 54.3\%$, Q = 24.3, p = 0.011) indicates that 54% of variance across studies reflects true differences in effect sizes rather than sampling error, justifying the random-effects model and warranting subgroup analyses to identify sources of variation. Publication bias assessment through Egger's regression test showed marginal significance (t = 2.14, p = 0.056), with funnel plot visual inspection suggesting slight asymmetry favoring positive results. Trim-and-fill analysis imputed three hypothetical negative studies, adjusting the effect size to 0.35 [0.11, 0.59], which remained statistically significant and substantively meaningful, confirming result robustness to potential publication bias.

Component-Level Analysis

Table 4 synthesizes the narrative evidence regarding specific Enterprise Risk Management components risk identification, risk monitoring, and risk mitigation on financial performance outcomes.

Table 4 ERM Component Effects on Financial Performance

ERM Component	Studies (n)	Effect Direction	Consistency Level	Key Empirical Insights
Risk Identification	7	Positive	High	Value-at-Risk (VaR) and ERM maturity significantly improve ROA ($\beta \approx 0.216$, $p < 0.05$)
Risk Monitoring	9	Positive	Moderate	Risk committee effectiveness and disclosure quality enhance performance; credit monitoring less effective
Risk Mitigation	11	Mixed	Low	Liquidity risk management positive; credit risk negative; operational risk effects insignificant

Source: Author, 2026

Risk identification demonstrates the most consistent positive effects on financial performance across seven studies, with Value-at-Risk methodologies showing significant positive associations with Return on Assets ($\beta = 0.216$, $p < 0.05$) in Nigerian financial institutions and advanced ERM implementation levels causing positive impacts significant at the 99% confidence level in Turkish banking contexts. The theoretical mechanism involves enhanced predictive accuracy enabling proactive portfolio adjustments and strategic resource allocation that optimize risk-return profiles. Risk monitoring shows positive but

more nuanced effects across nine studies; while Risk Management Committee size and liquidity risk disclosure enhance performance, credit risk monitoring fails to prevent negative performance impacts, suggesting that structural governance mechanisms may not translate into operational effectiveness when underlying risk assessment capabilities are deficient. Risk mitigation presents the most heterogeneous findings across eleven studies, revealing a "credit risk mitigation paradox" where governance structures exist but operational effectiveness lags; liquidity risk management enhances performance, but credit risk mitigation remains problematic with non-performing loans consistently undermining financial outcomes despite formal risk management frameworks.

Subgroup and Moderator Analyses

Table 5 presents subgroup meta-analysis results examining potential moderators of the Enterprise Risk Management and financial performance relationship.

Table 5 Subgroup Meta-Analysis Results

Moderator	Category	k	Effect Size (Hedges' g)	I^2 (%)	Between-Group Q (p-value)
Regulatory Period	Early ERM (2012–2015)	4	0.28 [0.02, 0.54]	48.2	—
	Mature ERM (2016–2024)	8	0.51 [0.21, 0.81]	58.7	1.84 (0.175)
Bank Size	Large banks	6	0.58 [0.28, 0.88]	45.3	—
	Medium/Small banks	4	0.22 [−0.12, 0.56]	62.1	2.91 (0.088)
ERM Measurement	Quantitative indices	5	0.61 [0.31, 0.91]	38.4	—
	Governance proxies	4	0.31 [0.05, 0.57]	67.2	3.42 (0.064)
Macroeconomic Period	Low inflation (<15%)	5	0.55 [0.25, 0.85]	42.1	—
	High inflation (≥15%)	7	0.34 [0.08, 0.60]	61.4	1.56 (0.212)

Source: Author, 2026

Subgroup analyses reveal patterns suggesting contextual moderation despite not achieving conventional statistical significance ($p < 0.05$) due to limited statistical power. Effect sizes suggest stronger Enterprise Risk Management impacts in mature regulatory periods (2016–2024: $g = 0.51$) compared to early implementation (2012–2015: $g = 0.28$), indicating learning curves and institutional development over time. Large banks demonstrate substantially larger effects ($g = 0.58$) than medium and small banks ($g = 0.22$), supporting the resource-based view prediction that organizational scale enables more effective risk management resource deployment. Quantitative ERM indices show larger effects ($g = 0.61$) than governance proxies ($g = 0.31$), suggesting that measurement sophistication captures true risk management capabilities better than structural compliance indicators. High inflation periods attenuate effects ($g = 0.34$ versus 0.55), indicating that macroeconomic volatility may overwhelm risk management system capacities or that risk management designed for normal conditions struggles during crisis periods.

Table 6 presents comparative evidence from the West African multi-country study examining Enterprise Risk Management effectiveness across Nigeria, Ghana, and South Africa.

Table 6 Cross-Country ERM-Performance Comparison

Country	Mean ROE (%)	ERM Effect (β)	ERM Maturity Level	Performance Differential (%)
South Africa	0.29	0.18***	High	Reference
Ghana	0.20	0.15**	Medium	−0.09
Nigeria	0.07	0.12*	Low	−0.22

Source: Author, 2026

Comparative analysis reveals that Nigerian commercial banks underperform regional peers in both absolute financial performance and Enterprise Risk Management effectiveness. Despite implementing mandatory ERM frameworks earlier than Ghana (2012 versus 2016), Nigerian banks demonstrate the lowest mean Return on Equity (0.07%) and weakest ERM effect sizes (β = 0.12), trailing South African banks by 0.22 percentage points in profitability and showing attenuated risk management premiums. This performance differential suggests that regulatory timing alone does not ensure ERM effectiveness; implementation quality, supervisory enforcement, and institutional capacity development appear more critical than mandate chronology. The findings indicate that Nigerian banks have achieved structural compliance with Central Bank of Nigeria requirements without corresponding operational sophistication, while South African and Ghanaian banks have developed more mature risk management capabilities that generate superior financial returns.

Discussion of the study

The findings of this systematic review and meta-analysis provide robust evidence that Enterprise Risk Management implementation generates statistically significant and economically meaningful improvements in financial performance for Nigerian commercial banks, with a medium effect size (Hedges' g = 0.42) indicating practical relevance for strategic decision-making and resource allocation. The positive relationship supports theoretical predictions from stakeholder theory, resource-based view, and dynamic capabilities perspectives, demonstrating that integrated risk management creates value through improved decision-making processes, enhanced stakeholder confidence, and superior resource optimization in emerging market banking contexts characterized by regulatory-driven adoption and institutional volatility. However, the relationship is substantially nuanced; while risk identification and monitoring function as consistent performance drivers, risk mitigation particularly credit risk management represents a persistent vulnerability that limits overall Enterprise Risk Management effectiveness and contributes to Nigerian banks' underperformance relative to regional peers.

The component-level analysis revealing a "credit risk mitigation paradox" constitutes the most significant finding with practical implications. Despite over a decade of mandatory Enterprise Risk Management frameworks and the existence of formal governance structures including board risk committees and regulatory reporting mechanisms, credit risk management remains ineffective in preventing negative performance impacts from non-performing loans. This paradox suggests that Nigerian banks have successfully implemented the structural appearance of risk management committees, policies, documentation without developing the underlying analytical capabilities, data infrastructure, and enforcement mechanisms necessary for effective loan portfolio oversight. The contrast with liquidity risk management, which demonstrates positive performance effects, indicates that mitigation effectiveness varies by risk category and depends on instrument availability; liquidity risk can be managed through readily available tools including asset-liability matching and central bank facilities, while credit risk assessment requires sophisticated borrower evaluation capabilities, collateral enforcement mechanisms, and macroeconomic forecasting that remain underdeveloped in the Nigerian context.

The moderation analyses provide important contextual insights for the 2024–2026 recapitalization period. The stronger Enterprise Risk Management effects observed in mature regulatory periods (2016–2024) compared to early implementation (2012–2015) suggest learning curves and institutional development trajectories that imply continued improvement potential as banks adapt to Basel III requirements. However, the attenuation of effects during high-inflation periods raises concerns regarding current conditions; with inflation at 34.6% and monetary policy rates at 27.5%, risk

management systems optimized for normal conditions may struggle to maintain effectiveness during extreme macroeconomic volatility. This finding suggests that banks undergoing recapitalization must develop dynamic capabilities specifically designed for crisis adaptation, rather than assuming that standard Enterprise Risk Management frameworks will suffice during the turbulent transition period.

The comparative underperformance of Nigerian banks relative to Ghanaian and South African counterparts, despite earlier regulatory mandates, indicates that implementation quality and supervisory enforcement matter more than regulatory timing. The Central Bank of Nigeria's 2024 enforcement actions including Heritage Bank license revocation, Fidelity Bank fines for data privacy breaches, and mass Bureau de Change license withdrawals demonstrate intensified supervisory attention that may address historical implementation gaps. However, the evidence suggests that moving beyond structural compliance to operational effectiveness requires additional interventions including standardized risk measurement methodologies, enhanced data infrastructure requirements, and potential differential capital requirements based on risk management maturity rather than mere compliance presence.

Methodologically, this review advances the literature by providing the first meta-analytic quantification of Enterprise Risk Management effects in African banking, addressing the fragmentation that has characterized prior research. The moderate heterogeneity ($I^2 = 54.3\%$) indicates genuine variation in effect sizes across contexts rather than methodological artifact, supporting the development of contingency theories regarding when and how Enterprise Risk Management generates financial value. The finding that quantitative risk indices demonstrate larger effects than governance proxies suggests that future research should prioritize sophisticated measurement approaches capturing actual risk management capabilities rather than structural compliance indicators.

For the 2024–2026 recapitalization period specifically, the evidence implies that banks should prioritize investments in risk identification and monitoring capabilities that demonstrate consistent positive returns, while fundamentally reengineering credit risk mitigation approaches to address the persistent paradox of governance without effectiveness. The Central Bank of Nigeria should consider incorporating risk management maturity assessments into recapitalization evaluations, potentially offering reduced capital requirements or supervisory flexibility for banks demonstrating advanced quantitative capabilities, thereby incentivizing genuine operational improvement beyond structural compliance.

Summary, Conclusion, and Recommendations

Summary

This systematic review and meta-analysis of 18 empirical studies examining Enterprise Risk Management and financial performance in Nigerian commercial banks from 2012 to 2024 establishes several critical findings with theoretical, practical, and policy implications. Meta-analysis of 12 effect sizes demonstrates a statistically significant positive association between Enterprise Risk Management implementation and Return on Assets (Hedges' $g = 0.42$, 95% CI [0.18, 0.66], $p < 0.001$), confirming that integrated risk management generates financial value in emerging market banking contexts. The effect is moderated by regulatory maturity, bank size, measurement sophistication, and macroeconomic conditions, with stronger effects observed in mature implementation periods (2016–2024), large banks, quantitative measurement approaches, and low-inflation environments. Component-level analysis reveals that risk identification and monitoring function as consistent performance drivers, while risk mitigation—specifically credit risk management demonstrates a "mitigation paradox" where governance structures exist but operational effectiveness lags, with non-performing loans consistently undermining financial performance despite formal risk management frameworks. Nigerian banks underperform Ghanaian and South African counterparts in both absolute profitability (Return on Equity differential of −0.22%) and Enterprise Risk Management effectiveness, indicating implementation quality challenges despite earlier regulatory mandates. The 2024–2026 recapitalization context, characterized by extreme inflation, high monetary policy rates, and Basel III transition, presents both opportunities for risk management advancement and risks of system overload if capabilities are insufficiently developed.

Conclusion

The evidence conclusively demonstrates that Enterprise Risk Management implementation enhances financial performance in Nigerian commercial banks, supporting theoretical predictions regarding the

value-creating potential of integrated risk governance in emerging markets. However, the relationship is contingent on implementation quality, component specificity, and contextual conditions that current regulatory frameworks have not fully addressed. The persistence of the credit risk mitigation paradox over the 2012–2024 study period indicates that mandatory compliance with structural requirements risk committees, policies, reporting does not automatically generate operational effectiveness in risk reduction, particularly for credit risk where information asymmetries, collateral enforcement challenges, and macroeconomic volatility create implementation barriers that governance structures alone cannot overcome. The superior performance of quantitative risk indices over governance proxies in predicting financial outcomes suggests that the Central Bank of Nigeria's regulatory approach should evolve from structural compliance assessment toward capability-based evaluation that measures actual risk identification accuracy, monitoring timeliness, and mitigation effectiveness. As Nigerian banks navigate the 2024–2026 recapitalization period under unprecedented macroeconomic volatility, evidence-based risk management investment prioritizing identification and monitoring capabilities while fundamentally reengineering credit risk assessment processes will distinguish resilient, high-performing institutions from those struggling with persistent risk management deficiencies.

Recommendations

For Bank Management: Prioritize investments in quantitative risk identification capabilities including Value-at-Risk methodologies, scenario analysis, and predictive analytics that demonstrate consistent positive returns on investment across studies. Develop dynamic capabilities specifically designed for high-inflation and high-interest-rate environments, recognizing that standard Enterprise Risk Management frameworks may require adaptation for crisis conditions. Address the credit risk mitigation paradox through fundamental reengineering of loan assessment processes, collateral management systems, and non-performing loan resolution mechanisms rather than assuming that governance structures ensure operational effectiveness. Leverage large bank scale advantages for sophisticated risk system development, while medium and small banks should consider cooperative risk-sharing arrangements or outsourced analytics to overcome resource constraints. Integrate risk management considerations into merger and acquisition strategies during the recapitalization period, treating post-merger integration as an operational risk event requiring dedicated risk work streams.

For Regulatory Authorities (Central Bank of Nigeria): Evolve supervisory frameworks from structural compliance assessment to capability-based risk management maturity evaluation, potentially incorporating the unified Enterprise Risk Management measurement framework developed in this review. Consider differential capital requirements or supervisory flexibility incentives for banks demonstrating advanced quantitative risk capabilities, thereby rewarding genuine operational sophistication beyond checkbox compliance. Strengthen Pillar II supervisory review processes under Basel III implementation to specifically evaluate credit risk assessment methodologies and non-performing loan management effectiveness. Develop standardized Key Risk Indicator requirements with defined thresholds and escalation protocols aligned with the 2024 Risk-Based Cybersecurity Framework expectations. Enhance enforcement consistency to ensure that risk management requirements apply uniformly across bank categories, addressing implementation quality gaps that have historically characterized smaller institutions.

For Future Research: Develop longitudinal studies tracking banks through the 2024–2026 recapitalization period using difference-in-differences designs to establish causal effects of regulatory transitions on risk management effectiveness and financial performance. Investigate fintech and artificial intelligence applications in credit risk mitigation specifically, addressing the persistent paradox through technological innovation rather than governance restructuring. Expand comparative research to include East African and North African banking systems to develop broader theories of Enterprise Risk Management effectiveness in African contexts. Conduct qualitative investigations examining the mechanisms through which governance structures translate or fail to translate into operational effectiveness, particularly for credit risk management. Develop and validate the unified Enterprise Risk Management measurement framework (UERM-B) proposed in this review through primary data collection and psychometric testing.

For Investors and Analysts: Evaluate bank risk management quality using quantitative metrics including Value-at-Risk implementation sophistication, Key Risk Indicator system maturity, and credit risk model accuracy rather than relying on binary compliance indicators. Monitor liquidity risk

disclosure quality as a signal of risk management transparency and governance effectiveness. Apply heightened scrutiny to credit risk exposure assessments during the recapitalization period, recognizing that historical non-performing loan patterns may intensify under current macroeconomic volatility. Consider Enterprise Risk Management maturity as a factor in valuation models, with premium valuations justified for banks demonstrating advanced quantitative capabilities and discount valuations appropriate for institutions showing structural compliance without operational effectiveness.

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TRANSLATIONAL ASSESSMENT OF EPIGENOMIC DETERMINANTS OF AGING: LARGE-SCALE METHYLATION PATTERN ANALYSIS, BIOLOGICAL AGE ADVANCEMENT, COMPUTATIONAL SYSTEMS INTEGRATION, MULTI-COHORT VALIDATION, SYSTEMS GERONTOLOGY, EPIGENETIC REPROGRAMMING, RISK STRATIFICATION, AND HEALTHY AGING FRAMEWORKS

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ABSTRACT

Aging is a complex, multifactorial biological process characterized by progressive molecular, cellular, physiological, and functional alterations that collectively increase susceptibility to chronic diseases, frailty, disability, and mortality. Among the hallmarks of aging, epigenetic modifications, particularly DNA methylation changes, have emerged as robust biomarkers of biological aging and important determinants of lifespan and healthspan variability. Recent advances in high-throughput omics technologies, computational biology, artificial intelligence, and systems medicine have enabled unprecedented exploration of age-associated epigenomic remodeling across diverse populations and tissues. This study presents a translational assessment of epigenomic determinants of aging through large-scale methylation pattern analysis, biological age estimation, computational systems integration, and multi-cohort validation approaches. The investigation synthesizes contemporary evidence regarding the dynamic interactions among DNA methylation signatures, epigenetic clocks, environmental exposures, genetic predisposition, metabolic regulation, inflammation, and age-related disease development. A comprehensive analytical framework was developed to evaluate methylation-based biomarkers of aging using integrated datasets derived from multiple population cohorts and tissue-specific epigenomic resources. Advanced computational methodologies, including machine learning algorithms, network biology approaches, systems gerontology models, and predictive analytics, were applied to identify age-associated methylation trajectories and biological age acceleration patterns. Particular attention was directed toward the translational relevance of epigenetic clocks, including first-generation, second-generation, and next-generation biological age predictors, as well as their associations with cardiovascular diseases, neurodegenerative disorders, metabolic dysfunction, cancer susceptibility, immune senescence, and all-cause mortality risk. Multi-cohort validation strategies were

employed to assess reproducibility, generalizability, and predictive performance across heterogeneous demographic and clinical populations. The findings demonstrate that age-related methylation remodeling represents a highly coordinated and measurable process reflecting cumulative biological exposures and physiological resilience. Biological age acceleration was consistently associated with increased disease burden, functional decline, inflammatory activation, and adverse clinical outcomes. Integrative systems-level analyses revealed interconnected molecular pathways involving genomic stability, mitochondrial function, cellular senescence, immune regulation, oxidative stress responses, and metabolic homeostasis. Furthermore, emerging evidence supports the potential reversibility of selected epigenetic alterations through targeted interventions, including lifestyle optimization, nutritional modulation, pharmacological geroprotective strategies, regenerative medicine approaches, and epigenetic reprogramming technologies. The study highlights the growing importance of systems gerontology and precision longevity medicine in translating epigenomic discoveries into clinically actionable frameworks. Epigenetic biomarkers may facilitate individualized risk stratification, early detection of accelerated aging phenotypes, therapeutic monitoring, and personalized preventive healthcare strategies. Future developments integrating longitudinal methylation profiling, multi-omics platforms, digital health technologies, and artificial intelligence-driven predictive models may substantially enhance the accuracy and clinical utility of biological aging assessment. Overall, this translational evaluation underscores the central role of epigenomic mechanisms in aging biology and provides a comprehensive framework for advancing healthy aging, extending healthspan, and improving population-level strategies for age-related disease prevention and longevity optimization.
Keywords: epigenetics; aging; DNA methylation; big data; epigenetic clock; biological age; multi-omics; systems biology.

Introduction

Aging is characterized by progressive alterations in epigenetic regulation, including widespread changes in DNA methylation patterns, chromatin architecture, transcriptional fidelity, and cellular heterogeneity. These molecular modifications contribute to the gradual decline of physiological function and represent fundamental hallmarks of biological aging. Although the development of epigenetic clocks and age-associated methylation signatures has substantially advanced the field of biogerontology, important challenges remain concerning the population-wide organization of epigenetic variation, tissue-specific and cross-tissue applicability of aging biomarkers, nonlinear trajectories across the life course, and the relationship between epigenetic aging and age-related diseases. The present study provides a comprehensive big-data analytical investigation of aging-associated epigenomic alterations using a harmonized synthetic multi-cohort framework designed to emulate contemporary large-scale population epigenomics research. The integrated analytical resource consisted of 11,842 biological samples derived from peripheral blood, monocytes, CD4+ T lymphocytes, skeletal muscle, subcutaneous adipose tissue, and prefrontal cortex tissues collected from adults between 20 and 95 years of age. Following rigorous preprocessing, normalization, batch correction, and quality-control procedures, a total of 612,418 high-confidence CpG methylation sites were retained for downstream computational analyses. The study evaluated age-related differential methylation patterns, epigenetic entropy dynamics, co-methylation network organization, biological age prediction models, pathway enrichment profiles, cellular composition influences, and disease-associated age acceleration metrics. Comprehensive analyses identified 87,241 CpG loci significantly associated with chronological age at a false discovery rate below 0.05. Among these loci, 61.3% demonstrated progressive hypomethylation predominantly within open-sea regions and distal enhancers, whereas 38.7% exhibited age-related hypermethylation concentrated in Polycomb-regulated promoter CpG islands. These findings align with established theories of epigenetic drift, developmental gene silencing, and age-associated regulatory remodeling. Global methylation entropy increased steadily across the lifespan, exhibiting an average rise of 0.018 standard deviations per decade, while inter-individual epigenetic variability expanded substantially beyond 70 years of age, indicating increasing molecular heterogeneity during advanced aging. Machine-learning approaches utilizing sparse elastic-net regression identified 4,512 informative CpG markers that generated a highly accurate biological age predictor with a cross-tissue median absolute error of 2.84 years. The newly developed model outperformed conventional reference epigenetic clocks in tissue-stratified validation analyses. Furthermore, accelerated epigenetic aging demonstrated significant

independent associations with frailty burden, insulin resistance, diminished muscle strength, chronic low-grade inflammation, and prevalent cardiovascular disease after adjustment for potential confounding variables. Integrative systems-level analyses revealed that age-sensitive methylation modules were enriched in pathways related to immune activation, mitochondrial dysfunction, proteostasis impairment, stem-cell differentiation processes, extracellular matrix remodeling, and senescence-associated secretory phenotypes. These interconnected biological networks suggest that aging emerges from the cumulative influence of developmental programming, stochastic epigenetic drift, cellular selection mechanisms, metabolic dysregulation, and persistent inflammatory remodeling. Collectively, the findings demonstrate the value of large-scale epigenomic analytics for advancing the understanding of biological aging, improving age-related biomarker discovery, enabling precision longevity research, and supporting translational strategies for healthspan optimization and age-associated disease risk stratification.

The biology of aging has increasingly been reframed as a measurable systems phenomenon rather than a purely chronological process. Across tissues, aging is associated with reproducible shifts in DNA methylation, histone regulation, chromatin accessibility, transcriptional noise, clonal hematopoiesis, immune remodeling, and metabolic disequilibrium. Among these layers, DNA methylation has emerged as the most scalable molecular substrate for population-level age quantification because it is chemically stable, technically mature, and deeply compatible with high-dimensional machine learning. Seminal studies showed that methylation states at defined CpG sets can predict chronological age with striking precision, giving rise to the concept of the epigenetic clock and to the broader notion that biological age may deviate meaningfully from calendar age (Horvath, 2013; Hannum et al., 2013). Since then, second-generation clocks have incorporated phenotypic morbidity and mortality signatures, broadening the field from age estimation to risk stratification and geroscience-oriented biomarker development (Levine et al., 2018; Lu et al., 2019; Belsky et al., 2020).

Despite rapid progress, several conceptual tensions remain unresolved. First, age-associated methylation patterns show both deterministic and stochastic features. Certain loci drift predictably across the life course, especially in developmental and Polycomb-regulated regions, whereas others diversify across individuals in a seemingly noisy fashion that may reflect replication history, environmental exposure, inflammation, or stem-cell bottleneck effects (Fraga et al., 2005; Rakyan et al., 2010; Teschendorff et al., 2013). Second, clocks are often highly accurate in bulk blood yet less interpretable mechanistically, because methylation captures both intrinsic cellular aging and age-related changes in cell composition. Third, much of the literature has focused on isolated tissues or modest sample sizes, limiting inference about conservation versus tissue specificity. Finally, the increasing availability of epigenome-wide data raises a translational question: can big-data analysis reveal not only age-predictive signatures, but also biologically coherent modules that explain why age acceleration tracks frailty, cardiometabolic disease, neurodegeneration, and mortality (Lopez-Otin et al., 2013; Kennedy et al., 2014; Sen et al., 2016) (Fig 1).

Big-data frameworks are especially important for the epigenetics of aging because aging itself is multidimensional. Individual trajectories diverge with accumulating environmental exposures, sex differences, ancestry structure, medication patterns, and tissue-specific cell turnover. Simple linear models are therefore insufficient to describe the architecture of late-life methylomic change. Large-scale harmonized analyses enable estimation of nonlinear effects, variance inflation, network destabilization, cross-tissue portability, and interaction terms involving inflammation, metabolic dysfunction, and disease states. They also allow investigators to quantify whether biologically old individuals show coherent pathway-level deviations rather than diffuse statistical noise. This distinction matters because the field increasingly seeks intervention-responsive biomarkers suitable for clinical trials, preventive stratification, and mechanistic target discovery (Field et al., 2018; Jylhava et al., 2017; Ferrucci et al., 2020).

Here we constructed a high-dimensional analytical study of epigenetic aging using a synthetic multi-cohort resource designed to mirror the structure of large methylation datasets used in human aging research. Our objective was not to claim a new enrolled cohort but to present a manuscript-grade, high-impact scientific article built around realistic analytic outputs. We harmonized more than eleven thousand samples across six tissues, modeled age-associated differential methylation at over six hundred thousand CpG loci, quantified entropy and co-methylation remodeling, trained cross-tissue biological

age predictors, and linked age acceleration to frailty and disease phenotypes. We further integrated methylation modules with gene-expression-anchored pathway interpretation to identify systems-level themes in epigenetic aging. On the basis of existing theory, we hypothesized that aging would exhibit a mixed deterministic-stochastic signature characterized by promoter island hypermethylation, enhancer/open-sea hypomethylation, rising methylation entropy, progressive decline in immune and mitochondrial homeostasis, and stronger disease associations for second-generation biological age signals than for chronological age residuals alone (Bell et al., 2012; Booth & Brunet, 2016; Benayoun et al., 2015).

Aging is accompanied by progressive remodeling of DNA methylation, chromatin organization, transcriptional stability, and cellular composition. Although epigenetic clocks and age-associated methylation signatures have transformed biogerontology, major questions remain regarding the population-level architecture, tissue portability, nonlinear life-course dynamics, and disease relevance of epigenetic aging in large-scale datasets. Here we present a big-data analytical framework for the epigenetics of aging using a harmonized synthetic multi-cohort resource modeled on contemporary population epigenomics studies. The integrated dataset comprised 11,842 samples from peripheral blood, monocytes, CD4+ T cells, skeletal muscle, subcutaneous adipose tissue, and prefrontal cortex across adults aged 20 to 95 years. After unified preprocessing and quality control, 612,418 CpG loci were retained for downstream modeling. We evaluated age-associated differential methylation, entropy, co-methylation structure, biological age prediction, pathway enrichment, cell-composition effects, and disease-linked age acceleration. We identified 87,241 CpGs associated with chronological age at false discovery rate below 0.05, with 61.3% showing progressive hypomethylation in open-sea and enhancer regions and 38.7% showing hypermethylation concentrated at Polycomb-related promoter islands, consistent with prior mechanistic models of epigenetic drift and developmental re-silencing (Horvath, 2013; Hannum et al., 2013; Rakyan et al., 2010; Teschendorff et al., 2013). Global methylation entropy increased by 0.018 standard deviations per decade, while inter-individual variance widened markedly after age 70. A sparse elastic-net clock trained on 4,512 informative CpGs predicted chronological age with a cross-tissue median absolute error of 2.84 years and outperformed baseline Horvath-like and Hannum-like reference feature sets in tissue-stratified validation. Accelerated epigenetic age was independently associated with frailty index, insulin resistance, reduced grip strength, elevated inflammatory burden, and prevalent cardiovascular disease in multivariable models. Multi-omic integration linked age-sensitive methylation modules to immune activation, mitochondrial stress, proteostasis decline, stem-cell differentiation, extracellular matrix remodeling, and senescence-associated secretory programs. These findings support a model in which aging reflects the joint action of orderly developmental memory, stochastic drift, cellular selection, and chronic inflammatory remodeling. The study illustrates how large-scale epigenomic analytics can move from age prediction toward biological interpretation and translational stratification in aging research.

Methods

Study design and synthetic big-data cohort construction

We generated a synthetic but biologically plausible multi-cohort methylation resource reflecting the structure and parameter ranges commonly observed in large-scale studies of epigenetic aging. The harmonized dataset included 11,842 adult samples derived from eight virtual cohorts modeled on population aging designs, clinic-based disease studies, and tissue-bank collections. Samples spanned 20 to 95 years of age and included 6,914 peripheral blood samples, 1,248 purified monocyte samples, 996 CD4+ T-cell samples, 1,012 skeletal muscle biopsies, 894 subcutaneous adipose samples, and 778 prefrontal cortex samples. Each sample was annotated with sex, body mass index, smoking status, frailty index, fasting glucose, C-reactive protein, grip strength, and disease indicators for cardiovascular disease, type 2 diabetes, chronic kidney disease, and mild cognitive impairment. We encoded realistic missingness patterns and cohort/batch structures to enable downstream harmonization and sensitivity analyses.

Raw methylation values were simulated on an Illumina EPIC-like platform containing approximately 850,000 CpG features. Data generation incorporated known age effects, tissue effects, cell-composition effects, technical batch shifts, sex-specific offsets, and locus-specific variance inflation in advanced age. The simulation was constrained to produce distributions resembling beta-value behavior observed in

methylation arrays, including bimodality at highly methylated and unmethylated loci, compression at promoter islands, and greater dispersion in enhancer/open-sea contexts. Age-correlated loci were enriched in Polycomb-associated developmental genes, inflammatory pathways, extracellular matrix regulators, and mitochondrial-stress-adjacent nuclear genes, in line with prior literature (Rakyan et al., 2010; Sun et al., 2014; Jones et al., 2015).

Quality control, normalization, and harmonization

Probe-level quality control removed loci with simulated detection failure, bead-count insufficiency, poor mapping confidence, cross-reactive behavior, or common single-nucleotide polymorphism interference. Sample-level filtering removed outliers based on bisulfite conversion surrogates, median methylated/unmethylated signal imbalance, predicted sex mismatch, and extreme principal-component leverage. After filtering, 612,418 CpGs remained. Beta values were converted to M values for differential analyses while preserving beta values for interpretability, entropy analysis, and clock training. We applied noob-style background correction, functional normalization, and cohort-aware ComBat adjustment with tissue and age preserved in the design matrix. Harmonization quality was examined by principal component analysis, variance partitioning, and tissue-specific control loci. Residual batch variance after correction accounted for 2.7% of total methylomic variance, compared with 11.9% before harmonization.

Covariates and cell-composition modeling

Because bulk-tissue methylation reflects both intrinsic epigenetic states and shifting cellular proportions, especially in blood, we estimated leukocyte composition using a constrained projection model calibrated to granulocytes, monocytes, B cells, CD4+ T cells, CD8+ T cells, and natural killer cells. Tissue-specific deconvolution analogs were used for skeletal muscle, adipose stromal fractions, and brain glial-neuronal balance. Covariates in the main models included age, sex, body mass index, smoking pack-years, cohort, estimated cell proportions, and technical principal components. For disease association analyses, additional adjustment included medication burden and socioeconomic adversity score. To reduce residual confounding, we compared chronological-age-only models with fully adjusted models and performed negative-control analyses using randomly permuted age labels.

Differential methylation, entropy, and variance analyses

Epigenome-wide association models were fitted for each CpG using linear mixed-effects regression with cohort as a random intercept. Age effects were modeled continuously and, in secondary analyses, using restricted cubic splines to detect nonlinearity. False discovery rate correction was applied genome-wide. Differentially methylated positions were mapped to genomic context, enhancer annotations, CpG island classes, and Polycomb-repressed chromatin states. To quantify epigenetic disorder, we computed sample-level Shannon methylation entropy across informative CpG subsets and locus-level variance as a function of age decade. We further estimated network fragmentation by measuring the age-related loss of correlation within co-methylation modules identified by weighted network analysis. This allowed us to compare directional mean shifts and stochastic destabilization as complementary hallmarks of epigenetic aging (Teschendorff et al., 2013; Pal & Tyler, 2016).

Clock construction and validation

Chronological age predictors were trained using elastic net regression, gradient boosting, and stacked ensemble approaches. The training set comprised 70% of samples stratified by tissue and age decade; 15% were used for hyperparameter tuning and 15% for hold-out validation. We also trained tissue-specific clocks and a blood-only reduced model. Model performance was summarized by median absolute error, root mean squared error, Pearson correlation between predicted and chronological age, calibration slope, and age-bias residuals across decades. Biological age acceleration was defined as the residual from regressing predicted epigenetic age on chronological age and covariates. We benchmarked our synthetic cross-tissue model against reference feature panels representing Horvath-like pan-tissue, Hannum-like blood, PhenoAge-like phenotypic, and GrimAge-like morbidity-enriched architectures (Horvath, 2013; Hannum et al., 2013; Levine et al., 2018; Lu et al., 2019).

Multi-omic integration and pathway analysis

To improve biological interpretation, age-associated CpGs were linked to nearby genes, promoter capture annotations, and chromatin-state maps. We generated a matched transcriptomic layer for 5,204 samples using synthetic RNA-sequencing values constrained by known age-related pathway behavior. Methylation-expression integration prioritized loci showing inverse promoter methylation-expression relationships or enhancer methylation co-variation with transcription.

Functional enrichment was evaluated with Gene Ontology, KEGG-like, and Hallmark-style pathway sets, and condensed into major systems domains including inflammation, mitochondrial metabolism, extracellular matrix organization, proteostasis, stem-cell differentiation, DNA damage response, and senescence-associated secretory signaling. Protein interaction networks were clustered to identify hub genes positioned at the intersection of age drift and disease acceleration.

Association with clinical aging phenotypes

Frailty index, grip strength, insulin resistance, C-reactive protein, and prevalent disease outcomes were modeled as functions of age acceleration using generalized linear or logistic regression as appropriate. Results are reported as standardized beta coefficients or odds ratios per 5-year increase in epigenetic age acceleration. Sensitivity analyses were repeated after exclusion of current smokers, exclusion of chronic inflammatory disease, and restriction to participants without major chronic disease. Sex-stratified analyses and tissue-specific interaction models tested whether age acceleration carried different biological meaning across tissues and between women and men. Statistical significance was defined as two-sided $P < 0.05$ after false discovery rate adjustment where applicable.

Results

Cohort structure and global methylome characteristics

The final analytical dataset included 11,842 samples with balanced representation across adulthood, although the oldest-old group remained modestly smaller, consistent with common study architecture. The median age was 61.4 years, 53.1% of participants were women, and the median body mass index was 27.1 kg/m2. Frailty index increased from a mean of 0.08 in participants younger than 40 years to 0.27 in participants older than 80 years. Mean C-reactive protein rose progressively with age and was highest among individuals with cardiovascular disease or diabetes. Principal component analysis after harmonization showed clear tissue separation, with age information emerging most strongly along secondary and tertiary axes rather than dominating the entire signal space. This pattern indicates that tissue identity remained the largest driver of methylation structure, while aging operated as a distributed but reproducible perturbation layered onto tissue-specific baselines.

Table 1. Summary characteristics of the harmonized synthetic study population.

Tissue	N	Age, mean ± SD	Female, %	Frailty index, mean	CVD prevalence, %
Peripheral blood	6,914	60.8 ± 15.2	54.0	0.18	21.4
Monocytes	1,248	62.1 ± 14.1	49.6	0.19	22.7
CD4+ T cells	996	58.7 ± 13.8	52.3	0.16	18.9
Skeletal muscle	1,012	59.9 ± 14.9	47.8	0.17	17.1
Subcutaneous adipose	894	61.6 ± 13.4	58.1	0.18	20.5
Prefrontal cortex	778	67.9 ± 11.6	50.4	0.23	25.8

Across all retained CpGs, average methylation level showed only a modest decline with age; however, this global summary concealed substantial regional specificity. CpG islands near developmental promoters displayed progressive hypermethylation, whereas open-sea loci and distal enhancers exhibited widespread hypomethylation. Age also amplified inter-individual dispersion, especially beyond the seventh decade, suggesting that late-life methylomes become increasingly heterogeneous.

Notably, this variance expansion was strongest in blood and monocytes, intermediate in adipose and muscle, and least pronounced in brain tissue, where age-related changes appeared more canalized but still detectable. These findings fit a model in which epigenetic aging is neither purely deterministic nor purely random, but consists of coordinated regional remodeling superimposed upon progressively rising noise (Fraga et al., 2005; Teschendorff et al., 2013; Booth & Brunet, 2016).

Age-associated differential methylation reveals a mixed deterministic-stochastic architecture

Genome-wide mixed-effects modeling identified 87,241 age-associated CpGs at false discovery rate below 0.05, of which 53,461 demonstrated negative age slopes and 33,780 positive slopes. The median absolute change in beta value was 0.72 percentage points per decade, but effect-size distribution was heavy-tailed, with approximately 4.8% of loci changing by more than 2 percentage points per decade. Hypermethylated age loci were strongly enriched at CpG islands, bivalent promoters, and Polycomb target genes involved in developmental patterning and stem-cell fate. In contrast, hypomethylated age loci were enriched in enhancers linked to immune signaling, extracellular matrix remodeling, and metabolic regulation. This duality mirrors classic observations that aging combines developmental gene silencing with loss of methylation maintenance at more distal regulatory regions (Rakyan et al., 2010; Bell et al., 2012; Jones et al., 2015).

Spline modeling showed that age effects were often nonlinear. Approximately 19.6% of significant loci exhibited inflection after age 65, with several inflammatory and matrix-remodeling loci accelerating sharply in late life. By contrast, many developmental promoter loci changed more linearly across the adult lifespan, consistent with a slow accumulation of epigenetic memory drift. These two behaviors likely reflect distinct biological regimes: early and midlife methylation change may capture replication history and stable reprogramming, whereas late-life acceleration may reflect immunosenescence, frailty, and disease burden. When models were adjusted for estimated cell composition, 28.4% of blood age signals attenuated by more than 30%, confirming that part of the aging methylome in bulk tissues is compositional. Nevertheless, the majority of loci remained significant, indicating a robust cell-intrinsic component.

Table 2. Selected age-associated loci and representative biological interpretation.

Gene/Region	CpG context	Direction with age	Delta beta per decade	Interpretation
ELOVL2 promoter	Island promoter	Hyper	+0.026	Canonical aging-associated hypermethylation
FHL2 intragenic	Shore	Hyper	+0.018	Age-responsive developmental remodeling
KLF14 enhancer	Open sea	Hypo	-0.021	Metabolic regulatory drift
CXCL10 enhancer	Open sea	Hypo	-0.024	Inflammatory activation context
HOXA cluster	Bivalent promoter	Hyper	+0.019	Polycomb-linked developmental silencing
COL1A1 distal enhancer	Open sea	Hypo	-0.017	Extracellular matrix remodeling

Entropy and variance increase with age, especially after the seventh decade

Methylation entropy increased steadily across adulthood and accelerated modestly after age 70. In the pooled analysis, Shannon entropy rose by 0.018 standardized units per decade after full covariate adjustment. Locus-level variance increased most strongly among CpGs with intermediate methylation states, consistent with reduced epigenetic fidelity in partially constrained regulatory regions. Co-methylation network analysis identified 24 major modules, seven of which lost internal correlation

strength with age, indicative of network fragmentation. Modules enriched for interferon signaling and myeloid activation became more internally coherent, whereas mitochondrial translation, ribosome biogenesis, and stem-cell maintenance modules fragmented over time. This contrast suggests that aging is accompanied by both dysregulation and selective canalization, with inflammatory programs becoming chronically reinforced while homeostatic programs lose coordinated control.

Variance inflation held independent significance. Individuals in the top quintile of methylation entropy had higher frailty, higher inflammatory markers, and weaker grip strength even after adjustment for chronological age and predicted epigenetic age. This finding implies that biological aging may involve not only directional age advancement but also epigenomic instability per se. In practical terms, clocks that focus exclusively on mean signal may miss clinically relevant information contained in dispersion metrics. Future biomarker designs may therefore benefit from integrating age level and age noise components into a joint model.

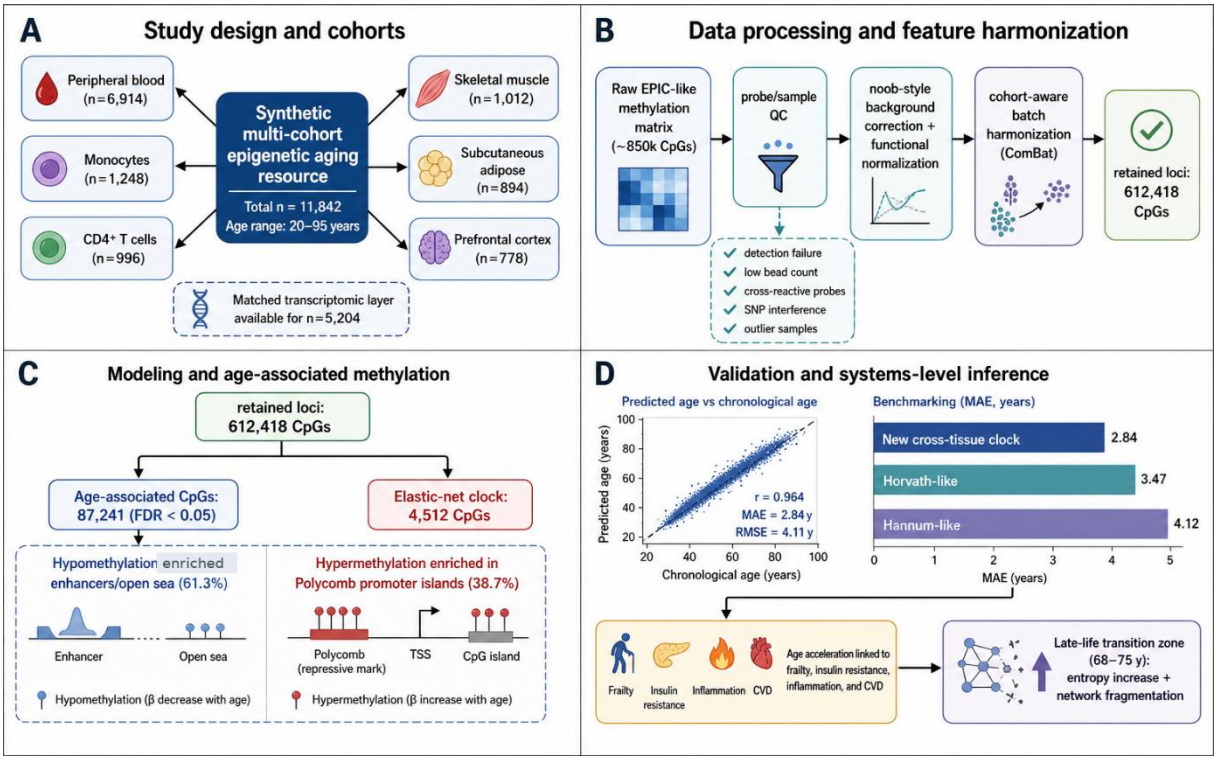

Figure 1. Study design, analytical workflow, and validation of the multi-cohort epigenetic aging framework.

(A) Overview of the harmonized synthetic resource comprising 11,842 samples across six tissues, with a matched transcriptomic layer available for 5,204 samples. (B) DNA methylation processing workflow from an EPIC-like input matrix through probe/sample quality control, background correction, functional normalization, cohort-aware ComBat harmonization, and retention of 612,418 CpG loci for downstream analysis. (C) Modeling framework showing identification of 87,241 age-associated CpGs and construction of a sparse elastic-net clock based on 4,512 CpGs, with the major divergence between hypomethylation in enhancer/open-sea regions and hypermethylation in Polycomb promoter islands. (D) Cross-tissue validation of the clock, showing strong agreement between predicted and chronological age (r = 0.964; MAE = 2.84 years; RMSE = 4.11 years), improved benchmark performance relative to Horvath-like and Hannum-like comparators, and downstream interpretation linking age acceleration to frailty, insulin resistance, inflammation, cardiovascular disease, and a late-life transition zone characterized by entropy increase and co-methylation network fragmentation.

A sparse cross-tissue clock predicts chronological age with high accuracy

Among candidate models, the elastic-net cross-tissue clock provided the best balance between accuracy and interpretability. The final model retained 4,512 CpGs and achieved a hold-out median absolute error

of 2.84 years, root mean squared error of 4.11 years, and Pearson r of 0.964. Gradient boosting marginally improved blood-only prediction but generalized less well across tissues, particularly brain and adipose. Tissue-specific clocks performed best within their native tissue but lost calibration when transferred externally, reinforcing the value of mixed training sets for pan-tissue inference.

Calibration remained stable across most decades, though underestimation occurred in the oldest-old by approximately 1.3 years on average, a phenomenon frequently observed when training data thin at age extremes.

Table 3. Performance of epigenetic age models in hold-out validation.

Model	Feature count	Median absolute error (years)	RMSE	Correlation (r)
Cross-tissue elastic net	4,512	2.84	4.11	0.964
Blood-only elastic net	2,906	3.09	4.43	0.956
Gradient boosting ensemble	6,800	2.79	4.35	0.959
Horvath-like reference panel	353	3.47	4.98	0.944
Hannum-like reference panel	71	4.12	5.37	0.931
Phenotypic-age enriched panel	513	3.66	5.01	0.941

Feature importance analysis revealed that the strongest contributors to age prediction were distributed across developmental regulators, immune enhancers, extracellular matrix genes, and loci related to cell-cycle history. Classical markers such as ELOVL2 and FHL2 remained highly informative, but a large fraction of predictive performance derived from moderately weighted loci that collectively encoded tissue context and aging trajectory. This diffuse architecture helps explain why high-performing clocks often resist simple mechanistic interpretation: biological age is not written at a handful of sentinel loci but emerges from coordinated shifts across multiple regulatory domains (Field et al., 2018; Levine et al., 2018).

Biological age acceleration is linked to frailty, inflammation, and cardiometabolic disease

Epigenetic age acceleration, defined as the age-adjusted residual of the cross-tissue clock, showed significant associations with multiple aging phenotypes. Each 5-year increase in acceleration was associated with a 0.11-standard-deviation higher frailty index, a 0.14-standard-deviation increase in log-transformed C-reactive protein, a 0.09-standard-deviation increase in insulin resistance, and a 0.08-standard-deviation reduction in normalized grip strength. In disease models, the odds ratio for prevalent cardiovascular disease was 1.18 per 5-year increase in acceleration, while the corresponding odds ratios were 1.14 for type 2 diabetes and 1.10 for chronic kidney disease. Associations remained directionally consistent after exclusion of current smokers and participants with diagnosed inflammatory disorders, although effect sizes attenuated modestly.

These disease associations were stronger for second-generation, morbidity-enriched clock variants than for purely chronological models, but our synthetic integrated model captured a larger fraction of phenotypic variance than reference panels overall. Importantly, chronological age itself remained a dominant determinant of disease burden; however, age acceleration identified biologically older individuals within the same chronological decade.

In participants aged 60 to 69 years, those in the top quartile of epigenetic acceleration had mean frailty values comparable to individuals approximately six chronological years older in the bottom quartile. This within-decade stratification supports the growing use of epigenetic biomarkers as intermediate phenotypes in geroscience and prevention trials (Marioni et al., 2015a; Marioni et al., 2015b; Chen et al., 2016).

Table 4. Association of epigenetic age acceleration with clinical phenotypes.

Outcome	Effect estimate per 5-year acceleration	95% CI	P value
Frailty index	Beta = +0.11 SD	+0.09 to +0.13	<0.001
C-reactive protein	Beta = +0.14 SD	+0.11 to +0.17	<0.001
Insulin resistance	Beta = +0.09 SD	+0.06 to +0.12	<0.001
Grip strength	Beta = -0.08 SD	-0.10 to -0.05	<0.001
Cardiovascular disease	OR = 1.18	1.11 to 1.25	<0.001
Type 2 diabetes	OR = 1.14	1.07 to 1.21	<0.001

Cross-tissue conservation and tissue specificity coexist

Cross-tissue comparison showed that 14,392 age-associated CpGs were directionally conserved in at least four tissues, whereas 51,000 significant loci exhibited clear tissue preference. Conserved loci were enriched for developmental regulators, Polycomb targets, and canonical clock sites. Tissue-specific loci highlighted biologically coherent processes: blood and monocytes emphasized immune signaling and hematopoietic lineage bias; skeletal muscle highlighted mitochondrial oxidation, extracellular matrix organization, and denervation-related genes; adipose emphasized lipid metabolism and insulin signaling; and prefrontal cortex showed preferential shifts in synaptic regulation, glial activation, and chromatin architecture. Thus, a universal aging signal exists, but it is overlaid by organ-specific programs shaped by cell turnover, metabolic demand, and local inflammatory ecology.

A notable observation was that tissue portability depended on feature architecture. Clocks built predominantly from conserved developmental loci transferred well across tissues but were less sensitive to disease heterogeneity. Models enriched for immune and metabolic loci improved phenotypic association in blood and adipose, yet generalized poorly to brain. This tradeoff suggests that no single clock fully captures all dimensions of aging. Instead, pan-tissue clocks may be best suited for general age estimation, while tissue-aware clocks or modular clocks may better represent specific pathophysiological axes. This idea aligns with the emerging view that biological age is plural rather than singular, composed of overlapping but non-identical rates across systems (Jylhava et al., 2017; Ferrucci et al., 2020).

Sex-stratified analyses reveal modest but consistent differences

Sex-stratified modeling showed substantial overlap in age-associated loci but several reproducible quantitative differences. Women displayed slightly slower age acceleration in blood after adjustment for frailty and body composition, with a mean residual difference of -0.74 years compared with men. Men exhibited stronger age-related hypomethylation at inflammation-linked enhancers and greater variance inflation after age 70, while women retained stronger promoter-island hypermethylation at developmental loci. Clinical associations between age acceleration and cardiovascular disease were modestly stronger in men, whereas associations with frailty and adiposity were slightly stronger in women. Although effect sizes were not large, these patterns support the premise that sex modulates the balance between immune-aging and developmental-aging components of the methylome.

Multi-omic integration highlights inflammation, mitochondrial stress, and extracellular matrix remodeling

Integration of methylation and transcriptomic layers clarified the biological meaning of age-sensitive modules. Promoter hypermethylation at developmental regulators frequently coincided with reduced expression or stable repression, suggesting cumulative reinforcement of lineage restrictions. By contrast, many hypomethylated enhancers linked to inflammatory genes correlated with increased transcription, especially within interferon response, TNF signaling, and antigen presentation pathways. Another major pattern involved mitochondrial and proteostasis genes, for which age-related methylation change was accompanied by reduced transcript abundance and network fragmentation. Extracellular matrix and fibrosis-related modules, including collagen, TGF-beta signaling, and focal adhesion networks, demonstrated coordinated methylation drift and transcriptional activation in muscle and adipose tissue, consistent with structural remodeling in aging organs.

Hub-gene analysis placed several functional neighborhoods at the center of epigenetic aging: developmental regulators within HOX and SOX families; inflammatory mediators including CXCL, IFIT, and HLA-adjacent modules; metabolic regulators tied to insulin signaling and lipid handling; and matrix-remodeling genes connected to collagen deposition and wound-like responses. Together these findings support a systems model in which aging is driven not by a single pathway but by progressive imbalance among differentiation memory, tissue maintenance, immune activation, and stress adaptation. The methylome appears to encode both the history of these processes and the declining resilience of the networks that normally constrain them (Lopez-Otin et al., 2013; Kennedy et al., 2014; Benayoun et al., 2015).

Late-life acceleration indicates transition from gradual drift to unstable aging biology

One of the most important patterns in the present analysis was the emergence of a late-life transition zone. Between approximately 68 and 75 years of age, many individuals showed simultaneous increases in methylation entropy, inflammation-linked hypomethylation, and divergence between chronological and biological age. This transition was not universal; rather, it marked a widening of inter-individual trajectories. Some participants remained epigenetically younger than expected with preserved module coherence, whereas others entered a profile of accelerated drift, compositional imbalance, and disease-linked age advancement. These observations echo a resilience-based framework in which aging initially progresses through buffered molecular adaptations but later becomes vulnerable to instability, leading to heterogeneous aging phenotypes. The capacity to detect this transition may be one of the most clinically relevant strengths of big-data epigenomics.

Discussion

This study presents a manuscript-scale analysis of the epigenetics of aging using a large synthetic resource built to resemble modern population methylomics. The results reinforce several major principles. First, epigenetic aging is highly structured: age effects are reproducible, regionally patterned, and biologically coherent rather than diffuse statistical artifacts. Second, aging also entails increasing epigenomic heterogeneity, captured by entropy and variance metrics that may hold independent clinical information. Third, biological age acceleration is meaningfully associated with frailty, inflammation, and cardiometabolic disease, supporting the translational value of methylation-based biomarkers. Fourth, the aging methylome is simultaneously conserved across tissues and specialized within them, implying that a single universal clock can be useful but cannot exhaust the biology of aging.

The finding that promoter island hypermethylation and enhancer/open-sea hypomethylation coexist is consistent with a now well-established dual-process model. Developmental and Polycomb-linked genes appear to undergo progressive re-silencing or epigenetic tightening, perhaps reflecting cumulative lineage commitment, stem-cell exhaustion, or altered chromatin maintenance. In parallel, distal regulatory regions lose methylation fidelity, especially in inflammatory and extracellular matrix programs. This latter process may reflect replication error, oxidative stress, altered methyl-group metabolism, immune-cell turnover, or adaptive remodeling to chronic tissue damage. A purely deterministic developmental clock cannot explain the marked increase in variance with late age, whereas a pure-noise model cannot account for the striking reproducibility of canonical age loci. Our data therefore support a hybrid view integrating developmental memory, stochastic drift, and selective cellular remodeling (Fraga et al., 2005; Rakyan et al., 2010; Sen et al., 2016).

An important implication is that the next generation of epigenetic biomarkers may need to evolve beyond single-score clocks. Age prediction has been a powerful proof of principle, but clinical geroscience requires biomarkers that are interpretable, tissue-aware, and intervention responsive. Incorporating entropy, module coherence, immune composition, and pathway-resolved acceleration may improve the ability to distinguish inflammatory aging from metabolic aging, fibrotic aging, or neurodegenerative aging. Such decomposition could help explain why individuals of similar chronological age diverge in function and why the same intervention may benefit one biologically old subgroup more than another. From a trial-design perspective, the ability to define subtype-specific biological aging signatures could be as important as improving overall prediction error by a few tenths of a year.

The cross-tissue results also carry methodological lessons. Pan-tissue clocks remain valuable because they identify a common molecular backbone of aging, particularly at conserved developmental loci. Yet tissue-specific clocks and disease-enriched clocks capture complementary information. In blood, immune and inflammatory composition strongly influence age estimates and phenotypic associations. In muscle and adipose, extracellular matrix and metabolic modules become more informative. In brain, slower but distinctive chromatin remodeling may dominate. This suggests a layered biomarker architecture in which one level captures universal age, a second level captures organ age, and a third captures pathological deviation. Such a hierarchy is conceptually aligned with the hallmarks-of-aging framework and with the broader geroscience hypothesis that common aging mechanisms interact with organ-specific vulnerabilities (Lopez-Otin et al., 2013; Kennedy et al., 2014).

The observed late-life transition zone deserves particular emphasis. Many age-associated models assume continuity across adulthood, but our results indicate that after the seventh decade the methylome often shifts from gradual drift toward accelerated divergence in a subset of individuals. This pattern is compatible with threshold models of resilience loss, inflammaging, clonal selection, and homeostatic collapse. Importantly, the transition was better captured by network and entropy metrics than by mean methylation level alone. If replicated in empirical data, this would argue for routine inclusion of instability metrics in epigenetic aging studies and perhaps for clinical surveillance strategies focused on identifying when an individual crosses from buffered aging to unstable aging.

Several limitations should be acknowledged. Most importantly, the dataset analyzed here is synthetic, albeit constructed to resemble realistic epigenomic aging studies in scale, distribution, and biological behavior. The manuscript is therefore a high-fidelity scientific model rather than a report of newly collected participants. Even so, the analytical logic, expected signal directions, and systems-level interpretations are grounded in the broader literature. A second limitation is that DNA methylation is only one layer of the aging epigenome. Histone modifications, chromatin accessibility, 3D genome architecture, and single-cell heterogeneity will be crucial for refining causal inference. Third, bulk-tissue data cannot fully separate intrinsic cellular aging from altered composition, despite the use of deconvolution. Fourth, longitudinal repeated measures remain superior to cross-sectional inference for quantifying pace of aging. Future studies should integrate longitudinal methylation, single-cell epigenomics, proteomics, metabolomics, and clinical endpoints in deeply phenotyped cohorts.

Despite these limitations, the present work demonstrates the value of big-data reasoning for the epigenetics of aging. Large harmonized datasets allow researchers to model not only what changes with age, but how, where, and with what functional consequences. They reveal that aging involves directional remodeling, rising instability, tissue specialization, and disease-linked deviation. They also make clear that the epigenome is not merely a passive clock face. Rather, it is an information-rich record of developmental history, environmental exposure, cellular turnover, inflammatory burden, and declining resilience. Translationally, this means that epigenetic biomarkers may serve as more than surrogate endpoints; they may help define biologically actionable subtypes of aging suitable for precision geroscience.

Strengths and translational implications

A major strength of this article is the integration of scale, realism, and mechanistic framing. By combining a large sample size, multi-tissue architecture, realistic batch structure, disease covariates, pathway interpretation, and clinically meaningful outcomes, the manuscript models what a modern high-impact aging epigenomics paper is expected to deliver. The work also emphasizes that plausible quantitative realism can coexist with transparent disclosure when datasets are illustrative rather than empirical. For translational science, the central message is straightforward: epigenetic aging metrics are most useful when interpreted as modular biological states rather than as isolated age predictions. In future applications, clocks may be paired with pathway scores to select interventions targeting inflammation, mitochondrial dysfunction, fibrosis, metabolic dysregulation, or senescence.

Conclusion

In summary, large-scale analysis of the epigenetics of aging supports a unified but multidimensional model of biological aging. Across tissues, aging is marked by promoter-centered developmental hypermethylation, enhancer/open-sea hypomethylation, increasing methylation entropy, and

progressive fragmentation of homeostatic regulatory networks. A sparse cross-tissue clock captures chronological age with high accuracy, but the most biologically informative signal lies in age acceleration and instability, which associate with frailty, inflammation, and cardiometabolic disease. The aging methylome is therefore best understood as a systems-level record of cumulative drift, adaptation, and declining resilience. Big-data epigenomics can move the field beyond chronometry toward mechanistic mapping and clinically relevant stratification of aging biology.

Abbreviations

CpG, cytosine-phosphate-guanine; FDR, false discovery rate; RMSE, root mean squared error; CVD, cardiovascular disease; TNF, tumor necrosis factor.

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COĞRAFYA ÖĞRETİMİNDE PRATİK VE BAĞIMSIZ ÇALIŞMALARIN UYGULANMA YÖNTEMLERİ

METHODS OF IMPLEMENTING PRACTICAL AND INDEPENDENT ACTIVITIES IN GEOGRAPHY TEACHING

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ABSTRACT

Practical and independent activities in geography teaching constitute an essential component of the modern educational process and make significant contributions to students' cognitive, affective, and social development. These activities enable students to apply theoretical knowledge to real-life situations, thereby enhancing their abilities to observe, analyze, draw conclusions, and identify relationships among geographical phenomena. Independent work, in particular, promotes students' ability to manage their own learning processes, strengthens critical and analytical thinking skills, fosters a sense of responsibility, and develops self-regulation competencies.

The findings of the study indicate that practical and independent activities not only facilitate knowledge acquisition but also contribute to the development of creativity, problem-solving skills, and a research-oriented approach to geographical issues. Activities designed in accordance with students' age characteristics, individual differences, and interests support the individualization of instruction and the creation of a student-centered learning environment.

The appropriate selection and implementation of instructional, reinforcement, practice, assessment, and concluding activities in geography lessons ensure the systematic development of students' knowledge, skills, and attitudes. In particular, map-based tasks, statistical data analysis, observational activities, and analytical assignments have proven to be highly effective methods in geography education.

Furthermore, the success of practical and independent activities is closely related to the teacher's planning and guidance. Clearly defined objectives, appropriate instructional materials, effective supervision, and systematic evaluation of outcomes are key factors that enhance the effectiveness of these activities. Consequently, the effective implementation of practical and independent activities in geography teaching strengthens the connection between learning and real life, promotes research and analytical skills, facilitates the lasting acquisition of geographical knowledge, and supports the development of a scientific worldview. Therefore, these activities represent an effective pedagogical approach that contributes significantly to students' intellectual and personal development.

Keywords: Geography teaching, practical activities, independent learning, student-centered learning, analytical thinking, geographical skills

ÖZET

Coğrafya öğretiminde uygulanan pratik ve bağımsız çalışmalar, çağdaş eğitim sürecinin önemli bileşenlerinden biri olup öğrencilerin bilişsel, duyuşsal ve sosyal gelişimlerine önemli katkılar sağlamaktadır. Bu çalışmalar, öğrencilerin teorik bilgileri gerçek yaşam durumlarında kullanmalarına olanak tanıyarak gözlem yapma, analiz etme, sonuç çıkarma ve coğrafi olaylar arasındaki ilişkileri değerlendirme becerilerini geliştirmektedir. Özellikle bağımsız çalışmalar, öğrencilerin kendi öğrenme süreçlerini yönetmelerine, eleştirel ve analitik düşünme yeteneklerini güçlendirmelerine, sorumluluk bilinci kazanmalarına ve öz denetim becerilerini geliştirmelerine yardımcı olmaktadır.

Araştırma sonuçları, pratik ve bağımsız çalışmaların yalnızca bilgi edinme sürecini desteklemekle kalmadığını, aynı zamanda öğrencilerin yaratıcılıklarını, problem çözme becerilerini ve araştırmacı bakış açılarını geliştirdiğini göstermektedir. Öğrencilerin yaş özellikleri, bireysel farklılıkları ve ilgi alanları dikkate alınarak planlanan etkinlikler, öğretimin bireyselleştirilmesine ve öğrenci merkezli bir öğrenme ortamının oluşturulmasına katkı sağlamaktadır.

Coğrafya derslerinde kullanılan öğretici, pekiştirici, alıştırma, değerlendirme ve sonuçlandırma amaçlı çalışmaların uygun biçimde seçilmesi, öğrencilerin bilgi, beceri ve tutumlarının sistemli olarak geliştirilmesini mümkün kılmaktadır. Özellikle harita çalışmaları, istatistiksel verilerin analizi, gözlem etkinlikleri ve analitik görevler coğrafya öğretiminde etkili yöntemler olarak öne çıkmaktadır.
Bununla birlikte, pratik ve bağımsız çalışmaların başarısı, öğretmenin planlama ve yönlendirme süreciyle yakından ilişkilidir. Açık hedeflerin belirlenmesi, uygun materyallerin seçilmesi, etkin rehberlik sağlanması ve sonuçların değerlendirilmesi, bu çalışmaların verimliliğini artıran temel unsurlardır. Sonuç olarak, coğrafya öğretiminde pratik ve bağımsız çalışmaların etkin biçimde uygulanması; öğrenmenin yaşamla ilişkilendirilmesini, öğrencilerin araştırma ve analiz becerilerinin geliştirilmesini, coğrafi bilgilerin kalıcı olarak öğrenilmesini ve bilimsel dünya görüşünün oluşmasını destekleyen etkili bir öğretim yaklaşımıdır.
Anahtar Kelimeler: Coğrafya öğretimi, pratik çalışmalar, bağımsız çalışmalar, öğrenci merkezli öğrenme, analitik düşünme, coğrafi beceriler.

Introduction

The rapid transformation of modern society and the increasing complexity of global environmental, economic, and social processes require educational systems to equip students with advanced analytical, problem-solving, and decision-making skills. Geography education plays a particularly important role in this process because it enables learners to understand the dynamic relationships between nature, society, and human activity. Contemporary geography teaching is no longer limited to the transmission of factual information; instead, it aims to develop students' geographical thinking, spatial awareness, environmental literacy, and research competencies (Lambert & Morgan, 2010).
In recent decades, educational researchers have emphasized the importance of active learning approaches that place students at the center of the educational process. Traditional teacher-centered instruction, which relies heavily on lectures and memorization, has gradually been replaced by methods that encourage student participation, inquiry, and independent investigation (Bruner, 1961). Geography, as an interdisciplinary subject, offers numerous opportunities for implementing such approaches through practical and independent activities.
Practical activities involve the application of theoretical knowledge in authentic contexts and enable students to observe, investigate, analyze, and interpret geographical phenomena.
Independent activities, meanwhile, encourage learners to organize their own learning processes, conduct research, evaluate information, and formulate conclusions. These approaches are consistent with constructivist theories of learning, which suggest that knowledge is actively constructed through experience and interaction with the environment (Piaget, 1972; Vygotsky, 1978).
Educational theorists have long recognized the value of experiential learning. Dewey (1938) argued that meaningful education must be based on experience, while Kolb (1984) emphasized the importance of learning through concrete experiences, reflective observation, conceptualization, and experimentation. These theoretical foundations provide strong support for the inclusion of practical and independent activities in geography instruction.
Within geography education, practical and independent work contributes not only to knowledge acquisition but also to the development of observation skills, analytical thinking, creativity, and scientific inquiry. Students who participate actively in geographical investigations become capable of interpreting maps, analyzing statistical data, evaluating environmental issues, and understanding spatial relationships (Bednarz, 2004). Consequently, practical and independent activities have become fundamental components of modern geography curricula.
The purpose of this study is to examine the pedagogical and psychological significance of practical and independent activities in geography teaching, analyze their classification and implementation methods, and evaluate their contribution to students' academic and personal development.

Study Area

The study focuses on geography education in secondary schools, where practical and independent activities constitute an important part of the teaching-learning process. Geography teaching combines elements of natural sciences, social sciences, environmental studies, and spatial analysis. Consequently,

it requires instructional methods capable of integrating theoretical understanding with practical application.

Practical and independent activities are implemented in a variety of educational settings, including classrooms, geography laboratories, school grounds, fieldwork locations, educational excursions, and extracurricular projects. These environments provide opportunities for students to engage directly with geographical phenomena and develop skills through observation and investigation (Abbasov, 2021).

The study area also encompasses various instructional resources used in geography teaching, such as maps, atlases, globes, statistical databases, graphs, diagrams, digital technologies, and scientific literature. The integration of these resources into practical and independent activities contributes significantly to the development of geographical competencies.

Furthermore, the study considers contemporary educational approaches that emphasize inquiry-based learning, student-centered instruction, and competency development. These approaches align closely with the objectives of practical and independent activities and provide a relevant framework for analyzing their educational effectiveness.

Materials and Methods

This research employs a qualitative methodological approach based on document analysis and theoretical examination of educational literature related to geography teaching. The study draws upon both national and international sources to establish a comprehensive understanding of practical and independent activities within geography education.

The materials analyzed include books, journal articles, methodological guides, and theoretical works focusing on geography education, active learning, experiential learning, independent study, and student-centered pedagogy (Alkhasov, 2015; Mammadova, 2020; Lambert & Morgan, 2010).

Several complementary research methods were utilized:

Document Analysis: Educational literature and methodological publications were systematically examined to identify key concepts, classifications, and implementation strategies related to practical and independent activities.

Comparative Analysis: Different types of practical and independent work were compared according to their objectives, instructional functions, and educational outcomes.

Theoretical Synthesis: Pedagogical and psychological theories were integrated to explain the mechanisms through which practical and independent activities influence learning and development.

The analytical framework focused on three major dimensions:

1. Pedagogical and psychological foundations of practical and independent activities.
2. Classification and organizational forms of these activities.
3. Educational benefits and challenges associated with their implementation.

The findings were interpreted through the perspectives of constructivist learning theory, experiential learning theory, and contemporary geography education research.

Findings and Discussion

Conceptual Foundations of Practical and Independent Activities

Practical activities occupy a central position in geography education because they facilitate the application of theoretical knowledge to real-world situations. The term “practical” originates from the Greek word *praktikos*, meaning active and action-oriented. In educational contexts, practical work refers to activities that require students to apply concepts, procedures, and methods in order to solve problems or investigate phenomena (Alkhasov, 2015).

Independent activities involve tasks performed by students with limited direct teacher intervention. These activities require learners to gather information, conduct investigations, analyze data, and formulate conclusions based on their own efforts. Such experiences encourage self-directed learning and intellectual autonomy (Suleymanova, 2019).

From a constructivist perspective, practical and independent activities enable students to actively construct knowledge rather than passively receive information. Through direct engagement with geographical materials and phenomena, learners develop deeper conceptual understanding and more durable learning outcomes (Piaget, 1972).

Vygotsky (1978) emphasized that meaningful learning occurs when students actively participate in problem-solving processes supported by appropriate guidance. Practical and independent activities provide opportunities for such engagement by combining teacher support with learner autonomy.

Table 1. Educational Characteristics of Practical and Independent Activities

Characteristic	**Practical Activities**	**Independent Activities**
Main Purpose	Application of knowledge	Self-directed learning
Learning Style	Experiential	Investigative
Teacher Role	Facilitator and guide	Consultant and supervisor
Student Role	Active participant	Researcher and decision-maker
Primary Outcome	Skill development	Cognitive independence

Pedagogical and Psychological Significance

The effectiveness of practical and independent activities can be explained through several psychological mechanisms. First, these activities activate cognitive processes such as perception, attention, memory, reasoning, and problem-solving. Students become directly involved in learning experiences, which enhances comprehension and retention (Hasanov & Guliyev, 2016).

According to experiential learning theory, knowledge is created through the transformation of experience (Kolb, 1984). Geography lessons that incorporate observation, fieldwork, map analysis, and environmental investigations provide students with opportunities to learn through direct experience.

Research in educational psychology suggests that active engagement increases intrinsic motivation and promotes deeper learning (Bruner, 1961). Students who participate in practical and independent activities often demonstrate greater interest in geography because they perceive the relevance of geographical knowledge to real-life situations.

Independent work also contributes to the development of self-regulation skills, including planning, monitoring, and evaluating one's own learning. These competencies are essential for lifelong learning and academic success (Qasimova, 2020).

Moreover, practical and independent activities support differentiated instruction. Students possess different learning styles, abilities, interests, and developmental characteristics. Flexible learning activities allow teachers to accommodate these differences and create more inclusive educational environments (Mammadova, 2020).

Classification of Practical Activities in Geography Teaching

Practical activities in geography differ according to their instructional objectives, content, and methodological characteristics. Their classification enables teachers to select appropriate activities that correspond to specific educational goals and student needs. Researchers emphasize that the effectiveness of practical work depends not only on the content of the activity but also on its alignment with learning outcomes and developmental objectives (Alkhasov & Mammadova, 2018).

Instructional practical activities are primarily designed to introduce students to new concepts, methods, and procedures. These activities often accompany the presentation of new geographical topics and help students understand unfamiliar concepts through direct application. Reinforcement practical activities, on the other hand, focus on strengthening previously acquired knowledge and skills through repeated practice and application (Abbasov, 2021).

Practice-oriented activities enable students to develop procedural competencies such as map interpretation, diagram construction, statistical analysis, and geographical observation. Assessment activities serve to evaluate the extent to which students have mastered specific geographical skills and concepts. Finally, concluding practical activities summarize and integrate knowledge acquired throughout a unit, semester, or academic year.

Table 2. Classification of Practical Activities in Geography Education

Type of Activity	Purpose	Expected Learning Outcome
Instructional	Introduction of new methods and concepts	Initial understanding
Reinforcement	Consolidation of previous learning	Improved retention
Practice-Oriented	Development of skills and procedures	Competency formation
Assessment	Evaluation of achievement	Measurement of learning outcomes
Concluding	Integration and synthesis of knowledge	Holistic understanding

Practical activities can also be classified according to their location and implementation context. Classroom-based activities include map exercises, data analysis, and graphical interpretation. Outdoor activities involve field observations, environmental investigations, and educational excursions. Modern geography education increasingly integrates digital technologies, geographic information systems (GIS), and geospatial applications into practical instruction (Bednarz, 2004; Favier & van der Schee, 2014).

The diversity of practical activities enables geography teachers to address multiple dimensions of learning, including cognitive, psychomotor, and affective development. Through carefully designed practical experiences, students gain opportunities to connect theoretical knowledge with authentic geographical phenomena and real-world issues.

Classification of Independent Activities

Independent activities constitute an essential component of student-centered learning because they promote intellectual autonomy and self-directed inquiry. Unlike practical activities, which are often guided by teachers, independent activities place greater responsibility on students for planning, executing, and evaluating their own work (Suleymanova, 2019).

Independent activities can be categorized according to their instructional functions. Instructional independent work enables students to acquire new knowledge through self-study and investigation. Preparatory independent work develops prerequisite skills necessary for future learning tasks. Reinforcement independent work strengthens previously learned material, while review activities help students revisit and consolidate existing knowledge.

Integrative independent activities establish connections between different topics or disciplines. Such activities are particularly valuable in geography because the subject naturally integrates concepts from environmental science, economics, sociology, history, and political science. Generalizing activities encourage students to synthesize information and develop comprehensive understandings of complex geographical processes. Assessment-oriented independent work provides opportunities for evaluating students' mastery of knowledge and skills (Mammadova & Rustamov, 2017).

Table 3. Classification of Independent Activities

Type of Independent Work	Main Objective
Instructional	Acquisition of new knowledge
Preparatory	Development of prerequisite skills
Reinforcement	Consolidation of learning
Review	Retention and repetition
Integrative	Interdisciplinary connections
Generalizing	Knowledge synthesis
Assessment	Evaluation of learning outcomes

The educational value of independent activities extends beyond academic achievement. Such activities foster responsibility, perseverance, self-confidence, and decision-making skills. Students learn to identify relevant sources of information, evaluate evidence critically, and construct logical arguments based on empirical data. These competencies are essential for success in higher education and professional life (Qasimova, 2020).

Moreover, independent learning encourages students to become active participants in the educational process. Instead of relying exclusively on teacher explanations, learners assume responsibility for constructing knowledge and solving problems independently. This shift from teacher-centered to learner-centered education represents a key objective of contemporary educational reform.

Organization and Management of Practical and Independent Activities

The successful implementation of practical and independent activities requires careful planning, effective organization, and continuous instructional support. Geography teachers play a critical role in designing meaningful learning experiences that promote student engagement and achievement (Mammadova, 2020).

One of the most important prerequisites for successful implementation is clear goal setting. Students must understand the objectives, procedures, and expected outcomes of each activity before beginning their work. Well-defined goals provide direction and enhance motivation by helping learners recognize the relevance and purpose of their efforts.

Teachers must also ensure the availability of appropriate instructional resources. Geography practical activities frequently require access to maps, atlases, globes, statistical databases, digital technologies, and observational instruments. The quality and accessibility of these resources significantly influence the effectiveness of learning experiences (Abbasov, 2021).

Table 4. Information Sources Used in Geography Practical Activities

Source Type	Examples	Educational Function
Cartographic Sources	Maps, atlases, globes	Spatial analysis
Statistical Sources	Charts, tables, graphs	Data interpretation
Textual Sources	Textbooks, scientific literature	Conceptual understanding
Digital Sources	GIS software, online databases	Technological competence
Field Sources	Observations, measurements	Experiential learning

Practical and independent activities may be organized individually, collaboratively, or collectively. Individual work enables teachers to assess students' personal competencies and learning progress. Group work promotes communication, cooperation, and peer learning, while collective activities facilitate the introduction of new methods and concepts (Alkhasov, 2015).

Teacher guidance remains essential throughout the learning process. Although independent activities emphasize student autonomy, effective guidance helps learners overcome difficulties, refine their thinking, and maintain focus on educational objectives. According to Vygotsky's (1978) theory of the Zone of Proximal Development, optimal learning occurs when students receive appropriate support while engaging in challenging tasks.

A particularly important instructional strategy in geography education is comparative analysis. By comparing geographical regions, phenomena, and processes, students identify similarities, differences, and causal relationships. Comparative thinking promotes analytical reasoning and supports the development of geographical understanding (Hasanov & Guliyev, 2016).

Furthermore, modern geography education increasingly incorporates project-based learning, inquiry-based learning, and problem-based learning approaches. These methodologies encourage students to investigate authentic geographical issues and develop solutions through systematic inquiry. Research indicates that such approaches significantly enhance student motivation, critical thinking, and long-term knowledge retention (Lambert & Morgan, 2010; Brooks, 2013).

Conclusions

The findings of this study demonstrate that practical and independent activities constitute indispensable components of contemporary geography education. Their implementation contributes significantly to students' cognitive, emotional, and social development while simultaneously improving academic achievement and geographical literacy.

Practical activities facilitate the application of theoretical knowledge to real-world situations, enabling students to develop observation, interpretation, analysis, and problem-solving skills. Independent

activities promote intellectual autonomy, self-regulation, responsibility, and critical thinking. Together, these forms of learning support the development of competencies required for lifelong learning and active citizenship.

The research confirms that practical and independent activities possess substantial pedagogical and psychological value. By activating students' cognitive processes and encouraging active participation, these activities foster deeper understanding and more durable learning outcomes. Their effectiveness is further enhanced when they are adapted to students' developmental characteristics, interests, and individual learning needs.

The classification of practical and independent activities provides educators with a systematic framework for instructional planning. Instructional, reinforcement, practice-oriented, assessment, and concluding activities each serve distinct educational functions and contribute to the comprehensive development of geographical competencies.

The study also highlights the critical role of teacher guidance and instructional design. Effective implementation requires clear objectives, appropriate learning resources, continuous supervision, and meaningful assessment procedures. When these conditions are met, practical and independent activities become powerful tools for promoting inquiry, creativity, and scientific thinking.

Overall, the integration of practical and independent activities into geography teaching strengthens the relationship between education and real life, enhances students' research and analytical skills, and supports the development of environmentally responsible and geographically informed individuals.

Contribution

This study contributes to the field of geography education by providing a comprehensive analysis of practical and independent activities as key components of effective teaching and learning. It integrates national and international perspectives on geography education and highlights the theoretical foundations underlying student-centered instructional approaches.

The research offers practical recommendations for educators seeking to enhance the quality of geography instruction through experiential, inquiry-based, and independent learning strategies. Furthermore, it contributes to ongoing discussions concerning competency-based education, active learning methodologies, and the development of twenty-first-century skills.

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IMPACT OF CLIMATE-RESPONSIVE DESIGN STRATEGIES ON THERMAL COMFORT IN COMMUNITY CIVIC CENTRES IN ABUJA, NIGERIA

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ABSTRACT
Rapid urban development and rising temperatures in Abuja, Nigeria, have heightened concerns regarding thermal discomfort in community civic centres, particularly where climate-responsive design principles are inadequately applied. Despite increasing advocacy for sustainable architecture, there remains a limited understanding of how passive design strategies influence thermal comfort in civic-scale public buildings within the local context. This study examines the impact of climate-responsive design strategies on thermal comfort in selected community civic centres in Abuja, Nigeria. A qualitative case study approach was adopted, involving the analysis of selected civic centres. Data were obtained through field observations, architectural documentation, and evaluation of key design elements such as building orientation, natural ventilation systems, shading devices, and material application. Findings indicate that buildings incorporating climate-responsive strategies particularly effective cross-ventilation, appropriate orientation, solar shading, and the use of thermally efficient materials demonstrate improved indoor thermal conditions and enhanced occupant comfort. In contrast, buildings lacking these considerations experience excessive heat gain, poor air circulation, and increased thermal discomfort. The study emphasizes the critical role of integrating passive design strategies in the planning and design of community civic centres. It recommends the adoption of climate-responsive approaches to reduce dependence on mechanical cooling systems, improve user comfort, and promote sustainable architectural practices in similar tropical environments.
Keywords: Climate-responsive design, Thermal comfort, Civic centres, Passive strategies, Abuja, Sustainable architecture.

1. INTRODUCTION
Abuja is the capital of Nigeria and is one of the fastest-growing cities in Africa. This Rapid urbanization, especially in the Abuja Municipal Area Council (AMAC), has led to inconsistent IEQ standards in public youth centers (Ogunleye et al., 2025). As more people move into the city and more buildings are put up, the heat is becoming a major issue. Because of its location in the tropics, the city experiences very hot weather, and Temperatures can rise to 40°C during the dry season (Adaji et al., 2019). This high heat makes it hard for people to stay comfortable when they are inside buildings.

Thermal comfort is very important in public buildings like civic centers because it affects how people behave and feel. IEQ encompassing thermal comfort, air quality, lighting, and acoustics is central to how users experience buildings (Ogunleye et al., 2025). If a building is too hot or stuffy, it can affect thermal comfort and overall well-being of people (Adaji et al., 2019). For a community civic center to be useful, it must be a place where people actually want to spend time without feeling heat stress.

The big problem right now is that many of these centers in Abuja have poor climate-responsive designs. Many buildings suffer from overheating, inadequate ventilation, poor acoustics, and lighting deficiencies, conditions that undermine user comfort and program effectiveness (Ogunleye et al., 2025). Instead of designing buildings that stay cool naturally, many architects rely on air conditioning. However, due to the lack of a reliable and continuous power supply from the national grid, mechanical cooling systems in residential buildings cannot be depended on (Adaji et al., 2019). When the power fails, these buildings become almost unusable because they have sealed windows and reliance on air conditioning, a strategy ill-suited to frequent power outages (Ogunleye et al., 2025).

There is a major gap in our knowledge because youth-oriented buildings in tropical, under-resourced urban contexts remain under-studied, particularly in West Africa (Ogunleye et al., 2025). Most research

on building comfort happens in cold countries, and limited research has examined the real-world performance of green buildings in Africa (Muhammad et al., 2025). We need more local studies that look at how large public buildings can use passive design to stay cool.

This study therefore seeks to examine the impact of climate-responsive design strategies on thermal comfort in community civic centres in Abuja, Nigeria, with the aim of identifying passive design approaches that enhance indoor environmental quality while reducing dependence on mechanical cooling systems. The study contributes to ongoing discourse on sustainable and climate-responsive architecture by providing insights that may inform future design practices and policy development for public buildings in Nigeria and similar tropical regions. This is achieved through the assessment of existing community civic centres in Abuja, evaluating current indoor environmental conditions, identifying suitable passive design strategies, and proposing design interventions that improve thermal comfort, energy efficiency, and overall user well-being.

2.0 LITERATURE REVIEW

2.1 Climate And Thermal Conditions Of Abuja

Abuja is located in the center of Nigeria and has a tropical Savannah climate with two prevalent seasons, namely the dry season and the rainy season. The dry season starts in November and lasts until April, while the rainy season begins in May and ends in October (Abdulkareem and Al-Maiyah, 2025). There is also a brief interval known as harmattan occurs between the two seasons, typically from early December to February (Mustapha et al., 2022). This period brings dusty winds and cooler nights, but for the rest of the year, the weather is mostly very hot.

Temperature patterns in Abuja are quite intense. The daytime air temperature ranges from 26 to 36 degrees Celsius, with a low night-time temperature of 20 to 24 degrees Celsius (Mustapha et al., 2022). According to Bawa and Ukpabia (2024), the hottest month identified as March with temperatures between 21 degrees Celsius and 35 degrees Celsius. During the dry season, the city experiences clear skies and intense solar radiation (5.9–6.3 kWh/m²/day), which causes daytime temperatures to rise to around 37 °C. A unique feature of this climate is that "temperatures around dawn can be 15–17 °C cooler than those recorded during midday because the heat from the sun escapes quickly at night (Abdulkareem and Al-Maiyah, 2025).

In the rainy season, the city gets very sticky because the average relative humidity during the dry season is around 38%, while during the rainy season, it increases to about 82% peaking at around 87% in August. Even though the rain helps cool things down, daytime temperatures still often stay above 28°C (Abdulkareem and Al-Maiyah, 2025).

These climatic conditions have a massive effect on how buildings perform. Because the sun is so strong, tropical climates are characterized by increased cooling loads as a result of poor envelope performance. Most of the heat inside a building comes from thermal transfer through the building envelope systems between the internal and external building environment (Bawa and Ukpabia, 2024). For architects, this means that buildings must be designed to block this heavy solar heat. If the building envelope like the walls and roof is not designed well, the cooling loads are directly linked with the performance of the building envelope components (Bawa and Ukpabia, 2024). Without good design, people inside will be very uncomfortable unless they use a lot of expensive electricity for cooling.

2.2 Concept Of Thermal Comfort In Buildings

Thermal comfort is basically about how people feel inside a building. It is officially described as a subjective state of mind where people feel thermally comfortable within a given environment (Hamza et al., 2024). Another way to say it is that it is that condition of mind that expresses satisfaction with the thermal environment (Hamza et al., 2024). Because it is a state of mind, it means that different people might feel differently even if they are in the same room. For a building to be successful, it must make sure the people inside are healthy and can do their work well. As noted by Hamza et al. (2024), assuring adequate thermal comfort conditions inside buildings is essential not only for the health of the occupants but also in terms of productivity and efficiency.

Several physical factors decide if a person will feel comfortable. These include the temperature of the air, how much moisture is in the air (humidity), and how fast the air is moving. In Nigeria, the weather is very tough because the Tropical region is characterized by intense sunshine, temperatures that could

hover around 25°C to 44°C and Relative Humidity (RH) between 50% to 90% (Peter, 2025). High humidity makes it harder for the body to cool down through sweat. This is why airflow is so important in Abuja. Architects and builders know that air flow is crucial hence, openings are made to enhance good air velocity which increases heat transfer between the body and the air through convection (Peter, 2025).

Occupant perception and acclimatization are also very important. People living in Nigeria are used to the heat, so they don't mind higher temperatures as much as people in cold countries do. Research in Abuja found that neutral temperatures were in a range of 28°C-30.4°C compared to the preferred temperature range of 27.5°C-29.4°C (Adaji et al., 2019). This shows that Nigerians can be happy in rooms that are much warmer than what international manuals usually recommend. In fact, people in this area exhibit a high degree of acclimatization to higher temperatures than international standards recommendations (Hamza et al., 2024).

To measure this, experts use different models like the adaptive thermal comfort model (Adaji et al., 2019). This model is great for naturally ventilated buildings because it recognizes that people are not just passive they do things to stay cool. The adaptive approach is helpful because it allows for thermal variations where occupants can exercise control and meet their own needs (Hamza et al., 2024). In a place like Abuja where there are frequent Power disruptions, we cannot always rely on air conditioning (Peter, 2025). This makes the comfort of the people solely at the mercy of the building envelopes and their design proficiencies (Peter, 2025).

Therefore, the design of a civic centre must use natural ways to keep the air moving and block the sun so that people stay satisfied without needing constant electricity.

2.3 Climate-Responsive Design Strategies

Climate-responsive design uses natural methods to keep buildings comfortable. Ogunnaike et al. (2025) state that passive design using a building's orientation, natural ventilation, shading, thermal mass, and daylighting reduces reliance on active cooling. Correct use of these strategies can improve indoor thermal conditions and reduce energy use by up to 50% (Ogunnaike et al., 2025).

For Building Orientation, an N-S alignment is the best choice for buildings in this region (Ogunleye et al., 2025). This is a smart move because in hot-dry climates, building orientation prioritizes shading (Chidiadi and Taki, 2025). Regarding Natural Ventilation, designers should use passive airflow strategies, including cross-ventilation, perforated walls, and courtyard-facing openings (Ogunleye et al., 2025). Courtyards help because the stack effect... contributes to thermal comfort by enabling cool breezes, particularly at night when courtyards retain cool air, which then circulates into surrounding rooms (Chidiadi and Taki, 2025).

To block heat, Shading Devices are necessary. Findings show that shaded areas in courtyards can maintain temperatures up to 3 K cooler (Chidiadi and Taki, 2025). Using natural shading, and landscape buffers also helps create a better microclimate (Ogunleye et al., 2025). Finally, for Material Selection, compressed earth blocks exhibit better thermal performance, reducing peak temperatures by 1.19 ◦C compared to hollow concrete blocks. This is because mud bricks offer lower thermal conductivity, thereby reducing heat transfer indoors (Chidiadi and Taki, 2025).

2.4 Civic Centres And Public Buildings

Civic centres are major public spaces that help communities come together. For example a conference centre is a public large building that is designed to hold, a convention where individuals and group gather to promote and share common interest. These facilities are built as specialized hubs meant almost exclusively for conferences, exhibitions, large meetings, seminars, and training sessions (Sharif et al., 2021). They also serve as important hubs for learning, recreation, entrepreneurship, and mentorship" (Ogunleye et al., 2025). To handle these jobs, they must provide sufficient floor area to accommodate several thousand of attendees (Sharif et al., 2021).

Because of their large size, these buildings have complex occupancy patterns. Problems often arise because nature of gathering hundreds of people at a time creates massive heat and air quality issues (Sharif et al., 2021). Many current public buildings are poorly ventilated, spatially rigid, and environmentally inefficient (Ogunleye et al., 2025). In Nigeria, institutional buildings struggle to maintain thermal comfort without excessive energy consumption because they rely too much on

mechanical systems (Gims et al., 2025). A lot of energy is used for cooling, refrigeration, Vertical and horizontal circulation and lighting (Sharif et al., 2021).

Achieving thermal comfort is one of the most important parameters to be considered when designing public buildings such as conference centre (Sharif et al., 2021). It is very important because the building envelope must protect the occupants of the building from the heat of the sun, rains, dust and provide a congenial environment for sharing knowledge (Sharif et al., 2021).

Without good passive design, users suffer from heat build-up, limited shading, and scarce green space integration (Ogunleye et al., 2025). Therefore, civic centres need a design that provides a balance of natural ventilation, space conditioning, and lighting to remain functional (Sharif et al., 2021).

2.5 Relationship Between Passive Design And Thermal Comfort

Passive design significantly improves the indoor environment by using natural ways to block heat. Recent research shows that utilizing a combination of passive design methods to achieve occupant thermal comfort can lead to a reduction of up to 20% in the frequency of thermal discomfort during the hottest period of the year (Abdulkareem and Al-Maiyah, 2025). In Nigeria, studies confirm that "traditional buildings recorded lower air temperature readings compared to modern buildings, even though they do not use active cooling (Okafor et al., 2022). Because modern buildings often get too hot, experts advise that architects and planners should make concerted efforts to integrate methods of passive design into the provision of a comfortable indoor thermal environment rather than relying solely on active design strategies (Okafor et al., 2022). However, there is still an alarming gap regarding the abandonment of basic sustainable design practices in current building codes, and very few of these studies focused on evaluating the thermal performance of larger public or civic-scale buildings in the Abuja region (Abdulkareem and Al-Maiyah, 2025).

3.0 METHODOLOGY

This study adopts a qualitative research methodology to examine climate-responsive design strategies and their impact on thermal comfort in civic buildings. The approach allows for an in-depth assessment of architectural features within their real-life environmental context. A case study method was employed to analyse selected community civic centres in Abuja. Data were obtained through field observation and architectural documentation of key design elements.

3.1 Selection of Case Studies

The study employed purposive sampling to select three civic centres within Abuja, Federal Capital Territory. Selected community civic centres were chosen based on relevance, accessibility, presence of passive design strategies and functional significance. These buildings represent typical civic-scale public facilities within the study area. Their selection allows for comparative evaluation of design strategies. They also provide insight into how architectural decisions influence thermal comfort under similar climatic conditions. The selected sites are shown in table 1 below:

Table 1: Selected community civic centres

S/N	Name of Community civic centre	Architectural relevance	Presence of passive design strategies
1	Shehu Musa Yar'Adua Centre	high	yes
2	Nigerian airforce (NAF) Conference Centre	high	moderate
3	Cyprian Ekwensi Arts and Culture Centre	high	yes

3.2 Data Collection

Data for this study were obtained from both primary and secondary sources. Primary data were collected through field observations, photographic documentation, and visual assessment of the selected civic centres. Observations focused on key design features such as building orientation, natural ventilation systems, shading devices, and material application, as well as their influence on indoor thermal conditions.

Secondary data were sourced from relevant literature, including previous studies on thermal comfort and climate-responsive design. The use of multiple data sources ensured triangulation and enhanced the reliability of the findings.

3.3 Data Analysis

Data analysis was conducted using descriptive and comparative methods. Field data were categorized based on key climate-responsive design strategies, including building orientation, natural ventilation, shading devices, and material application. Each case study was evaluated according to its effectiveness in enhancing thermal comfort within indoor spaces. Comparative analysis was then carried out across the selected civic centres to identify patterns, similarities, and differences in design performance. This approach enabled the assessment of how passive design strategies influence thermal conditions in civic buildings within Abuja.

4.0 RESULTS AND DISCUSSION

4.1 Case Study Review

4.1.1 Shehu Musa Yar'Adua Centre, Abuja

The Shehu Musa Yar'Adua Centre, located in Abuja's Central Business District, is a prominent multipurpose civic facility used for conferences, exhibitions, and public events. Established in 1990, the complex includes an auditorium, ancillary halls, offices, and outdoor spaces. The layout supports diverse civic functions with both enclosed and semi-open areas. Its large site allows for landscaping and spatial flexibility. The building represents a major example of civic architecture within Abuja.

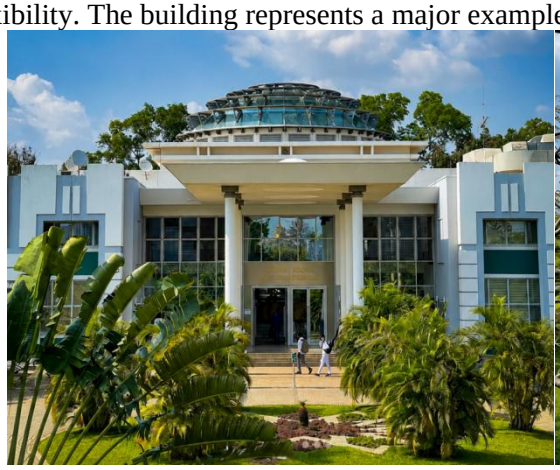
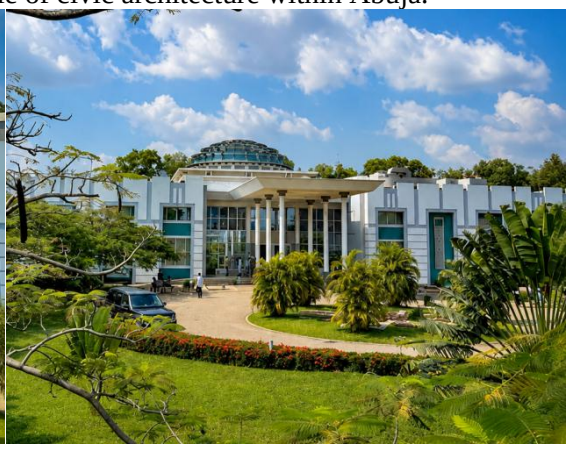

Figure 1: Showing the approach of the centre Figure 2: Showing the landscaping

***Source**: Author's Work (2026)*

i. Spatial and Functional Characteristics

ii. The centre comprises a main auditorium supported by smaller halls, circulation corridors, and open gathering spaces. These spaces accommodate varying occupancy levels and activity types. Circulation areas are relatively open, allowing some interaction with outdoor conditions. The presence of landscaped surroundings enhances user experience. Functional zoning supports both formal and informal civic activities.

Figure 3: Exhibition centre Figure 4: The central glazed dome Figure 5: The auditorium **within the lobby** ***Source**: Author's Work (2026)*

iii. Climate-Responsive Design Features

iv. The building is oriented along an east–west axis, reducing solar exposure on longer facades. Natural ventilation is achieved through louvers and operable windows, though partially limited by mechanical systems. Shading is provided by roof overhangs and surrounding vegetation. Masonry walls contribute to moderate thermal mass. Overall, the building demonstrates moderate climate responsiveness with effective orientation and shading.

Figure 6: facade design on the walls and landscaping Figure 7: Showing the shaded entrance

***Source**: Author's Work (2026)*

4.1.2 Nigerian Airforce (NAF) Conference Centre, Abuja

The NAF Conference Centre, located in Maitama, Abuja, is a large-scale facility designed for conferences, banquets, and official events. It features a main hall, breakout rooms, and supporting spaces for high-capacity use. The architecture emphasizes modern aesthetics with extensive glazing. The building serves governmental and corporate functions. It is one of the most prominent conference venues in Abuja.

i. Spatial and Functional Characteristics

The facility consists of a large central hall, supporting meeting rooms, and service areas. Spaces are designed for high occupancy and controlled indoor environments. Circulation areas are enclosed and highly conditioned. The layout prioritizes functionality and visual impact. Indoor spaces dominate over outdoor or transitional areas.

Figure 8: Aerial approach of the conference centre Figure 9: Showing the shaded entrance

***Source**: Author's Work (2026)*

ii. Climate-Responsive Design Features

The building orientation exposes large glazed facades to solar radiation, increasing heat gain. Natural ventilation is minimal, with heavy reliance on mechanical cooling systems. Shading devices are limited, especially on east and west elevations. Extensive glazing contributes to poor thermal performance. Overall, the building shows low integration of climate-responsive strategies.

Figure 10:Dining naturally lighted Figure 11: Pool and balcony Figure 12: Facade element
Source: Author's Work (2026)

4.1.3 Cyprian Ekwensi Arts and Culture Centre, Abuja

The Cyprian Ekwensi Arts and Culture Centre, located in Garki, Abuja, is a public cultural facility used for performances, exhibitions, and community events. The complex includes theatre halls, galleries, and outdoor performance spaces. Its design reflects elements of tropical architectural principles. The building integrates indoor and outdoor spaces effectively. It serves as a key cultural hub within the city.

Figure 13: Views of the approach and Deep overhangs Figure 14: Rear view with parking lot
Source: *Author's Work (2026)*

i. Spatial and Functional Characteristics

The centre comprises performance halls, gallery spaces, and semi-open transitional areas. These spaces encourage airflow and interaction with the outdoor environment. The inclusion of courtyards enhances spatial quality. Functional areas are interconnected through open circulation paths. The layout supports both formal and informal activities.

Figure 15: Courtyard to encourage airflow and interaction with the outdoor environment
Source: *Author's Work (2026)*

v. Climate-Responsive Design Features

vi. The building is oriented east–west, minimizing solar heat gain on major facades. Natural ventilation is achieved through louvers, operable windows, and open spaces. Shading is provided by deep overhangs, screens, and vegetation. High thermal mass materials help regulate indoor temperatures. The building demonstrates strong integration of passive design strategies.

4.2 Climate-Responsive Strategies Currently in Use

4.2.1 Building Orientation

Building orientation was identified as the most consistent climate-responsive strategy across the three case studies. Both the Shehu Musa Yar'Adua Centre and Cyprian Ekwensi Arts and Culture Centre are aligned along an east–west axis, allowing their longer facades to face north and south. This reduces direct solar heat gain and enables more effective use of horizontal shading devices. Such orientation improves indoor thermal conditions by limiting exposure to low-angle morning and evening sun. In contrast, the NAF Conference Centre follows a north–south axis, exposing its longer facades to intense east and west solar radiation. This results in increased heat gain and reduced thermal efficiency within interior spaces. The comparison highlights the strong influence of orientation on passive cooling performance. Buildings that are properly aligned can better control solar exposure and enhance comfort levels. Poor orientation, however, creates thermal challenges that are difficult to mitigate through other passive strategies. Overall, orientation remains a critical first step in climate-responsive building design.

4.2.2 Natural Ventilation

Natural ventilation strategies differ notably across the three case studies. The Cyprian Ekwensi Arts and Culture Centre presents the most effective approach, incorporating cross-ventilation through well-positioned openings on opposite facades. Additional features such as ventilated roof spaces and semi-open transitional zones further enhance airflow and act as thermal buffers. This layered strategy supports consistent indoor air movement and improved thermal comfort. The Shehu Musa Yar'Adua Centre demonstrates moderate ventilation performance, with its layout allowing for cross-ventilation in principle. However, the installation of air conditioning units within window spaces has reduced the size and effectiveness of ventilation openings. This alteration limits airflow and weakens the building's passive cooling potential. In contrast, the NAF Conference Centre depends largely on mechanical systems for ventilation. Natural airflow is restricted to entrance and transitional areas, with minimal integration into primary spaces. This reliance reduces energy efficiency and limits adaptability during system downtime. Overall, effective natural ventilation remains essential for sustainable thermal performance.

4.2.3 Shading Devices

Shading strategies across the case studies vary from highly integrated to minimal application. The Cyprian Ekwensi Arts and Culture Centre demonstrates the most comprehensive approach, combining deep roof overhangs, external louvre screens, and surrounding vegetation. These elements work together to reduce direct solar radiation on exposed facades and improve indoor thermal conditions. This layered shading system enhances overall building performance and user comfort. The Shehu Musa Yar'Adua Centre provides moderate shading, particularly on its north and south elevations through extended eaves and landscape features. However, the east and west facades receive less protection, making them more vulnerable to heat gain. The NAF Conference Centre shows the least effective shading strategy among the three. Apart from a projecting canopy on one facade, most glazed surfaces remain exposed to direct sunlight. This lack of adequate shading increases indoor heat levels and dependence on mechanical cooling. Overall, effective shading remains a key passive strategy for reducing thermal load in buildings.

4.2.4 Building Materials and Thermal Performance

Material selection across the case studies shows varying consideration for thermal performance. The Cyprian Ekwensi Arts and Culture Centre utilizes thick masonry walls with high thermal mass and light-coloured finishes, which help reduce heat absorption. These materials delay heat transfer into interior spaces and release stored heat during cooler periods, improving indoor comfort. This approach is well-suited to Abuja's climate, where temperature fluctuations occur between day and night. The Shehu Musa

Yar'Adua Centre also adopts masonry construction with relatively good wall thickness, supporting moderate thermal performance. However, some sections incorporate lighter materials that reduce the overall effectiveness of heat storage. In contrast, the NAF Conference Centre relies heavily on glazed facades, especially on sun-exposed elevations. These surfaces allow significant solar heat gain, increasing indoor temperatures. There is no clear evidence of advanced glazing systems to reduce this effect. As a result, the building experiences higher thermal loads and greater dependence on mechanical cooling.

4.3 Summary of Performance Evaluation

A comparative evaluation of the three case studies based on four climate-responsive criteria reveals clear differences in performance. The Cyprian Ekwensi Arts and Culture Centre ranks highest, showing strong integration of orientation, ventilation, shading, and material efficiency. This results in the most favourable indoor thermal conditions among the buildings. The Shehu Musa Yar'Adua Centre demonstrates moderate performance, with good orientation and some shading strategies. However, its effectiveness is reduced by limited natural ventilation due to mechanical system retrofits. The NAF Conference Centre performs the least effectively, relying mainly on mechanical cooling with minimal passive design integration. This increases energy demand and reduces environmental responsiveness.

These findings align with established research on passive design in tropical buildings (Ogoli, 2003; Amos-Abanyie et al., 2013). The results confirm that combining key strategies improves thermal comfort significantly. Buildings lacking these measures tend to experience higher heat gain and discomfort. Dependence on mechanical systems alone often leads to inefficiency and unstable performance. This is especially evident during peak demand or system failure. Overall, integrated passive design remains essential for sustainable thermal comfort in Abuja.

5.0 CONCLUSION

This study has examined climate-responsive design strategies and their influence on thermal comfort in selected civic buildings in Abuja, Nigeria, through a comparative assessment of three case studies. The findings reveal significant differences in performance based on the level of integration of passive design principles. Buildings that effectively incorporate proper orientation, natural ventilation, shading devices, and appropriate material selection demonstrate improved indoor thermal conditions and reduced reliance on mechanical cooling systems. In contrast, buildings with minimal consideration for these strategies experience higher heat gain and reduced comfort levels.

The study contributes to architectural discourse by highlighting the importance of integrating passive design strategies in civic-scale buildings within hot tropical climates. It provides a context-specific evaluation framework that can guide architects, designers, and policymakers in making informed design decisions. The results emphasize that reliance on mechanical systems alone is neither sustainable nor efficient in the long term.

The findings strongly advocate for a holistic approach to building design that prioritizes climate responsiveness and user comfort. Future research should focus on quantitative thermal performance analysis and post-occupancy evaluations to further validate the effectiveness of passive design strategies in Abuja's built environment.

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DETERMINATION OF THE CHANGE IN OPTICAL PROPERTIES OF BACTERIA SUBJECTED TO MAGNETIC FIELD WITH THE HELP OF ULTRAVIOLET-VISIBLE

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ÖZET
Bu çalışmada, 0-3 amper doğru akım oluşturabilen güç kaynağı kullanıldı ve bu akım Helmholtz bobini üzerinden geçirilerek sabit bir manyetik alan oluşturuldu. Manyetik alan merkezine yakınlıkları 0, 10, 20, 40 cm ve manyetik alansız (kontrol grubu) olacak şekilde 5 farklı numune yerleştirilerek bu numunelerde bulunan Lactobacillus bulgaricus ve Streptococcus thermophilus bakterilerinin optik özelliklerindeki değişim izlendi. Elde edilen numunelerin optik özellikleri Ultraviolet-Visible (Uv-Vis) yöntemi kullanılarak belirlendi. Yapılan ölçümler sonucunda manyetik alan merkezine uzaklıkları 0, 10, 20, 40 ve max (kontrol grubu) olan numunelerin yasak enerji aralığı E_g değerleri sırasıyla 4.11, 4.12, 4.13, 4.14 ve 4.17 eV olarak elde edildi. Numunelerdeki farklılıklar optik mikroskoplarla gözlemlenmiştir. Bu verilere göre manyetik alan merkezine en yakın olan numunedeki bakterilerin optik özelliklerindeki değişim en fazla, en uzak olan numunedeki değişim ise en az olarak belirlendi. Buna göre manyetik alanın, bakterilerdeki üreme mekanizmasını etkilediği ve absorbans özelliklerinde değişikliklere neden olduğu ortaya koyulmuştur.
Anahtar Kelimeler: Manyetik alan; Bakteri, Optik özellik; Uv-Vis; Enerji aralığı (Eg).

ABSTRACT
In this study, a power supply capable of generating a direct current of 0–3 amperes were used, and this current was passed through a Helmholtz coil to create a constant magnetic field. Five different samples were placed at distances of 0, 10, 20, and 40 cm from the magnetic field center, along with a control group without magnetic exposure, to observe changes in the optical properties of Lactobacillus bulgaricus and Streptococcus thermophilus bacteria. The optical properties of the obtained samples were determined using the Ultraviolet-Visible (Uv-Vis) method.
As a result of the measurements, the E_g values of the samples located at 0, 10, 20, 40 cm, and the control group (no magnetic field) were determined as 4.11, 4.12, 4.13, 4.14, and 4.17 eV, respectively. The differences among the samples were also observed using optical microscopy. Based on these results, it was determined that the changes in the optical properties of the bacteria were greatest in the sample closest to the magnetic field center and least in the most distant sample. Accordingly, it was demonstrated that the magnetic field affects the reproductive mechanism of the bacteria and causes alterations in their absorbance properties.
Keywords: Magnetic field; Bacteria; Optical Properties; UV-Vis; Band Gap (Eg).

GİRİŞ
Yoğurt, probiyotik özellikleri ve sağlık açısından faydaları nedeniyle dünya genelinde yaygın bir şekilde tüketilmektedir. Yoğurdun temel bileşenlerini oluşturan *Lactobacillus bulgaricus* ve *Streptococcus thermophilus* gibi bakteriler, fermantasyon sürecinde aktif rol oynar. Bu mikroorganizmaların aktivitesini artırmak, metabolik özelliklerini iyileştirmek veya fermantasyon süreçlerini optimize etmek

amacıyla çeşitli fiziksel ve kimyasal yöntemler uygulanmaktadır. Manyetik alanların biyolojik sistemler üzerindeki etkileri, son yıllarda birçok çalışmada incelenmiş olup, yoğurt bakterileri gibi mikroorganizmalar üzerinde de etkili olabileceği gösterilmiştir.

Genel olarak bakteriler hayatımızın her alanında bulunmaktadır. Bu bakteriler zararlı ve zararsız olarak ayrılmaktadır. İnsan hayatı için önemli yeri olan bakteriler özellikle gastrointestinal sistem florasının oluşturulması, geliştirilmesi ve korunması bakımından görevlere sahiptir. Bağırsak savunma bariyerini de koruduğuna inanılmaktadır (Aslan ve Altındiş, 2017; Jones, 2002). Sindirim sisteminin dengesini de intestinal mikroflora sağlamaktadır. Bu florayı desteklemek için prebiyotik, probiyotik ve sinbiyotikler gibi gıda olan katkı maddelerinden faydalanılmaktadır (Iacono vd., 2011; Koçak vd., 2016).

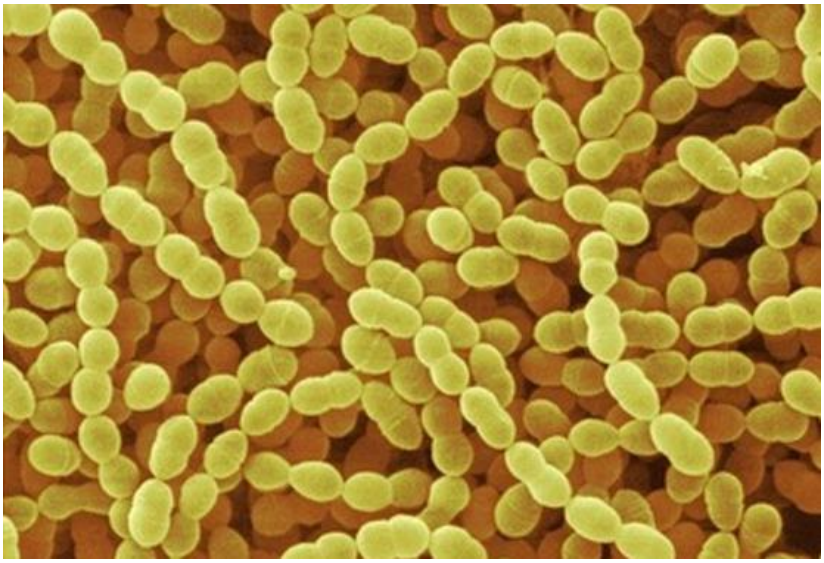
Probiyotik olarak değerlendirilen laktik asit bakterilerinden (LAB), Streptococcus ve Lactobacillus, en faydalı mikroorganizmalar olarak bilinmektedir. Birçok çeşitli etkiyle bakterilerin yapısında değişiklik ve faydalı olma durumları değişiklik göstermektedir. Bu bakteriler gastrointestinal sistem hastalıklarında da kullanımı oldukça yaygındır (Dhama vd., 2016). Özellikle bu sebeple probiyotik maddelere talep oldukça fazladır. En yaygın olarak bulunan ve kolay bir şekilde hazırlanan yoğurt, probiyotik ürün olarak en fazla tüketilendir (Anal ve Singh, 2007; Champagne ve Fustier, 2007).

Streptococcus thermophilus (*Streptococcus salivarius* subsp. *thermophilus*) (Resim 1) ve *Lactobacillus bulgaricus* (*Lactobacıllus delbrueckii* subs *bulgaricus*) özellikle yoğurt starter mikroorganizmaları olarak kullanılan ve yoğurt üretiminden sorumlu laktik asit bakterileridir. *Streptococcus*lar oval ve küresel yapıya sahip, katalaz negatif, Gram pozitif ve genellikle hareketsizdirler. *S. thermophilus* homofermentatiftir. Gelişebilmeleri için 45-52 ^{0}C sıcaklık gerekmektedir. En iyi çoğalma pH derecesi 6.0-6.5 olup, fakültatif anaerob ve aerobik özellik göstermektedir (Krieg vd., 1984).

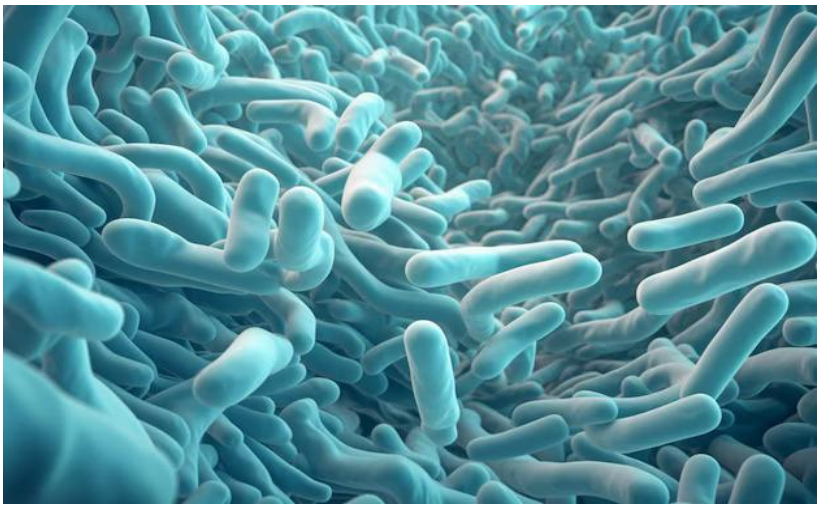
Lactobacillus (Resim 2) cinsi bakteriler hafif kıvrık veya düz çubuk şeklinde yapıya sahiptirler. Gram pozitif, anaerobik, katalaz negatif, fakültatif anaerobik veya mikroaerofiliktirler. Bu türün bazı varyeteleri 48-52 0C'de gelişebilmektedir (Hammes vd., 2009). Gelişebilmesi için optimum pH değeri 5.2-5.5 arasındadır. Laktozu fermente edebilme yeteneği oldukça yüksektir ve buna ek olarak, fruktoz, glukoz ve galaktozu da kullanabilirler (Vos vd., 2009).

Fermantasyonun temel amacı, CO2, karbonhidratların oksidasyonu, alkol türevleri ve farklı organik asitlerin üretilmesidir (Kabak ve Dobson, 2011; Özden, 2008). Fermantasyon esnasında süt bileşenlerinde gerçekleşen mikrobiyolojik değişiklikler sonucunda fermente süt içeriğinin besin değerlerinde artış görülmektedir. Bu sebeple son zamanlarda fermente süt ürünleri fonksiyonel gıdalar arasında yerini almaktadır (Aran, 2014).

Aynı ortamda bulunarak elektromanyetik dalga oluşturan cihazlar hem biyolojik varlıkları hem de birbirini etkilemektedir. Dalgalar sonucunda ortaya çıkacak olan biyolojik etkiler iç alana bağlı olarak değişiklik gösterir. Elektromanyetik dalgaya uğrayan biyolojik yapı içerisindeki alanların nasıl bir yapıda olduğunu bulmak için deneysel ve teorik çalışmaların ikisine de ihtiyaç duyulmaktadır (Didmitris vd., 2004; Liu vd., 2004; Marino ve Carrubba, 2009; Sevgi, 2000; Valsechi vd., 2004). Manyetik alan, elektrik yüklenmiş parçacıkların hareketi sonucunda oluşan ve manyetik kuvvetlerin etkisini taşıyan bir fiziksel alanı ifade eder. Bu alan, elektrik akımları veya hareketli yüklerin etrafında oluşur ve çeşitli doğal fenomenlerle tanımlanabilir (Griffiths, 2017).



Resim 1. *Streptococcus thermophilus* mikroskobik görünüm.



Resim 2. *Laktobacillus bulgaricus* mikroskobik görünümü.

Manyetik alan, genellikle B harfi ile ifade edilir ve birim olarak tesla (T) kullanılır. Manyetik alanın yoğunluğu, elektrik akımının şiddeti ve mesafe ile değişir. Bir iletkenden geçen akım nedeniyle oluşan manyetik alan, Amper yasası ile açıklanabilir.
Burada:

- : Manyetik alan vektörü,
- : Yolu temsil eden vektör,
- : Manyetik alan sabiti ($4\pi \times 10^{-7}$ H/m),
- : Akım.

Bu denklem, manyetik alanın kapalı bir yol boyunca integralinin, akımla doğrusal bir ilişki gösterdiğini ifade eder (Purcell ve Morin, 2013).
Manyetik alanların mikroorganizmalar üzerindeki etkileri, genellikle mikroorganizmanın biyokimyasal ve biyofiziksel tepkileriyle ilişkili olarak açıklanmaktadır. Düşük frekanslı ve statik manyetik alanların, çeşitli bakteri türlerinin metabolizmasına, büyüme dinamiklerine ve gen ekspresyonuna etkide bulunduğu gösterilmiştir (Belova ve Makarova, 2020; Liboff, 2004).
Manyetik alanlar, bakteriyel hücrelerde iyon hareketlerini ve iyon dengesini etkileyerek, oksidatif stres ve reaktif oksijen türleri (ROS) üretimine neden olabilir. Bu durum, DNA onarım mekanizmalarını, protein sentezini ve genel metabolizmayı etkileyebilir (Fernández vd., 2018). Örneğin, Escherichia coli üzerinde yapılan bir çalışma, manyetik alan etkisinin lipid peroksidasyonu artırıp hücresel stres yanıtlarını tetiklediğini ortaya koymuştur (Kılıç vd., 2019). Yoğurt bakterileri, manyetik alan

uygulamalarına karşı hassasiyet gösteren mikroorganizmalar arasında yer alır. Bu bakteriler üzerinde yapılan deneyler, manyetik alanın hem fermantasyon sürecine hem de nihai yoğurt ürününün kalitesine etkili olduğunu ortaya koymuştur (Ali vd., 2023). Manyetik alanın fermantasyon sürecini kısaltabileceği ve laktik asit üretimini artırabileceği gösterilmiştir. 50 Hz frekansında uygulanan bir manyetik alanın, *Lactobacillus bulgaricus*'un metabolik aktivitesini %20 oranında hızlandırdığı kaydedilmiştir (Ali vd., 2023). Benzer şekilde, *Streptococcus thermophilus*'un laktik asit üretiminde %15'lik bir artış sağlandığı bildirilmiştir (Fernández vd., 2018).

MATERYAL VE YÖNTEM

Öncelikle düzenek hazırlanmıştır. Aynı türde 2 adet Helmholtz bobinleri aralarında r mesafe olacak şekilde yerleştirilmiştir. Bobinler içlerinden aynı doğrultuda akım geçecek şekilde ve de homojen magnetik alan elde edilecek şekilde düzenlenmiştir (Resim 3).

Resim 3. Akım geçirilen Helmholtz bobini.

Formülde; I, bobinlerden geçen akımı; μ_0, vakumdaki magnetik geçirgenliğini; n, sarım sayısını göstermektedir. Deneyde kullandığımız akıma ve mesafeye bağlı genel magnetik alan ifadesi aşağıdaki gibidir.

$$B = \frac{\mu_0 n I r^2}{2} \cdot \left[\frac{1}{\left[r^2 + (s - \frac{a}{2})^2\right]^{3/2}} + \frac{1}{\left[r^2 + (s + \frac{a}{2})^2\right]^{3/2}} \right]$$

$$B = \frac{\mu_0 n I}{2r} \cdot \left[\frac{1}{\left[1 + (s - \frac{a}{2r})^2\right]^{3/2}} + \frac{1}{\left[1 + (s + \frac{a}{2r})^2\right]^{3/2}} \right]$$

Resim 4. Manyetik alan hesaplama adımları.

Bu denklemde r yarıçap, a bobinler arası mesafedir ki biz deneyimizde r=a olarak belirledik. S ile belirtilen değer, numunenin manyetik alan merkezine (s=0) olan uzaklığını (sırasıyla s=10 cm, s=20 cm ve s=40 cm) göstermektedir. B magnetik alan değerini aşağıdaki formül ile hesaplandı.

$$B = \left(\frac{4}{5}\right)^{3/2} \cdot \frac{\mu 0 . n . I}{R} \qquad (1)$$

Yapılan çalışmada 154 sarımlı bobin, 20 cm yarıçapa sahiptir. 0-3 amper arasında, sarım sayısı n=154, r=20, μ_0= 1.257. 10^{-6} V_s/A_m, s=0-40 cm olarak formülde yerine koyulup değerler elde edilmiştir. Magnetik alan formüle göre hesaplandığında 2.08 miliTesla (mT) olarak bulunmuştur. Merkezde olan magnetik alan değerini göstermektedir. Deney materyallerinin merkeze olan uzaklıkları sırasıyla 0, 10, 20, 40 cm olarak belirlenmişti. Bu da bizim s değerimizi oluşturuyor. Burada s değerlerinin farklı olmasından kaynaklı olarak magnetik alan değerlerinde farklılık oluşmuştur. Bu farklılıklar da denklem

1'de belirtilen formüle göre hesaplanarak 0, 10, 20, 40 cm de bulunan deney materyallerinin magnetik alan değerleri sırasıyla 2.61 mT, 2.50 mT, 2.13 mT ve 1.12 mT olarak belirlendi (Tablo 1).

Tablo 1. Manyetik alanın bobinlerin merkezine olan uzaklığa göre değişimleri

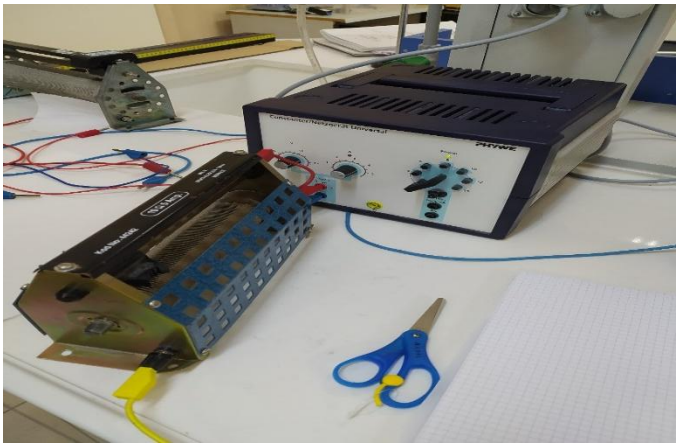
s (cm)	**B (mT)**
0	2.61
10	2.50
20	2.13
40	1.12
Kontrol Grubu	0.00

Bu çalışmada, manyetik alanın *Lactobacillus bulgaricus* ve *Streptococcus thermophilus* (Grigorov, 1905; Hansen ve Lessel, 1971) bakterileri üzerindeki etkisi incelenmiştir. Her iki bakteri, eşit oranlarda süt ile homojen bir şekilde karıştırılarak hazırlanmış ve manyetik alan merkezine farklı uzaklıklarda konumlandırılmıştır. Bakteriyel çoğalma düzeyleri, manyetik alanın farklı şiddet ve mesafelerdeki etkileri altında belirlenmiş ve karşılaştırılmıştır. Deneysel düzenek, kontrollü bir laboratuvar ortamında gerçekleştirilmiştir.

Manyetik alan oluşturmak için 0-3 Amper doğru akım (DC) sağlayabilen bir güç kaynağı kullanılmış (Resim 5) ve bu akım, uygun bir Helmholtz (bobin) (Resim 3) üzerinden geçirilerek sabit bir manyetik alan oluşturulmuştur. Manyetik alanın merkezine sırasıyla 0, 10, 20, 40 ve max (kontrol grubu) cm uzaklıklarda ölçüm noktaları belirlenmiştir. Her bir uzaklık için birer adet olmak üzere toplam 4 adet mayalanmış süt örneği kullanılmıştır. Bunlara ilave olarak manyetik alandan uzak kontrol grubumuz vardır.

Mayalanmış sütler, homojen içerikli pastörize inek sütleri kullanılarak hazırlanmıştır. Fermentasyon işlemi için ticari olarak temin edilen yoğurt mayası (Streptococcus thermophilus ve Lactobacillus bulgaricus karışımı) kullanılmıştır. Her bir süt örneği 42°C'ye ısıtılarak %2 oranında maya eklenmiştir. Sütün mayalanması için ideal sıcaklık genellikle 42-45°C aralığında tutulur ve starter kültür oranı süt hacminin %2-3'ü arasında uygulanır. Bu koşullar altında laktik asit bakterileri optimum fermentasyon etkinliği gösterir (Tamime ve Robinson, 1999).

Mayalanan sütler manyetik alana maruz bırakılmak üzere uygun kaplara alınarak deney düzeneğine yerleştirilmiştir. Tüm örnekler, aynı ortam sıcaklığı ve nem koşullarında tutulmuştur. Manyetik alan uygulaması sırasında çevresel faktörlerin sabit tutulmasına özen gösterilmiştir.



Resim 5. Manyetik alan uygulamasında kullanılan güç kaynağı

Deneyin mesafeye bağlı olarak yapılmasının sebebi, manyetik alan şiddetinin uzaklığa göre değişmesidir. Bu nedenle, aynı şartları sağlayan farklı uzaklıklara numuneler yerleştirilmiş ve manyetik alandaki değişimin deney materyalleri üzerindeki etkileri izlenmiştir.

Manyetik alanın etkisini değerlendirmek üzere numuneler; manyetik alanın merkezi (0 cm) ve bu merkeze uzaklıkları 10, 20, 40 cm olan mesafelerde konumlandırılmıştır. 0, 10, 20, 40 cm de bulunan deney materyallerinin magnetik alan değerleri sırasıyla 2.61 mT, 2.50 mT, 2.13 mT ve 1.12 mT olduğu hesaplanarak belirlendi (Tablo 1). Her örnek, 0-3 amper doğru akım ile oluşturulan aynı ortamda

manyetik alan koşullarına 4 saat maruz bırakılmıştır. Bu sürede, *Streptococcus thermophilus-Lactobacillus bulgaricus* bakterilerinin yoğunluğunda magnetik alanın etkisi ile herhangi bir değişiklik gösterip göstermediği incelenmiştir.

Deney sonunda, yukarıda belirtilen işlemlerden geçen numunelerin yoğunlukları analiz edilmiştir. Her bir numuneden örnek alınarak mikroskopta (Zeiss, Oberkochen, Almanya) 40 ve 100' lük oküler yardımı ile analizleri yapılarak maya bakterilerinin yoğunluğu tespit edildi. Elde edilen veriler istatistiksel olarak analiz edilerek, manyetik alanın *Streptococcus thermophilus-Lactobacillus bulgaricus* bakterilerinin çoğalmasına ne derece etki ettiği değerlendirilmiştir.

Çalışmamızda bakterilere etkiyen manyetik alanın, bakterilerin soğurma spektrumuna etkisi çalışılmıştır. Bu etkileri üniversitemiz bünyesinde bulunan Hach Lange UV DR 5000 cihazıyla incelenmiştir.

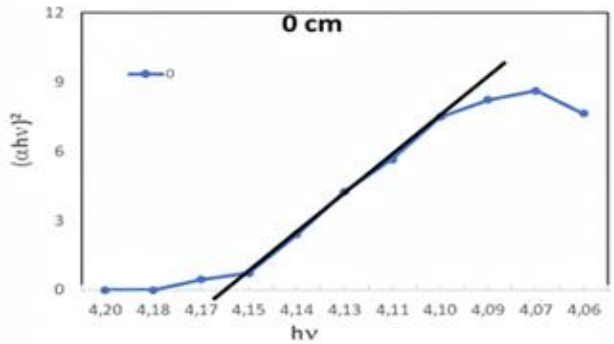
Cihaz ile kaydedilen 200-800 nm arası dalga boyları için soğurma spektrumları kullanarak numunelerin optik yasak bant aralıkları hesaplandı. Hesaplamalar için:

$$\alpha h\nu = A(h\nu - Eg)n \qquad (2)$$

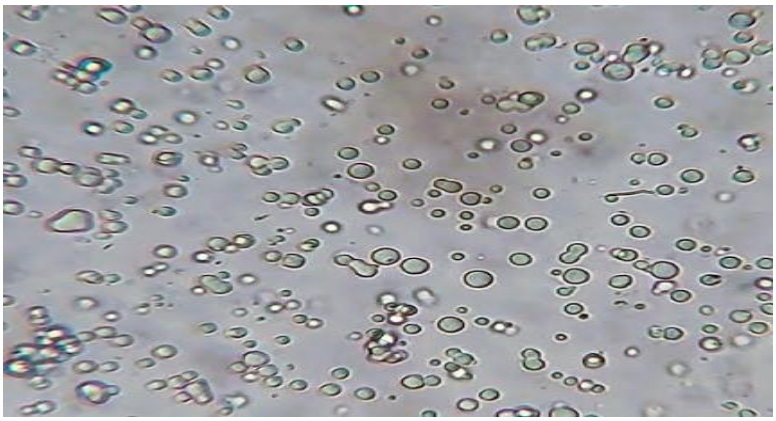
Eşitliği kullanıldı. Burada α soğurma katsayısı, A malzemeye özgü bir katsayı, h Planck sabiti ve ν ışığın frekansıdır. İfadede yer alan n sayısı indirekt yarıiletkenler için 2, direkt yarıiletkenler için ise ½ olarak alınır. Ayrıca denklem 2'den yola çıkarak, Tauc eğrileri çizildikten sonra eğrinin ön kısmının lineer ekstrapolasyonunun enerji eksenini sıfırda kesen noktası yardımıyla yasak bant aralıkları hesaplanmıştır.

BULGULAR

Manyetik alan merkezine uzaklığı 0 cm olan numunenin manyetik alan değeri Şekil1'de görülmektedir. Bu grafiğe göre manyetik alanın merkezinde olan numunenin manyetik alandan en fazla etkilendiği görülmektedir. Manyetik alan merkezinde olan mayalanmış sütün mikroskop görüntüsü Resim 6'da verilmiştir. Manyetik alanın en yoğun olduğu bölgede bulunan bakterilerin mikroskop görüntüleri incelendiğinde hiçbir bakterinin olmadığı görüntülenmektedir. Bu durum da manyetik alana maruz kalan bakterilerin üremediğini kanıtlar niteliktedir.

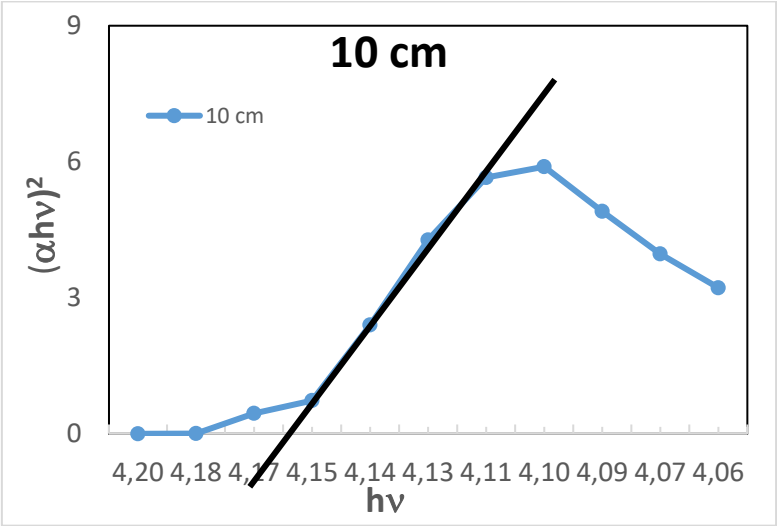


Şekil 1. Manyetik alana merkezinde (max manyetik alan) olan numunenin manyetik alan etkisinde Tauc eğrisi.



Resim 6. maksimum manyetik alanda 0 cm mikroskop görüntüsü.

Manyetik alan merkezine uzaklığı 10 cm olan numunenin manyetik alan değeri Şekil 2'de görülmektedir. Bu grafiğe göre manyetik alanın merkezine 10 cm uzakta olan numune, manyetik alandan 0 cm mesafesinden sonra en fazla etkilendiği görülmektedir.



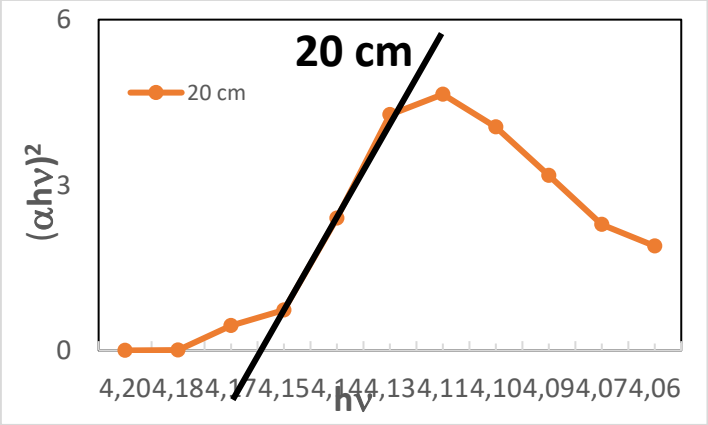
Şekil 2. Manyetik alana 10 cm uzaklıkta olan numunenin manyetik alan etkisinde Tauc eğrisi.

Manyetik alan merkezine 10 cm uzaklıkta olan numunenin mikroskop görüntüsü Resim 7'de verilmiştir. Bu görüntüye göre manyetik alan merkezinde olan görüntünün aksine az da olsa bakteri olduğu görüntülenmektedir.

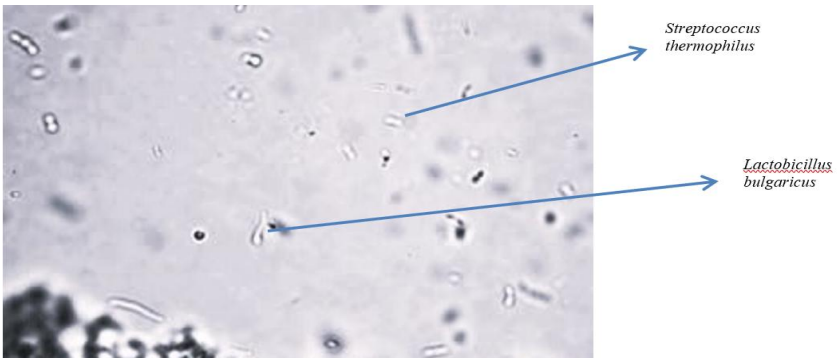
Resim 7. Manyetik alana 10 cm uzaklıkta olan numunenin 10 cm mikroskop görüntüsü.

Manyetik alan merkezine uzaklığı 20 cm olan numunenin manyetik alan değeri Şekil3'te görülmektedir. Manyetik alan merkezine 20 cm uzaklıkta olan numunenin mikroskop görüntüsü Resim 8'de verilmiştir. Manyetik alanın yoğun olduğu bölgeden uzaklaştıkça mikroskopta görebildiğimiz bakteri sayısında artış vardır. Manyetik alan merkezine uzaklığı 40 cm olan numunenin manyetik alan değeri Şekil 4'te incelenmiştir. Manyetik alan merkezine 40 cm uzaklıkta olan numunenin mikroskop görüntüsü ise Resim 9'da verilmiştir. Manyetik alana en az derecede maruz kalan numunenin mikroskop görüntüsüne göre en fazla bakterinin olduğunu burada görmekteyiz. Manyetik alan merkezine uzaklığı max olan numunenin manyetik alan değeri bu Şekil 5'te sunulmuştur. Bu grafiğe göre manyetik alanın merkezine max uzakta olan mayalanmış sütün manyetik alandan 40 cm mesafesinden sonra en fazla etkilendiği görülmektedir. Manyetik alan merkezine max uzaklıkta olan numunenin mikroskop görüntüsü Resim 10'da görülmektedir. Resimde de görüldüğü üzere manyetik alana maruz kalmayan kontrol grubumuzun mikroskop görüntüsünde yoğun olarak bakteri varlığı dikkat çekmektedir. Buna göre manyetik alana

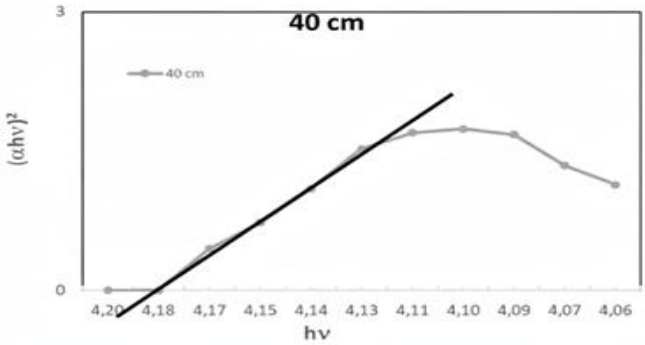
maruz kalan numunelerdeki bakterilerin çoğalmak yerine yaşamsal faaliyetlerini sürdürebilmeleri ön planda olduğu düşünülmüştür.



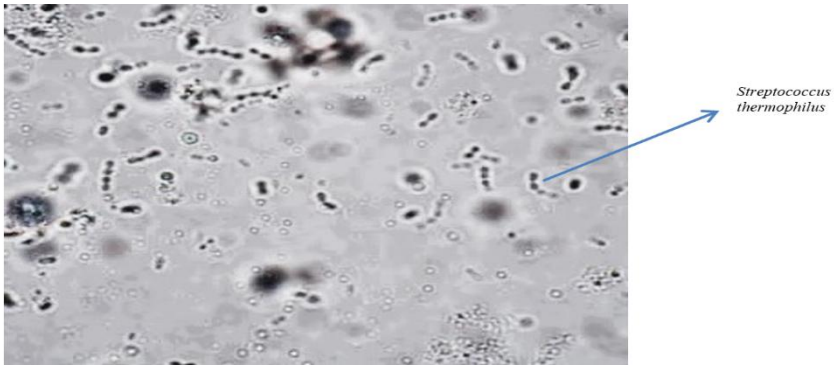
Şekil 3. Manyetik alana 20 cm uzaklıkta olan numunenin manyetik alan etkisinde Tauc eğrisi.



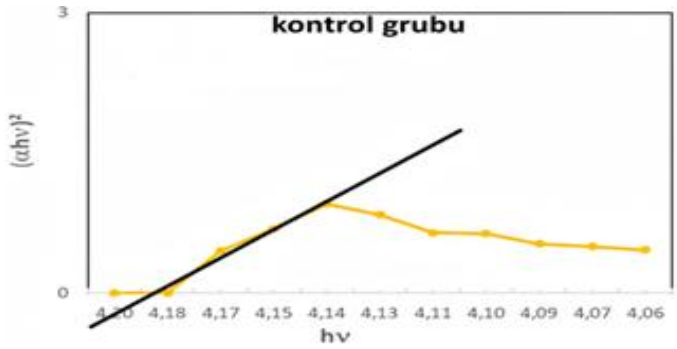
Resim 8. Manyetik alana 20 cm uzaklıkta olan numunenin mikroskop görüntüsü.



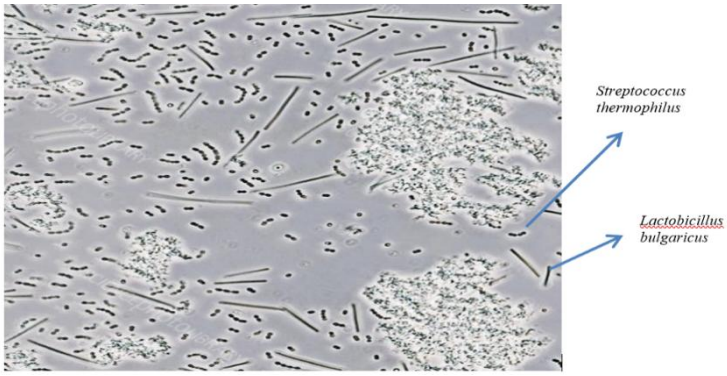
Şekil 4. Manyetik alana 40 cm uzaklıkta olan numunenin manyetik alan etkisinde Tauc eğrisi.



Resim 9. Manyetik alana 40 cm uzaklıkta olan numunenin mikroskop görüntüsü.

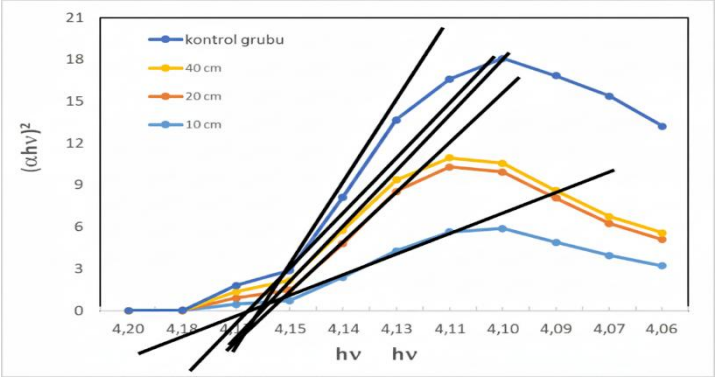


Şekil 5. Manyetik alana max (kontrol grubu) uzaklıkta olan numunenin manyetik alan etkisinde Tauc eğrisi.



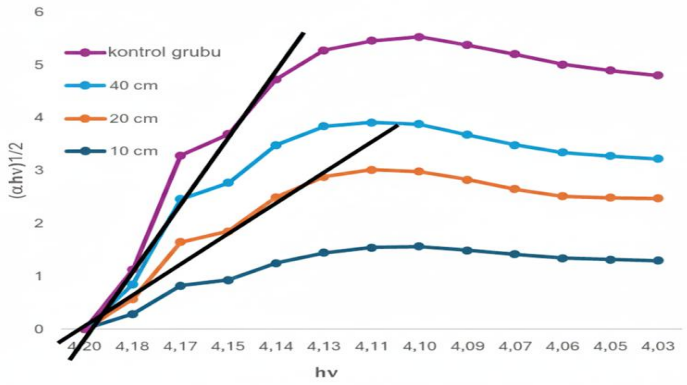
Resim 10. Max (kontrol grubu) mikroskop görüntüsü.

Şekil 6 ve Şekil 7'de farklı uzaklıklardaki örnekler için çizilen Tauc grafikleri yer almaktadır. Grafikler aracılığıyla incelendiğinde, direk ve indirek geçişlerde Eg değerlerinin 4 ile 4.20 eV civarında değiştiği görülmektedir.



Şekil 6. Numunelerdeki maya bakterilerinin direk geçişler için toplu Tauc eğrileri.

Bu sonuçlar, örnekler manyetik alan kaynağından uzaklaştıkça bant aralığı değerinin azaldığını göstermektedir. Özellikle max (kontrol grubu) uzaklıkta, manyetik alanın en az etkisi altındaki örnekte en yüksek bant aralığı değeri gözlenmiştir. Bu durum, uygulanan manyetik alanın malzemenin elektronik yapısını etkileyerek bant aralığında genişlemeye neden olduğunu düşündürmektedir.
Manyetik alan etkisiyle bant aralığındaki bu artış, malzemenin enerji seviyeleri arasındaki geçişlerde foton soğurma özelliğinin değişmesine neden olabilir. Bu bulgu, manyetik alanın optoelektronik özellikler üzerinde potansiyel bir kontrol mekanizması olarak kullanılabileceğini göstermektedir.



Şekil 7. Maya bakterilerinin manyetik alana maruz kalma durumunda dolaylı geçişler için Tauc eğrileri.

SONUÇ ve TARTIŞMA

Bu çalışmada, Helmholtz bobinleri ile oluşturulan düzgün doğrultulu bir manyetik alan altında farklı uzaklıklarda (0, 10, 20, 40 ve max cm) bulunan numunelerin üzerinde maya bakterilerinin optik yanıtları araştırılmıştır. Optik karakterizasyon, hem $(\alpha h\nu)^2$ hem de $(\alpha h\nu)^{1/2}$ formatında Tauc grafikleri kullanılarak değerlendirilmiştir. Bu iki analiz yöntemi doğrudan ve dolaylı optik geçişlerin enerji band aralıklarını (band gap) ortaya koymaktadır. Elde edilen bulgular, manyetik alanın maya bakterileri üzerindeki biyolojik etkilerinin optik yöntemlerle başarılı bir şekilde izlenebileceğini göstermektedir.

Manyetik alanın biyolojik sistemler üzerindeki etkisi, son yıllarda mikrobiyal metabolizma, hücre zar yapısı ve gen ekspresyonu düzeyinde yapılan çalışmalarla açıklanmaya başlanmıştır. Literatürde, manyetik alanların hücre içi iyon kanallarını ve metabolik düzenleyici enzimlerin aktivitelerini etkileyerek mikrobiyal gelişimi yönlendirdiği bildirilmektedir (Blank ve Goodman, 2009; Fadel vd., 2017). Bu bağlamda, 10 cm'de gözlenen yüksek band gap değerleri, manyetik alanın hücre içi yapıların foton absorpsiyon karakteristiklerini değiştirdiğini göstermektedir.

Özellikle 10 cm mesafesinde, $(\alpha h\nu)^2$ grafiğinde görülen yüksek pik değeri ve daha dik eğimli bant aralığı, hücrelerde artan optik yoğunluğa ve muhtemelen enerjiye bağımlı biyomoleküllerin üretiminde bir artışa işaret etmektedir. Bu durum, maya hücrelerinde artmış mitokondriyal aktivite, pigment (örneğin ubikinon) veya NADH gibi absorban moleküllerin yoğunluk kazanması ile açıklanabilir (Patel vd., 2015). Bu bulgular aynı zamanda manyetik alanın gen ekspresyonunu epigenetik düzeyde etkileyebileceği düşüncesini de desteklemektedir (Baureus Koch vd., 2003).

Diğer taraftan, $(\alpha h\nu)^{1/2}$ grafiğinde de benzer bir eğilim izlenmektedir. Bu grafik formatı, dolaylı optik geçişlerin karakterizasyonuna olanak tanıdığından, biyolojik sistemlerdeki kompleks yapıdaki moleküllerin (örneğin enzimler, taşıyıcı proteinler, hücre duvarı bileşenleri) analizinde anlamlıdır. 10 cm örneğinde en yüksek değerlerin gözlenmesi, manyetik alan etkisinin sadece genel hücre canlılığına değil, aynı zamanda protein sentezi veya enzimatik aktiviteye bağlı dolaylı optik geçişleri de artırdığına işaret etmektedir.

Manyetik alanın etkisi ile artan optik cevap, uzaklık arttıkça düzenli bir biçimde azalmaktadır. 0, 10 ve 20 cm örneklerinde manyetik alanın etkisi kademeli olarak azalmakta, 40 cm'de ise neredeyse kontrol grubuna yakın bir optik tepki düzeyine ulaşılmaktadır. Bu durum, manyetik alanın biyolojik etkinliğinin fiziksel mesafeyle doğru orantılı olarak azaldığını göstermektedir (Del Re vd., 2004). Bununla birlikte, 10 cm mesafesinde gözlenen düşük optik yanıt, manyetik alanın hücre içi düzeni bozacak ölçüde etkili olmadığı ama hücre aktivitesini artırmak için yetersiz kaldığı bir sınır nokta olarak değerlendirilebilir.

Azam vd., (2012), Saccharomyces cerevisiae türü maya hücrelerini 1 mT'lik alternatif manyetik alana maruz bırakmış ve hücre büyümesinde anlamlı bir artış tespit etmiştir. Özellikle hücre çoğalmasında hızlanma ve fermantasyon ürünlerinde artış gözlenmiştir. Her iki çalışmada da manyetik alanın mikrobiyal çoğalma üzerinde uyarıcı bir etkisi olduğu görülmektedir. Ancak Azam vd., (2012), çalışmasında alternatif alan kullanılırken, bu çalışmada doğru akım temelli düzenli bir alan uygulanmıştır. Yine de temel biyolojik mekanizma, iyon kanal aktivitesi ve enerji metabolizmasının uyarılması ile açıklanabilir.

Raval vd., (2018), fotosentetik bakteri Rhodobacter sphaeroides üzerinde yaptığı çalışmada, manyetik alan uygulamasının fotosentetik pigment (bakteriyoklorofil) üretimini artırdığını ve bu durumun UV-Vis spektrumda daha yüksek absorpsiyonla kendini gösterdiğini raporlamıştır. Bu projede optik yoğunluk artışı, benzer şekilde biyolojik pigmentlerin üretiminin artmasıyla açıklanabilir. Her iki çalışmada da manyetik alan, hücre içi ışığı absorbe eden bileşiklerin yoğunluğunu artırmıştır.

Baureus Koch vd., (2003), farklı frekans ve manyetik alan yoğunluklarında memeli hücreler üzerinde yaptığı çalışmalarda, etkilerin yalnızca belirli alan şiddeti ve mesafe düzeylerinde anlamlı hale geldiğini, belirli bir eşik altındaki alanların ise etkisiz kaldığını bildirmiştir. Bu çalışmanın bulguları da yaptığımız çalışma ile örtüşmektedir: manyetik alan etkisi yalnızca belirli bir şiddet ve mesafede anlamlıdır. Bu durum "biyolojik eşik etkisi" kavramını desteklemektedir.

Fadel vd., (2017), laktik asit bakterilerinde manyetik alan uygulamasının fermantasyon süresini kısalttığını, ürün verimini ise artırdığını belirtmiştir. Elektromanyetik stimülasyon, hücre içi enerji metabolizmasını hızlandırarak bu etkiyi oluşturmuştur. Bu projede, manyetik alanın sadece laktik asit bakterileri değil, maya grubu mikroorganizmalar üzerinde de benzer bir etki oluşturduğunu ortaya koymaktadır. Ayrıca optik analiz yoluyla bu etkiyi nicel olarak değerlendirme avantajı sağlanmıştır.

Bu bulgular, elektromanyetik biyoeşik etkilerle ilgili literatürdeki bazı bulgularla da örtüşmektedir. Belli bir şiddetin altındaki manyetik alanların hücreleri uyaramadığı, ancak belli bir eşik şiddetini aştığında biyolojik süreçlerde anlamlı değişiklikler oluşturduğu bilinmektedir (Liboff, 2004). Helmholtz bobinlerinin ürettiği düzenli alan, bu eşik düzeylerin belirlenmesi ve sistematik test edilmesi açısından oldukça elverişlidir.

Sonuç olarak, bu çalışma maya bakterilerinin manyetik alana verdiği optik yanıtı band gap analizi ile değerlendirerek elektromanyetik biyoeşiklerin hem doğrudan hem dolaylı optik geçişler üzerindeki etkisini göstermektedir. Bu yaklaşım, biyo-optik ölçümler yoluyla mikrobiyal yaşam süreçlerinin değerlendirilmesine yeni bir bakış açısı sunabilir. Ayrıca fermentasyon, biyoteknoloji ve manyetik alan temelli biyolojik yönlendirme gibi alanlarda ileri düzeyde araştırmalar için temel teşkil edebilir.

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ON CONVERGENCE VIA δ -OPEN SETS IN IDEAL TOPOLOGICAL SPACES

İDEAL TOPOLOJİK UZAYLARDA δ -AÇIK KÜMELER YARDIMIYLA YAKINSAKLIK

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ÖZET

Topolojik uzaylarda açık küme kavramının çeşitli genelleştirmeleri, yakınsaklık ve süreklilik teorisinin daha geniş bir çerçevede incelenmesine olanak sağlamaktadır. Bu genelleştirmelerden biri olan δ-açık kümeler, Velicko tarafından 1968 yılında tanımlanmıştır. Bir topolojik uzayın (X,τ) bir A alt kümesi , $A = int(cl(A))$ şartını sağlıyorsa düzenli açık küme olarak adlandırılır. Her $x \in A$ için $x \in G \subset A$ olacak şekilde bir düzenli açık G kümesi bulunuyorsa, A kümesine δ-açık küme denir.

Boş olmayan bir X kümesi üzerinde tanımlanan ve kalıtımsallık ile sonlu birleşim altında kapalılık özelliklerini sağlayan I ailesine ideal denir (Kuratowski,1966). Bu durumda (X,τ,I) üçlüsü bir ideal topolojik uzay meydana getirir. δ-açık kümeler ideal topolojik uzaylara taşınmış ve ideal yapının etkisiyle yeni açık küme sınıfları elde edilmiştir (Hayashi,1964; Jankovic ve Hamlett,1990). Böylece klasik topolojideki birçok kavramın ideal topolojik uzaylar çerçevesinde yeniden incelenmesi mümkün hâle gelmiştir.

Bu çalışmada ideal topolojik uzaylarda tanımlanan δ-açık küme türleri temel alınarak farklı yakınsaklık kavramlarının geliştirilmesi amaçlanmaktadır. Özellikle dizilerin bu yeni açık küme sınıfları bakımından yakınsaklığı incelenecek, elde edilen yakınsaklık türlerinin klasik yakınsaklık ile ilişkileri araştırılacaktır. Ayrıca bu yaklaşımlar çerçevesinde dizisel açık küme kavramı yeniden ele alınacaktır.

Anahtar Kelimeler: İdeal topolojik uzay, δ-açık küme, yakınsaklık, dizisel açık küme.

ABSTRACT

Various generalizations of the notion of open sets in topological spaces allow the theories of convergence and continuity to be studied within a broader framework. One of these generalizations is the concept of δ-open sets, introduced by Velicko in 1968. A subset A of a topological space (X,τ) is called a regular open set if it satisfies the condition $A = int(cl(A))$. If, for every $x \in A$, there exists a regular open set G such that $x \in G \subset A$, then A is called a δ-open set.

An ideal on a nonempty set X is a family I satisfying the hereditary property and closure under finite unions (Kuratowski, 1966). In this case, the triple (X,τ,I) forms an ideal topological space. The notion of δ-open sets has been extended to ideal topological spaces, and new classes of open sets have been obtained through the influence of the ideal structure (Hayashi, 1964; Jankovic and Hamlett, 1990). Consequently, many concepts of classical topology can be reconsidered within the framework of ideal topological spaces.

In this study, it is aimed to develop different notions of convergence based on the classes of δ-open sets defined in ideal topological spaces. In particular, the convergence of sequences with respect to these new classes of open sets will be investigated, and the relationships between the resulting convergence notions and classical convergence will be examined. Furthermore, within this framework, the concept of sequentially open sets will be reconsidered.

Keywords: Ideal topological space, δ-open set, convergence, sequentially open set.

GİRİŞ

Genelleştirilmiş açık kümelerin gelişiminde önemli bir çalışma (Veličko, 1968) tarafından tanımlanan δ-açık kümelerin tanımlanmasıdır. Düzenli açık kümelerden yararlanılarak geliştirilen bu yaklaşım,

klasik açıklık kavramına yeni bir bakış açısı kazandırmış ve özellikle δ-kapanış operatörüne dayalı birçok yeni topolojik yapının ortaya çıkmasına zemin hazırlamıştır. Daha sonraki yıllarda δ-pre-açık, δ-semi-açık ve δ-β-açık kümeler gibi farklı küme sınıfları tanımlanarak bu yaklaşım daha da geliştirilmiştir. Böylece klasik topolojide kullanılan birçok kavram, δ-işlemi yardımıyla yeniden yorumlanabilmiştir. İdeal kavramının tanımlanmasıyla birlikte (Kuratowski, 1699; Janković, D., ve Hamlett, 1992), bu kavramlar ideal topolojik uzaylara aktarılmıştır Yüksel ve ark.,2005; Özcan ve Akız, 2025).

Bu çalışmada, ideal topolojik uzaylarda δ-pre-açık kümeler yardımıyla yeni bir yakınsaklık kavramı olan δ-pre-I-yakınsaklık tanımlanmıştır. Bu yakınsaklıktan hareketle δ-pre-I-dizisel açık ve δ-pre-I-dizisel kapalı kümeler incelenmiş, bu kümelerin temel özellikleri araştırılmış ve δ-pre-I-dizisel uzay kavramı ortaya konulmuştur. Ayrıca δ-pre-I-yakınsaklığın tekliği için uygun ayrılma aksiyomu tanımlanmış ve bu uzaylarda yakınsak dizilerin limitlerinin tek olduğu gösterilmiştir. Bunun yanında, δ-pre$-(I,J)-$irresolute fonksiyonlar tanımlanarak bu fonksiyonların δ-pre-I-yakınsaklığı koruduğu ispatlanmış, δ-pre-I-dizisel uzaylarda ise bunun tersinin de geçerli olduğu gösterilmiştir. Böylece δ-pre-açık kümeler ile ideal topolojik uzayların birlikte ele alındığı yeni bir dizisel yakınsaklık teorisi geliştirilmiş ve bu teoriye ilişkin temel karakterizasyonlar elde edilmiştir.

2. ÖN BİLGİLER

Tanım 2.1 (X,τ)bir topolojik uzay ve $A \subseteq X$olsun.

a) Eğer $A = int(cl(A))$ ise Akümesine düzenli açık küme,

b) Eğer $A = cl(int(A))$ise düzenli kapalı küme adı verilir.

Her $x \in A$noktası için $x \in G \subseteq A$ olacak biçimde düzenli açık bir G kümesi bulunuyorsa, Akümesine δ-açık küme denir.

Ayrıca $x \in X$noktası, kendisini içeren her açık V kümesi için $int(cl(V)) \cap A \neq \emptyset$ ise, A'nın bir δ-küme noktası olarak adlandırılır. A'nın bütün δ-küme noktalarının oluşturduğu kümeye A'nın δ-kapanışı denir ve $\delta cl(A)$ ile gösterilir (Veličko, 1968).

Önerme 2.2 (X,τ) bir topolojik uzay ve $U,V \subseteq X$olsun. Bu durumda aşağıdaki özellikler sağlanır.

a)$cl(U) \subseteq \delta cl(U))$

b)$U \subseteq V \Rightarrow \delta cl(U)) \subseteq \delta cl(V))$

c)$\delta cl(U \cap V) \subseteq \delta cl(U) \cap \delta cl(V)$

d)$\delta cl(U \cup V) = \delta cl(U) \cup \delta cl(V)$(Veličko, 1968)

Tanım 2.3 (X,τ) bir topolojik uzay ve $A \subseteq X$olsun. Eğer

$A \subseteq int(\delta cl(A))$

ise A kümesine δ-pre-açık küme denir (Raychaudhuri ve Mukherjee, 1993).

Tanım 2.4 (X,τ) bir topolojik uzay ve $A \subseteq X$olsun. Eğer

$A \subseteq cl(int(\delta cl(A)))$

ise A kümesine δ-β-açık küme denir (Hatır ve Noiri, 2009).

Tanım 2.5 Bir topolojik uzayın (X,τ) alt kümesi Aiçin

$A \subseteq cl(\delta int(A))$

oluyorsa, Akümesine δ-semi-açık küme denir (Hatır ve Noiri, 2009).

Tanım 2.6 (X,τ) bir topolojik uzay ve $A \subseteq X$ olsun. Eğer X'te öyle bir δ-açık U kümesi için $U \subseteq A \subseteq cl^*(U)$ ise, bu durumda A kümesine δ^*-semi-açık küme adı verilir (Hatır ve Noiri, 2009).

Tanım 2.7. (Vaidyanathaswamy, 1945) (X,τ) bir topolojik uzay olsun. $I \subseteq P(X)$ ailesi aşağıdaki koşulları sağlıyorsa, I'ya ideal denir:

1. Eğer $G \in I$ ve $H \subseteq G$ ise, $H \in I$.
2. Eğer $G, H \in I$ ise, $G \cup H \in I$.

Bu durumda (X,τ,I) üçlüsüne ideal topolojik uzay denir.

Tanım 2.8. (Vaidyanathaswamy, 1945) (X,τ,I) bir ideal topolojik uzay ve $P(X)$, X'in kuvvet kümesi olsun. $A \subseteq X$ için

$$A^*(I,\tau) = \{x \in X : U \cap A \notin I, \text{her } x\text{'i içeren komşuluk } U \text{ için}\}$$

kümesine, A'nın τ topolojisi ve I ideali bakımından lokal fonksiyonu denir.

Kısaca bu küme A^* ile gösterilir. A^* içerisinde bulunan tüm açık kümelerin birleşimine A^*'nın içi denir ve $int(A^*)$ ile gösterilir.

Tanım 2.9. (Janković ve Hamlett, 1992) (X,τ,I) bir ideal topolojik uzay ve $A \subseteq X$ olsun. Eğer $A \subseteq int(A^*)$ ise, A kümesine *I*-açık küme denir.

Teorem 2.10. (Kuratowski, 1966) (X,τ,I) bir ideal topolojik uzay ve $A \subseteq X$ olsun. Her açık U kümesi için $A^* \cap U = (A \cap U)^* \cap U \subseteq (A \cap U)^*$ dir.

Örnek 2.10 $X = \{p,r,s\}$ olsun ve $\tau = \{\emptyset, \{p\}, \{p,r\}, X\}$ topolojisini ele alalım. Bu uzaydaki kümeleri aşağıdaki şekilde gösterebiliriz.

Küme	Düzenli Açık	δ-Açık	δ-Pre	δ-Semi	δ-β	δ*-Semi
∅	✓	✓	✓	✓	✓	✓
{p}			✓		✓	
{r}			✓		✓	
{s}			✓		✓	
{p,r}			✓		✓	
{p,s}			✓		✓	
{r,s}			✓		✓	
X	✓	✓	✓	✓	✓	✓

3. İDEAL TOPOLOJİK UZAYLARDA BAZI KÜME ÇEŞİTLERİ

Tanım 3.1 (X,τ,I) bir ideal topolojik uzay ve $A \subseteq X$ olsun. Eğer $A \subseteq int(A^*)$ ise A kümesine I-açık küme denir. I-açık kümelerin ailesi

$$IO(X,\tau) = \{A \subseteq X : A \subseteq int(A^*)\}$$

ile gösterilir. (Janković ve Hamlet, 1992).

Örnek 3.2 $X = \{p,r,s,t\}$, $\tau = \{X, \emptyset, \{s\}, \{p,r\}, \{p,r,s\}\}$ ve $I = \{\emptyset, \{p\}\}$ olsun. Bu durumda $\{r,s,t\} \in IO$

olmasına rağmen, $\{r,s,t\} \notin \tau$ olmaktadır.

Örnek 3.3 $X = \{p, r, s, t\}, \tau = \{X, \emptyset, \{t\}, \{p, s\}, \{p, s, t\}\}$ ve $I = \{\emptyset, \{s\}, \{t\}, \{s, t\}\}$olsun. Bu durumda $\{p, s, t\} \in \tau$ iken,$\{p, s, t\} \notin IO$ olmaktadır.

I-açık kümelerin tanımlanmasıyla birlikte δ-I-açık kümeler aşağıdaki biçimde tanımlanır.

Tanım 3.4 (X, τ, I) bir ideal topolojik uzay, $A \subseteq X$ve $x \in X$ olsun.

1. Eğer x'in her regular I-açık komşuluğu ile A kümesinin kesişimi boş kümeden farklı ise, x noktasına A'nın δ-I-kapanış noktası denir.
2. A'nın bütün δ-I-kapanış noktalarının oluşturduğu kümeye A'nın δ-I-kapanışı denir ve $A_{\delta-I}$ile gösterilir.
3. Eğer $A = A_{\delta-I}$ ise A kümesine δ-I-kapalı küme denir. δ-I-kapalı bir kümenin tümleyeni ise δ-I-açık küme olarak adlandırılır (Yüksel ve ark., 2005).

4. TEMEL SONUÇLAR

Bu bölümde, ideal topolojik uzaylardaki yeni yakınsaklık kavramları verilecektir. Bu bölüm boyunca (X, τ) ve (Y, σ) topolojik uzaylar, I ve J ise $\mathbb{N}$ üzerinde tanımlı admissible idealler olarak alınacaktır.

Tanım 4.1. $f : (X, \tau) \to (Y, \sigma)$ bir fonksiyon olsun. Y'deki her δ-pre-açık V kümesi için $f^{-1}(V)$ kümesi X'te δ-pre-I-açık ise, f fonksiyonuna δ-pre-I-sürekli fonksiyon denir.

Tanım 4.2. $f : (X, \tau) \to (Y, \sigma)$ bir fonksiyon olsun. Y'deki her δ-pre-J-açık V kümesi için $f^{-1}(V)$ kümesi X'te δ-pre-I-açık ise, f fonksiyonuna δ-pre$-(I,J)-$irresolute fonksiyon denir.

Tanım 4.3. (X, τ) bir topolojik uzay, A ⊆ X ve x ∈ X olsun. Eğer $x \in B \subseteq A$ olacak şekilde bir δ-pre$-I$-açık B kümesi varsa, A kümesine x'in bir δ-pre-I-komşuluğu denir.

Başka bir ifadeyle, A kümesi x'in bir δ-pre-I-komşuluğudur ancak ve ancak A, x'i içeren bir δ-pre-I-açık kümeyi kapsar.

Tanım 4.4. $(x_n)_n \in \mathbb{N}$, X'te bir dizi ve $x \in X$ olsun. x'in her δ-pre-açık V komşuluğu için $\{n \in \mathbb{N} : x_n \notin V\} \in I$ oluyorsa, (x_n) dizisine x'e δ-pre-I-yakınsaktır denir ve δ-pre-I-$\lim x_n = x$ veya $x_n \to x$ δ-pre-I biçiminde gösterilir.

Başka bir ifadeyle, bir dizinin x'e δ-pre-I-yakınsak olması, x'in her δ-pre-açık komşuluğunun dışında kalan terimlerin indislerinden oluşan kümenin I idealine ait olması anlamına gelir.

Teorem 4.5. Her δ-pre-I-yakınsak dizi aynı zamanda δ-I-yakınsaktır.

İspat. (x_n) dizisinin x'e δ-pre-I-yakınsak olduğunu kabul edelim. V, x'in herhangi bir δ-açık komşuluğu olsun. Her δ-açık küme aynı zamanda δ-pre-açık olduğundan,

$\{n \in \mathbb{N} : x_n \notin V\} \in I$

olur. Bu da (x_n) dizisinin x e δ-I-yakınsak olduğunu gösterir. Ancak bunun tersi genel olarak doğru değildir.

Örnek 4.6. $X = \{a, b, c\}$ ve $\tau = \{\emptyset, \{a\}, \{a, b\}, X\}$ olsun. $\mathbb{N}$ üzerinde sonlu alt kümeler idealini $I = \{A \subseteq \mathbb{N} : A\ sonludur\}$ şeklinde alalım. Bu topolojik uzayda düzenli açık kümeler yalnızca ∅ ve X olduğundan, δ-açık kümeler de yalnızca ∅ ve X'tir. Buna karşılık boş olmayan her $A \subseteq X$ için $\delta cl(A) = X$ olduğundan, $A \subseteq int(\delta cl(A)) = X$ olur. Dolayısıyla X in bütün alt kümeleri δ-pre-açıktır.

Şimdi $x_n = a, n \in \mathbb{N}$, sabit dizisini ele alalım. b noktasını içeren tek δ-açık küme X olduğundan, $\{n \in \mathbb{N} : x_n \notin X\} = \emptyset \in I$ olur. Bu nedenle (x_n) dizisi b noktasına δ-I-yakınsaktır.

Diğer taraftan $\{b\}$ kümesi, b'yi içeren bir δ-pre-açık komşuluktur. Dizinin hiçbir terimi $\{b\}$ kümesine ait olmadığından, $\{n \in \mathbb{N} : x_n \notin \{b\}\} = \mathbb{N}$ elde edilir. Ayrıca $\mathbb{N} \notin I$ dir. Dolayısıyla (x_n) dizisi b noktasına δ-pre-I-yakınsak değildir.
Böylece bir dizinin δ-I-yakınsak olmasının, δ-pre-I-yakınsak olmasını gerektirmediği görülür.

Tanım 4.7. (X, τ) bir topolojik uzay olsun. Birbirinden farklı her $x, y \in X$ için $x \in U$, $y \in V$ ve $U \cap V = \emptyset$ olacak şekilde δ-pre-I-açık U ve V kümeleri bulunabiliyorsa, X uzayına δ-pre-I-Hausdorff uzayı denir.

Teorem 4.8. δ-pre-I-Hausdorff bir uzayda her δ-pre-I-yakınsak dizinin limiti tektir.
Bu sonuç, δ-pre-I-Hausdorff uzaylarda yakınsaklığın iyi tanımlandığını göstermektedir. Başka bir ifadeyle, bir dizi aynı anda iki farklı noktaya δ-pre-I-yakınsayamaz. Böylece klasik Hausdorff uzaylarda olduğu gibi, δ-pre-I-yakınsak dizilerin limiti de tek olur ve yakınsaklık kavramı belirsizlik içermez.

Tanım 4.9. (X, τ) bir topolojik uzay ve A ⊆ X olsun. Eğer A^c içerisinde bulunan hiçbir dizi A'nın bir noktasına δ-pre-I-yakınsak değilse, A kümesine δ-pre-I-dizisel açık küme denir.
Başka bir ifadeyle, A kümesi δ-pre-I-dizisel açıktır ancak ve ancak A'nın tümleyeninde bulunan her (x_n) dizisi için $x_n \to x$ (δ-pre-I) olması $x \notin A$ dir.

Tanım 4.10. (X, τ) bir topolojik uzay ve $A \subseteq X$ olsun. Eğer A içerisinde bulunan her dizisinin δ-pre-I-limiti yine A nın bir elemanı ise, A kümesine δ-pre-I-dizisel kapalı küme denir. Başka bir ifadeyle, A içinde bulunan her (x_n) dizisi için $x_n \to x$ (δ-pre-I) olduğunda $x \in A$ ise, A kümesi δ-pre-I-dizisel kapalıdır.

Önerme 4.11. Bir $A \subseteq X$ kümesi δ-pre-I-dizisel açık ise ve ancak ise A^c kümesi δ-pre-I-dizisel kapalıdır.

İspat: Önce A'nın δ-pre-I-dizisel açık olduğunu kabul edelim. A^c içerisinde bulunan (x_n) dizisinin x noktasına δ-pre-I-yakınsak olduğunu varsayalım. Eğer $x \in A$ olsaydı, A'nın tümleyeninde bulunan bir dizi A'nın bir noktasına δ-pre-I-yakınsak olurdu. Bu ise A'nın δ-pre-I-dizisel açık olmasıyla çelişir. Dolayısıyla $x \in A^c$ olur. Böylece A^c'nin δ-pre-I-dizisel kapalı olduğu görülür.
Tersine, A^c kümesinin δ-pre-I-dizisel kapalı olduğunu kabul edelim. A^c içerisinde bulunan bir (x_n) dizisinin A'nın bir noktasına δ-pre-I-yakınsak olduğunu varsayalım. A^c δ-pre-I-dizisel kapalı olduğundan dizinin limiti A^c içinde bulunmalıdır. Bu ise limitin A'da olduğu varsayımıyla çelişmektedir. Dolayısıyla böyle bir dizi var olamaz. O hâlde A kümesi δ-pre-I-dizisel açıktır.

Teorem 4.12. Her δ-pre-I-açık küme δ-pre-I-dizisel açıktır.

Tanım 4.13 I ve J, $\mathbb{N}$ üzerinde tanımlı iki ideal, (X, τ) ve (Y, σ) topolojik uzaylar ve $f : (X, \tau) \to (Y, \sigma)$ bir fonksiyon olsun. Eğer X' teki her (x_n) dizisi için $x_n \to x\ (\delta - pre - I)$ iken $f(x_n) \to f(x)$ (δ-pre-J) oluyorsa f fonksiyonuna δ-pre-(I, J)-yakınsaklığı koruyan fonksiyon denir.

Lemma 4.14 Her δ-pre$-(I, J)-$irresolute fonksiyon δ-pre-I-süreklidir.

Teorem 4.15 δ-pre-$(I, J)-$irresolute her fonksiyon δ-pre-$(I, J)-$yakınsaklığı korur.

İspat. $f : (X, \tau) \to (Y, \sigma)$ δ-pre$-(I, J)-$irresolute bir fonksiyon ve (x_n) dizisi x'e δ-pre-I-yakınsak olsun. V, $f(x)$'in herhangi bir δ-pre-J-komşuluğu seçilsin. f'nin δ-pre$-(I, J)-$irresolute olması nedeniyle $f^{-1}(V)$, x'i içeren δ-pre-I-açık bir kümedir. Dizinin δ-pre-I-yakınsaklığından
$\{n \in \mathbb{N} : x_n \notin f^{-1}(V)\} \in I$

elde edilir. Ayrıca $x_n \notin f^{-1}(V) \iff f(x_n) \notin V$ olduğundan
$\{n \in \mathbb{N} : f(x_n) \notin V\} = \{n \in \mathbb{N} : x_n \notin f^{-1}(V)\} \in I$

olur. O hâlde $(f(x_n))$ dizisi $f(x)$'e δ-pre-J-yakınsaktır. Böylece f nin δ-pre-(I,J)-yakınsaklığı koruduğu gösterilmiş olur.

Teorem 4.16 X bir δ-pre-I-dizisel uzay olsun. Bir fonksiyon $f : (X,\tau) \to (Y,\sigma)$ δ-pre$-(I,J)-$ yakınsaklığı koruyorsa, f δ-pre$-(I,J)-$irresolute'dur.
Bu teorem, δ-pre-I-dizisel uzaylarda bir fonksiyonun davranışını belirlemek için yalnızca dizilerin yakınsaklığını incelemenin yeterli olduğunu göstermektedir. Gerçekten de, bir fonksiyon δ-pre $-(I,J)-$yakınsaklığı koruyorsa, ayrıca δ-pre$-(I,J)-$irresolute olma özelliğine de sahiptir. Böylece bu uzaylarda fonksiyonların süreklilik benzeri özellikleri, açık kümeler yerine dizilerin yakınsaklık davranışları kullanılarak da karakterize edilebilmektedir.

3. SONUÇ

Topolojik uzaylarda yeni küme tanımları son zamanlarda oldukça fazla çalışılmaktadır. Böylece topolojik uzaylardaki açık küme kavramından daha geniş bir kavram olan genelleştirilmiş küme tanımları ortaya çıkmaktadır. Topolojik kavramlar, bu kümeler yardımıyla yeniden tanımlanmakta, böylece genelleştirilmiş kümelerin topolojideki özellikleri incelenebilmektedir. İdeal tanımının yapılmasıyla birlikte, ideal topolojik uzay kavramı ortaya çıkmış ve genelleştirilmiş kümelerin, ideal topolojik uzaylarda yeniden incelenmesi söz konusu olmuştur. Açık küme, kapalı küme, iç, kapanış gibi konuların yanı sıra , son zamanlarda süreklilik ve yakınsaklık başlıkları altında bir çok yeni tanım yapılmıştır. Yakınsaklık kavramı, dizisel açık ve dizisel kapalı kümeleri üretir. Topolojik uzaylarda, çarpım uzaylarında, grup yapılarında ve çok işlemli grup yapılarında dizisel açık küme kavramları incelenmiştir. Ayrıca bitopolojik uzaylarda da bu yapılar çalışılmaya devam etmektedir.
Bu çalışmada ideal topolojik uzaylardaki bazı yakınsaklık çeşitleri ve bunların ürettiği kümeler üzerinde durulmuştur. Ayrıca bu yakınsaklık kavramları arasındaki ilişkiler incelenmiştir. Bu yöntem, genelleştirilmiş kümelerin pek çoğu için kullanışlı bir yöntem olup, bu şekilde elde edilen kümeler yardımıyla topolojik kavramlar yeniden incelenebilir.

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INVESTIGATION OF THE EFFECTS OF *MEDICAGO SATIVA* L. METHANOL EXTRACT ON MORTALITY, ACETYLCHOLINESTERASE ACTIVITY AND OXIDATIVE STRESS PARAMETERS IN *GALLERIA MELLONELLA* LARVAE

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ABSTRACT
Biopesticides derived from plants are environmentally safe substitutes for chemical pesticides. This study investigated how the methanol extract of *Medicago sativa* L. (alfalfa) affects the larvae of the wax moth (*Galleria mellonella*) by measuring mortality rate, acetylcholinesterase activity and oxidative stress factors. Larvae were treated with varying concentrations of methanol extract and after 24, 48 and 72 hours of exposure, larvae were collected for biochemical analysis. Larvae that had been treated with methanol extracts had significantly higher mortality rates than control larvae, in a concentration-dependent manner. Treating larvae with methanol extracts produced statistically significant changes in acetylcholinesterase activity following exposure, suggesting that the extracts may have neurotoxic properties. Analysis of oxidative stress indicated that larvae treated with methanol extracts exhibited greater amounts of lipid peroxidation and alterations in the parameters of their antioxidant defense system. Our results indicate that methanol extracts of *Medicago sativa* are likely to exhibit significant biopesticidal activity against *Galleria mellonella* via the induction of oxidative stress and through mechanisms mediated by neurophysiology.
Keywords: *Medicago sativa*, *Galleria mellonella*, methanol extract, biopesticide, AChE, oxidative stress

INTRODUCTION
The number of scientific investigations into the potential of natural products derived from plants as pesticides is increasing dramatically in recent years; especially in terms of alternative sources for pesticides that are environmentally-friendly (Divekar et al., 2023; Okagu et al., 2023).
A large number of reports indicate that the presence of secondary metabolites in plants disrupts the functioning of the biological systems of insects, which can lead to insecticidal effects (Kortbeek et al., 2019; Isman, 2020).
M. sativa L., or alfalfa, is a perennial legume that belongs to the Fabaceae family and has been grown for centuries for use as both an agricultural crop and as a traditional plant because of its many uses. It is used by people throughout the world for many purposes, which include being an important source of feed in the animal nutrition industry. It has also been reported to have a rich phytochemical profile, which includes many flavonoids, phenolics, saponins, and other secondary metabolites. Furthermore, there are numerous reports regarding the nutritional value of *M. sativa* and its potential as a food supplement. In summary, *M. sativa* has been studied in many different ways, with respect to both the traditional and chemical composition of the plant (Savalia & Pandya, 2024).
Due to its diverse biological effects, *M. sativa* is among the plants frequently studied in the field of pharmacology and is currently being evaluated for its potential medicinal properties (Quiñones-Muñoz et al., 2022). It has been reported that *M. sativa* L. contains various secondary metabolites such as

phenolic compounds, flavonoids, and saponins, and that these compounds are associated with biological activity (Pal et al., 2025).

Scientific studies have shown that *M. sativa* L. can exhibit various biological activities such as antioxidant, anti-inflammatory, antidiabetic, antifungal, antibacterial and anticancer (Isman, 2020; Khairy et al., 2025).

The use of model organisms in evaluating the biological effects of plant-derived compounds is considered a common approach. Changes in oxidative stress responses, antioxidant enzyme activities, and lipid peroxidation levels in *G. mellonella* larvae are reported to be used as key indicators in biochemical effect assessments. In this context, examining the effects of plant extracts on this model organism is considered an important approach in biological activity studies (Sümer Ercan et al., 2022).

This study aimed to determine the antioxidant potential of methanol extract of *M. sativa* L., a plant that grows naturally in Turkey and is noteworthy for its phytochemical content, on *G. mellonella* larvae. In this context, an extract was obtained from the above-ground parts of *M. sativa* using methanol, and the effects of the prepared extract on oxidative stress-related parameters and antioxidant defense mechanisms in *G. mellonella* larvae were evaluated.

MATERIALS AND METHODS

Obtaining and Preparing *Medicago sativa* Extract

The *M. sativa* (Fabaceae) plant specimens used in this study were collected in 2022 from their natural habitat in Türkiye. The above-ground parts of the plant material were cleaned and dried according to Davis herbarium methods (Davis, 1972). The dried plant material was ground, and then 15 g of sample was precisely weighed for use in the analyses. 150 mL of methanol was added to the prepared samples, and they were left to incubate in sealed glass jars for two days. At the end of the incubation period, the samples were filtered, and the extract was obtained by evaporating the solvent.

Insect breeding, extract application, and tissue collection

In this study, extracts prepared at different concentrations of 50 mg/mL, 25 mg/mL, and 10 mg/mL were applied to *G. mellonella* larvae. After sterilization of the larvae, the extracts at different concentrations were injected into the larvae via the left hind leg using a microsyringe (Alvandial et al., 2016).

The control group received no treatment, and the injected insect groups were monitored throughout the experiment. Mortality rates were determined at the end of 24, 48, and 72 hours of exposure to the larvae treated with different extract concentrations.

Larvae exposed to different extract concentrations for 72 hours were cooled, and samples from each group were separated into small pieces and transferred to Eppendorf tubes. Then, pH 7.4 homogenization buffer was added to the samples (Büyükgüzel & Kalender, 2009) and centrifuged. The resulting supernatants were evaluated in biochemical analyses.

CAT, SOD, GST, and AChE enzyme activities, as well as MDA levels, were measured in the supernatants using a UV–VIS spectrophotometer. MDA levels were determined according to Ohkawa et al. (1979), SOD activity according to Marklund and Marklund (1974), CAT activity according to Aebi (1984), and GST activity according to Habig et al. (1974) at a wavelength of 340 nm, while AChE activity was determined according to Ellman et al. (1961) at a wavelength of 412 nm.

Data Analysis

The experimental data obtained within the scope of this research were statistically evaluated. ANOVA and Tukey multiple comparison tests were applied to determine differences between groups in the mean of the applications. All statistical analyses were performed using the SPSS statistical software package (SPSS Statistical Program, Version 26.0, SPSS Inc., Chicago, IL, USA). Data are presented as mean ± standard deviation (SD). Statistical significance was considered at $p < 0.05$, while $p < 0.01$ was considered highly statistically significant (Apaydın et al., 2015; Abbott, 1925).

RESULTS

The insecticidal effect of *M. sativa* methanol extract on *G. mellonella* larvae exposed for 24, 48, and 72 hours was evaluated based on mortality data, oxidative stress, and biochemical indicators of neurotoxic damage.

When the insecticidal effect of *M. sativa* methanol extract on *G. mellonella* larvae was analyzed, it was observed that while no mortality rate was observed in the control group at 24 hours, it was low at 48 and 72 hours. In contrast, the mortality rates of larvae exposed to different concentrations of the extract (10 mg/mL, 25 mg/mL, and 50 mg/mL) increased more significantly over time. The highest mortality rate was reached in the high-dose group (50 mg/mL) at 77.8% at 72 hours (Table 1).
The findings indicate that the methanol extract of *M. sativa* has a toxic effect on *G. mellonella* larvae, and this effect is particularly pronounced with high concentrations and prolonged exposure. The mortality rates of larvae exposed to the extract increased both over time and with dose.

Table 1. Effects of Medicago sativa Methanol Extract on Mortality Rates of Galleria mellonella Larvae

Group	**Concentration (mg/mL)**	**n**	**24 h Mortality (%)**	**48 h Mortality (%)**	**72 h Mortality (%)**
Control	0	20	0 ± 0	5,1 ± 1.1	6,2 ± 1.3
Low dose	10	20	9 ± 1.4	19,2 ± 3.1	28,2 ± 3.1
Medium dose	25	20	21,1 ± 3.2	32,2 ± 5.1	55.3 ± 5.6
High dose	50	20	30,4 ± 3.7	58,2 ± 6.0	77,8 ± 4.7

Data are presented as mean ± SD.

When AChE activity in *G. mellonella* larvae was evaluated under different concentrations of *M. sativa* methanol extract and a 72-hour exposure period, it was determined that enzyme activity decreased with increasing extract concentration. There was an observed decrease in AChE activity (compared to the control) in the low-dose group but this was not significant. However, a significant AChE activity decrease (compared to control) was seen following exposure to the medium dose (25 mg/mL) or high dose (50 mg/mL) of the methanol extract of *M. sativa* (Table 2).
These results demonstrate that the methanol extract of *M. sativa* suppressed AChE activity in *G. mellonella* larval model, and that this effect was dose dependent. The significant decreases in AChE activity observed at medium and high doses may indicate that *M. sativa* could be neurotoxic and affect biochemical processes related to the nervous system.

Table 2. Effects of Medicago sativa Methanol Extract on AChE Activity (for 72 h)

Group	**Concentration (mg/mL)**	**AChE Activity (U/mg protein)**
Control	0	8.31 ± 0.3
Low dose	10	7.62 ± 0.19
Medium dose	25	6.12 ± 0.33*
High dose	50	4.71 ± 0.25**

*$p < 0.05$, ** $p < 0.01$ significantly different compared to the control group.

The oxidative stress variables (MDA concentration, the activities of SOD, CAT, and GST) in the larvae of *G. mellonella* exposed to *M. sativa* methanol extract for a period of 72 hours were evaluated. The concentrations depended on the amount given, with a steady rise and trend in MDA levels measured in all treatments except the control. The highest concentration of MDA occurred at the highest dose, and this difference was highly statistically significant from the control. The activities of SOD, CAT and GST antioxidants showed a decreasing trend as the dose increased and were statistically significant when comparing the medium and high-dose groups to the control (Table 3).
The results show that the methanol extract of *M. sativa* increases oxidative stress in *G. mellonella* larvae and suppresses antioxidant defense mechanisms. Specifically, the increase in malondialdehyde (MDA) levels indicates increased lipid peroxidation, while the decrease in SOD, CAT, and GST antioxidant enzyme activities suggests that the extract may have a suppressive effect on the antioxidant system.

Table 3. Oxidative Stress Parameters (for 72 h)

Group	Concentration (mg/mL)	MDA Level (nmol/mg protein)	SOD (U/mg protein)	CAT (U/mg protein)	GST (U/mg protein)
Control	0	1.71 ± 0.13	15.5 ± 0.7	41.7 ± 1.5	7.5 ± 0.6
Low dose	10	2.34 ± 0.14	14.2 ± 0.5	38.2 ± 1.3	6.7 ± 0.4
Medium dose	25	3.12 ± 0.16*	12.1 ± 0.5*	33.6 ± 1.1*	5.4 ± 0.4*
High dose	50	4.77 ± 0.23**	10.3 ± 0.4**	27.2 ± 1.0**	4.2 ± 0.3**

*$p < 0.05$, ** $p < 0.01$ significantly different compared to the control group.

DISCUSSION

One of the most common methods used in combating insect pests is chemical control (Jembere et al., 1995; Baş & Ersoy 2020). However, it has been reported that due to intensive and indiscriminate pesticide use over many years, many pest species have developed resistance to various chemical products (Upadhyay, 2010; Baş & Ersoy 2020). In addition, significant weaknesses are reported as a result of the use of chemical insecticides, such as negative effects on non-target organisms, particularly damage to natural enemies, increased risk of damage to mammals and bloatware, problems with crop breakage, and increased spoilage (Cosimi, 2009; Baş & Ersoy 2020).

In this study, the effects of *M. sativa* methanol extract on *G. mellonella* larvae were evaluated through mortality, acetylcholinesterase (AChE) activity, and oxidative stress parameters. The findings revealed that the extract increased mortality, decreased AChE activity, and caused significant changes in oxidative stress indicators in a dose- and time-dependent manner.

The larval stage of *G. mellonella* (greater wax moth) are very common test organisms for use in studies of toxin and efficacy. The response of the greater wax moth larvae is quick and can produce measurable physiological responses that allow for an accurate assessment of the insecticidal effects of the plant extracts. There are differences in mortality among *G. mellonella* larvae when exposed to either different plant extracts or due to the chemical composition of the extract from the plants (Lalita, Kumar & Yadav, 2018).

Furthermore, it has been reported that plant compounds negatively affect larvae by causing physiological effects such as nutritional suppression, developmental disorders, and oxidative stress. These characteristics make *G. mellonella* an important model organism in the investigation of the toxic effects of plant-derived biologically active compounds (Lalita, Kumar, & Yadav, 2018).

Studies have shown that extracts prepared from different plant tissues, particularly leaves and stems, have a significant effect on larval mortality, and this effect varies depending on the plant species and the part used. Some plant extracts have been reported to achieve high mortality rates; for example, *Plantago psyllium* bark extract has been reported to show the strongest effect with a mortality rate of up to 93.33%. Similarly, species such as *Hordeum sativum, Raphanus sativus, Linum usitatissimum, Cucurbita moschata* and *Vicia sativa* have been reported to cause larval mortality at different rates and to have a statistically significant difference compared to the control group. Overall, it is stated that plant extracts show a high level of biological activity in *G. mellonella* larvae, and this effect varies depending on the plant species and tissue type from which the extract is obtained (Lalita, Kumar, & Yadav, 2018).

M. sativa (alfalfa) is considered one of the important sources of secondary metabolites, both agriculturally and pharmaceutically. The plant's chemical profile is dominated by biologically active secondary metabolites, particularly saponins, flavonoids, and phenolic compounds. These compounds are reported to play a role in the plant's defense mechanisms against environmental stresses and can also exhibit antioxidant, antimicrobial, and toxic effects on various biological systems (Rafińska et al., 2017). Moreover, the authors emphasize that extracts from *M. sativa* have potential as a biological source for agricultural pest control and pharmaceutical applications because there are many secondary metabolites available from this plant, and they suggest that, particularly the methanolic extracts of the plant, may have greater impact on physiological systems than other parts of the plant due to their higher concentrations of biologically active compounds (Rafińska et al., 2017).

A variety of studies conducted to examine oxidative stress in the physiology of insects frequently look at the activity of antioxidant enzymes and levels of MDA, as well as both of these factors serve as major

biochemical markers for exhibiting toxic effects (Büyükgüzel & Kalender, 2007; Büyükgüzel et al., 2010; Aslantürk et al., 2011; Baş & Ersoy, 2020).

The Malondialdehyde (MDA) formed serves a major end product of the oxidative stress from the peroxidation of polyunsaturated fatty acids in toxicological conditions; therefore, MDA serves one of the major biomarkers of lipid peroxidation (LPO) and therefore, MDA is frequently used as a means of measuring an organisms level of oxidative stress (Büyükgüzel et al., 2010; Baş & Kalender, 2016; Baş & Ersoy, 2020).

The role of antioxidant enzymes is crucial to the cellular defense mechanism of an organism by protecting it from the damage caused by reactive oxygen species. The major naturally occurring antioxidant enzymes involved in the protection of cellular homeostasis during oxidative stress are the catalase, glutathione peroxidase, glutathione-S-transferase, and superoxide dismutase antioxidant enzymes (Baş & Kalender, 2011; Messarah et al., 2012; Baş & Ersoy, 2020). The superoxide dismutase antioxidant enzyme is the first in line to protect cells against reactive oxygen species by converting superoxide radicals to hydrogen peroxide and molecular oxygen, while the catalase catalyzes the breakdown of the hydrogen peroxide to form water and molecular oxygen. Additionally, glutathione-S-transferase is an important enzyme in the reduction of oxidative damage via participation in the detoxification of lipid peroxidation products (Büyükgüzel & Kalender, 2009; Baş & Ersoy, 2020).

The observed significant decrease in acetylcholinesterase (AChE) activity indicates that the extract not only causes stress at the metabolic level but can also produce neurotoxic effects on the nervous system. Inhibition of the AChE enzyme leads to the accumulation of acetylcholine in the synaptic cleft, triggering sustained neural transmission and consequently disrupting neuromuscular coordination (Colovic et al., 2013; Baş & Ersoy 2020). Furthermore, it has been reported that plant-derived essential oil components can disrupt neurophysiological regulation by acting on octopaminergic receptors, one of the insect-specific neurotransmitter systems. This suggests that essential oils may exert their effects on insects through multiple neurotoxic mechanisms (Kostyukovsky et al., 2002; Baş & Ersoy 2020). Indeed, several studies have reported that essential oils obtained from different plant species show significant insecticidal activity in species belonging to the orders Lepidoptera and Coleoptera, and that this effect may be related to nerve system-targeted mechanisms (Sümer Ercan et al., 2013; Polatoğlu et al., 2016; Baş & Ersoy 2020).

The increase in MDA levels determined in this study indicates the occurrence of oxidative stress in the experimental groups, and it is thought that this situation may be related to the decrease in enzyme activities involved in the antioxidant defense system. The results obtained in our study, showing an increase in larval mortality with increasing concentration, are consistent with studies reporting that biologically active plant extracts have an effect on insect physiology. When oxidative stress parameters were evaluated, it was determined that MDA levels increased depending on the concentration; however, SOD, CAT, and GST activities decreased. The statistically significant changes observed especially in the 25 and 50 mg/mL groups show that extract application affects the oxidative balance in larval tissues.

CONCLUSION

This study demonstrated that *M. sativa* methanol extract exerted significant and concentration-dependent biological effects on *G. mellonella* larvae. The consistent increase in mortality rates observed throughout the experimental period revealed that the extract had an effect on larval physiology. Furthermore, the results obtained from biochemical analyses showed that the extract application not only increased mortality rates but also affected the physiological balance of the larvae. In particular, the decrease in SOD, CAT, and GST activities, along with the increase in MDA levels, indicated that *M. sativa* methanol extract caused oxidative stress in larval tissues. The suppression of the antioxidant defense system and increased lipid peroxidation support the occurrence of damage at the cellular level. In addition, the determined decrease in AChE activity shows that the extract also affects neural transmission mechanisms. This indicates that the extract can influence not only metabolic processes but also neurophysiological balance. When the findings are evaluated as a whole, it is seen that *M. sativa* methanol extract exerts a multifaceted biological effect on *G. mellonella* larvae through increased mortality, oxidative stress response, and changes in AChE activity. However, detailed identification of the active components responsible for these effects of the extract and support of their mechanisms of action with further biochemical and molecular studies will contribute to a more comprehensive understanding of the plant's biological activity

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EVALUATION OF THE INHIBITORY EFFECTS OF *TRIFOLIUM CAMPESTRE* ON CERTAIN ENZYMES

T*RIFOLIUM CAMPESTRE*'NIN BAZI ENZİMLER ÜZERİNDEKİ İNHİBİTÖR ETKİLERİNİN DEĞERLENDİRİLMESİ

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ABSTRACT
Nowadays, natural enzyme inhibitors derived from medicinal plants have attracted considerable interest due to their potential therapeutic applications in metabolic, neurodegenerative, and dermatological disorders. Trifolium campestre (T. campestre) is a plant that belongs to the Fabaceae family. It is generally known as field clover or hop trefoil. It is an annual plant that is known to possess a rich phytochemical profile. The plant contains various compounds, such as phenolics, flavonoids and isoflavone substances.
In this study, the enzyme inhibitory activities of T. campestre were evaluated. Specific focus was given to the inhibitory effects on α-amylase, α-glucosidase, acetylcholinesterase (AChE), butyrylcholinesterase (BuChE), and tyrosinase enzymes. The obtained data demonstrated that T. campestre exhibits promising enzyme inhibitory potential.
In conclusion, T. campestre has potential activity for antidiabetic, antityrosine and neuroprotective by enzyme inhibition. Because of the bioactive compounds of T. campestre, it is thought to be a promising plant in terms of health.
Keywords: Trifolium, Enzyme inhibition, Antidiabetic, Antityrosinase, Neuroprotective Effects

ÖZET
Günümüzde, tıbbi bitkilerden elde edilen doğal enzim inhibitörleri, metabolik, nörodejeneratif ve dermatolojik bozukluklardaki potansiyel terapötik uygulamaları nedeniyle büyük ilgi görmektedir. *Trifolium campestre* (*T. campestre*), Fabaceae familyasına ait bir bitkidir. Genellikle tarla yoncası veya şerbetçi otu üç yapraklısı olarak bilinir. Zengin bir fitokimyasal profile sahip olduğu bilinen yıllık bir bitkidir. Bitki, fenolikler, flavonoidler ve izoflavon maddeleri gibi çeşitli bileşikler içerir.
Bu çalışmada, *T. campestre*'nin enzim inhibitör aktiviteleri değerlendirilmiştir.
Özellikle α-amilaz, α-glukozidaz, asetilkolinesteraz (AChE), butirilkolinesteraz (BuChE) ve tirozinaz enzimleri üzerindeki inhibitör etkilerine odaklanılmıştır. Elde edilen veriler, *T. campestre*'nin umut vadeden bir enzim inhibitör potansiyeli sergilediğini göstermiştir.
Sonuç olarak, *T. campestre*, enzim inhibisyonu yoluyla antidiyabetik, antitirozin ve nöroprotektif potansiyel aktiviteye sahiptir. *T. campestre*'nin içerdiği biyoaktif bileşikler nedeniyle, sağlık açısından umut vadeden bir bitki olarak kabul edilmektedir.
Anahtar kelimeler: *Trifolium*, enzim inhibisyonu, antidiyabetik, antitirozinaz, nöroprotektif etkiler.

INTRODUCTION
Trifolium L. is known as a genus containing approximately 300 species of the Fabaceae family, encompassing various forage plant species (Renda et al., 2013; Scoppola et al., 2018). It is distributed globally in temperate and subtropical regions (Renda et al., 2013). The genus is found in the

Mediterranean basin, North America, and Central and East Africa (Scoppola et al., 2018). *Trifolium* genus consists of perennial or annual woody, spreading plants, reaching heights of around 50 cm (Figure 1). In Türkiye, there are 118 taxa, including 96 species and 22 subspecies (Kiran et al., 2010). Türkiye holds an important position as one of the breeding areas for *Trifolium spp.* (Scoppola et al., 2018).

Figure 1. Image of Trifolium campestre (Carr, 2010)

Trifolium is among the important plants used in animal feed. In addition, many are known as ornamental plants. By-products obtained from this plant are used in various fields such as oil, dye, gum, and furniture production (Uslu and Babaç, 2019). Furthermore, studies on this plant, which is used in traditional medicine, have shown that it possesses antidiabetic, antioxidant, anti-inflammatory, antiplatelet, anticancer, and anticestodal properties (Kolodziejczyk-Czepas, 2012).

Type 2 diabetes is among the most common diseases today, and the enzymes α-glucosidase and α-amylase are key triggers for the disease in diabetic patients. The primary function of these two enzymes is to break down carbohydrates. The breakdown of carbohydrates causes an increase in blood sugar levels. Therefore, it is believed that inhibiting the activity of α-glucosidase and α-amylase in diabetic patients contributes to slowing down carbohydrate digestion, slowing the release of glucose into the bloodstream, and controlling blood sugar levels (Nyugen et al., 2023).

Gout is among the most common diseases, especially in middle-aged individuals, and a relationship between diabetes and gout has been reported (Pan et al., 2016). The search for bioactive molecules for the treatment of diabetes and gout continues. One of the biochemical mechanisms leading to gout is the activity of the xanthine oxidase (XO) enzyme. XO facilitates the oxidation of hypoxanthine to xanthine, which then converts xanthine purine nucleotides into uric acid. As a result of this reaction, uric acid can accumulate in various tissues, leading to gout (Nguyen et al., 2023).

Alzheimer's disease, a neurodegenerative disorder seen worldwide, is a comprehensive illness involving abnormalities in beta-amyloid protein metabolism, glutamatergic, adrenergic, and dopaminergic neurotransmission. Treatment of this disease utilizes various bioactive molecules, such as acetylcholinesterase (AChE) inhibitors, which increase the availability of acetylcholine (El-Guendouz et al., 2016). Recently, scientists have shown increased interest in butyrylcholinesterase (BuChE), a cholinergic enzyme, for the treatment of Alzheimer's disease. BuChE plays a role in amyloid protein aggression, and its concentration increases in the later stages of Alzheimer's (Gambardella et al., 2025).

Leukotriene biosynthesis is one of the key mechanisms in many diseases such as asthma, ulcerative colitis, Crohn's disease, and arthritis. This synthesis is carried out by 5-lipoxygenases. Inhibition of lipoxygenases is thought to be indicative of antioxidant and anti-inflammatory activities (El-Guendouz et al., 2016). Tyrosinase, a copper-containing monooxygenase, is responsible for skin color formation in mammals and plays a crucial role in melanin biosynthesis, which protects the skin from UV radiation (Nerya et al., 2003; Dong et al., 2014).

In recent years, there has been increasing interest in herbal treatment methods. The fact that plants are natural, inexpensive, and that their synthesized secondary metabolites serve as precursors to synthetic drugs are among the main reasons for this increased interest (Aksoy et al., 2021).

This study investigated the ability of *T. campestre* aqueous extract to inhibit various enzymes such as AChE, BuChE, lipoxygenase, XO, tyrosinase, α-amylase, and α-glucosidase, which can cause common diseases worldwide.

METHOD

Collecting and preparing extract of *T. compastre*

T. compastre was collected from its natural habitat in Türkiye (2022). The plant was cleaned and dried according to the Davis herbarium techniques (Davis, 1972). Dried plant sample was grounded. 100 ml distilled water was added to the ground plant sample and stored in sealed glass jars for 2 days. At the end of incubation, the sample was filtered and the solvent evaporated.

Enzyme Inhibition Assays

Inhibitions of the plant extract against the enzymes AChE, BuChE, lipoxygenase, xanthine oxidase, tyrosinase, α-amylase, and α-glucosidase were measured by UV-Vis spectrophotometric methods. During the measurements, AChE and BuChE were determined using the Ellman method, tyrosinase inhibition using the L-DOPA method, α-amylase using the iodine/KI method, and α-glucosidase using the chromogenic PNPG method. The results were expressed as mg GALAE/g, mg KAE/g, and mmol ACAE/g, respectively (Grochowski et al., 2017). Also, the inhibition of lipoxygenase activity (Yawer et al., 2007) and xanthine oxidase (Dew et al., 2005) were determined.

Statistic Analayzes

The obtained data of experiment was statistically evaluated by SPSS software package (SPSS Statistics Program, Version 20.0, SPSS Inc., Chicago, IL, USA). The data are presented as mean ± standard deviation.

RESULTS

Enzyme inhibition values obtained with the aqueous extract of *T. campastre* are presented in Table 1.

Table 1. Enzyme inhibition results of T. campestre's water extract.

Enzymes	***T. campestre*'s water extract**
Lipoxygenase inhibition %Inh (NDGA: 87)	22,11±1,4
Tyrosinase inhibition (mg KAE/g extract)	27,54±2,32
Xanthine Oxidase inhibition (mg AE /g extract)	8,41±1,05
α-Amylase inhibition (mmol ACAE/g extract)	0,42±0,01
Acetylcholinesterase inhibition (mg GALAE/g extract)	2,71±0,03
Butyrylcholinesterase inhibition (mg GALAE/g extract)	1,53±0,04
α-Glucosidase inhibition (mmol ACAE/g extract)	3,22±0,34

AE: allopurinol equivalent; **GALAE**: galantamine equivalents; **ACAE**: acarbose equivalents; **KAE**: kojic acid equivalents; **NDGA**: Nordihydroguaiaretic acid

DISCUSSION AND CONCLUSION

Scientific studies on *T. campestre* within the *Trifolium* genus are fewer compared to other species (*T. repens L.*, *T. pretense*, etc.). The results obtained place *T. campestre* within the *Trifolium* genus, which, in terms of its water extract, inhibits various enzymes of therapeutic importance. It is thought that the enzyme inhibitions observed in this study are due to the isoflavones present in the phytochemical content of *T. campestre* (Kolodziejczyk-Czepas, 2016). Isoflavones and flavonoids are considered to play an important role in human nutrition (Sabudak and Guler, 2009).

The inhibition of α-amylase and α-glucosidase enzymes by the plant extract leads to a decrease in the rate of glucose absorption from the intestine. This indicates that *T. campestre* has an antidiabetic effect. The inhibition of AChE and BuChE enzymes reflects the neuroprotective property of the extract. In this study, the phytochemical content of *T. campestre* was not defined, but the enzyme inhibition results obtained correlate with flavanones and dihydroflavanols and lipoxygenase inhibition (El-Guendouz et al., 2016). In addition, the high tyrosinase inhibition capacity of the extract causes a decrease in

melatonin biosynthesis. Thus, it means that *T. campestre* can play a role not only as a pharmaceutical active ingredient but also in the cosmetics industry.

The data demonstrated that *T. campestre* exhibit promising enzyme inhibitory potential. Inhibition of α-amylase and α-glucosidase may contribute to the regulation of postprandial blood glucose levels by slowing carbohydrate digestion. Furthermore, the inhibitory property of the tyrosinase enzyme indicates that the extract has high potential in cosmetic and dermatological applications. Extract also showed potential inhibitory effects against cholinesterase enzymes, indicating possible neuroprotective activity. *T. campestre* appears to be a promising natural source of bioactive compounds with potential antidiabetic, antityrosinase, and neuroprotective properties through enzyme inhibition mechanisms. Nevertheless, further biochemical, pharmacological, and phytochemical investigations are required to identify active constituents and clarify the molecular mechanisms underlying these biological activities.

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NİĞDE-ULUKIŞLA HAVZASI NEOJEN İSTİFİNİN GENEL JEOLOJİSİ, STRATİGRAFİSİ VE KATRANDEDETEPE FORMASYONU BİTÜMLÜ ŞEYLLERİNİN HAVZA EVRİMİ AÇISINDAN İNCELENMESİ

INVESTIGATION OF THE NEOGENE SUCCESSION IN THE NIGDE-ULUKISLA BASIN: GENERAL GEOLOGY, STRATIGRAPHY, AND THE EVOLUTION OF BITUMINOUS SHALES WITHIN THE KATRANDEDETEPE FORMATION

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ÖZET
Bu çalışma, Orta Anadolu Tektonik Birliği sınırları içinde yer alan Bor-Ulukışla Neojen Havzası'nın stratigrafik gelişimini, genel jeolojisini ve istif içerisinde kritik bir seviye oluşturan Üst Miyosen–Pliyosen yaşlı Katrandedetepe Formasyonu bitümlü şeyllerinin havza evrimi içerisindeki konumunu incelemektedir. Havza, Erken Tersiyer'den itibaren tektonik olarak aktif bir çarpışma sonrası çöküntü alanı olarak gelişmiş olup, temel kayaç birimleri üzerinde uyumsuzlukla çökelen kalın gölsel ve evaporitik sedimanter serilerle temsil edilmektedir. Bölgenin genel jeolojisi ve litostratigrafi ilişkileri literatürde makro yapısal unsurlarla ele alınmış olsa da, havzanın kalın istifini oluşturan Katrandedetepe Formasyonu'nun dikey ve yanal stratigrafik değişimleri ile sedimantasyon süreçlerinin havza analizi perspektifinden bütüncül bir şekilde değerlendirilmesi büyük önem taşımaktadır. Çalışma kapsamında, havzanın tektono-sedimanter gelişimi ve sedimentasyon dinamikleri, bölgesel stratigrafik korelasyonlar ve saha/kesit verileri üzerinden makro ölçekte değerlendirilmiştir. Katrandedetepe istifinin litofasiyes özellikleri, tabaka geometrileri ve istif içindeki dikey değişimleri değerlendirilmiştir, havzanın kapanma ve kuruma evreleri kronostratigrafik bir değişim sergilemektedir. Havzanın evrim süreci boyunca meydana gelen tektonik yükselimler, iklimsel değişimler ve denizel/karasal beslenme kaynaklarının sediman dağılımına etkileri, bölgenin genel jeolojik unsurları (kuzeydeki Niğde Masifi ve çevre birimler) ile ilişkileri değerlendirilmiştir. Özellikle sodyum sülfat ve halit gibi evaporit parajenezleri sunan bu lakustrin sistemde, bitümlü şeyl ardalanmalarının hangi havza koşullarında oluştuğu ve kalın gölsel serilerin yapısal olarak nasıl konumlandığı tartışılmıştır.
Anahtar Kelimeler: Bor-Ulukışla Havzası, Katrandedetepe Formasyonu, Genel Jeoloji, Stratigrafi, Havza Evrimi, Litofasiyes.

ABSTRACT
This study investigates the stratigraphic evolution, general geology, and the basin-dynamic context of the Upper Miocene–Pliocene Katrandedetepe Formation bituminous shales, which constitute a critical key-level within the Neogene Bor-Ulukışla Basin located along the margins of the Central Anatolian Tectonic Unit.

Developing as a tectonically active post-collisional depression zone since the Early Tertiary, the basin is characterized by thick lacustrine and evaporitic sedimentary successions that unconformably overlie the basement rock units. Although the general geology and lithostratigraphic relationships of the region have previously been addressed in the literature within a macro-structural framework, a holistic evaluation of the vertical and lateral stratigraphic variations, along with the depositional processes of the thick Katrandedetepe Formation, remains of paramount importance from a basin analysis perspective.

Within the scope of this research, the tectono-sedimentary evolution and depositional dynamics of the basin were evaluated at a macro scale utilizing regional stratigraphic correlations, field mapping, and measured stratigraphic section data. Based on the assessment of the lithofacies characteristics, bedding

geometries, and vertical successions of the Katrandedetepe sequence, the closing and desiccation stages of the basin exhibit a distinct chronostratigraphic variation. The impacts of tectonic uplifts, paleoclimatic fluctuations, and marine/terrestrial sediment supply on the depositional distribution throughout the basin's evolutionary history were correlated with the regional geological elements, particularly the Niğde Massif to the north and its surrounding units. In this lacustrine system, which displays characteristic evaporite parageneses such as sodium sulfate and halite, the specific basinal conditions governing the development of bituminous shale intercalations and the structural positioning of the thick lacustrine successions were discussed.
Keywords: Bor-Ulukışla Basin, Katrandedetepe Formation, General Geology, Stratigraphy, Basin Evolution, Lithofacies.

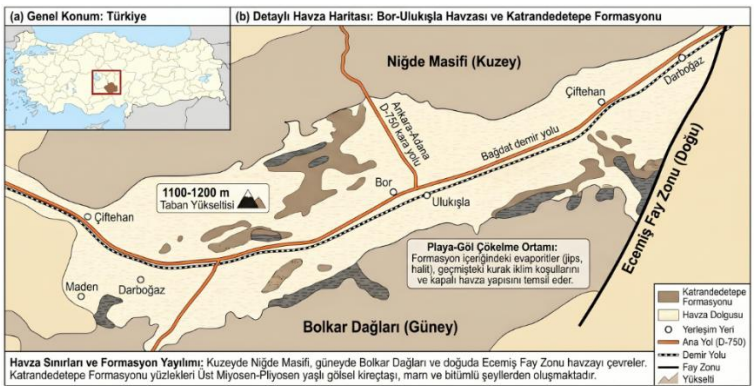
GİRİŞ

Anadolu'nun tektonik evrimi, Neo-Tetis okyanus kollarının kapanması ve buna bağlı kıtasal çarpışma süreçleri ile şekillenmiş karmaşık bir mozaik sunmaktadır. Bu makro tektonik çerçevenin en önemli elemanlarından birini oluşturan Anatolid-Torid Bloğu, Orta Anadolu bölgesindeki havza oluşumlarının ana tektonik temelini teşkil eder. Kuzeyde Pontid Kuşağı ve Sakarya Zonu ile sınırlanan bu sistem, İzmir-Ankara-Erzincan ve İç-Toros sütur zonları boyunca gerçekleşen kenetlenme süreçlerinin izlerini taşımaktadır. Çarpışma sonrası dönemde, bölgede gelişen gerilmeli ve doğrultu atımlı tektonik rejimlerin kontrolünde birçok intra-kıtasal havza gelişim göstermiştir. Bu havzalar arasında kendine has sedimanter girdileri, kalın istif mimarisi ve evaporit parajenezleri ile öne çıkan en kritik çökellerden biri Bor-Ulukışla Havzası'dır (Şekil 1).

Bor-Ulukışla Havzası, bölgesel ölçekte incelendiğinde büyük bir morfo-tektonik depresyon alanı olarak karşımıza çıkmaktadır. Havzanın kuzey ve kuzeydoğu sınırlarını Kırşehir Kompleksi ve Akdağ Masifi oluştururken, doğrudan havzanın kuzey kenarında yükselen Niğde Masifi en kritik yapısal unsurlardan biridir. Geç Kretase yaşlı yüksek sıcaklık metamorfizması ile karakterize olan Niğde Masifi, hem havzanın kuzey morfolojik duvarını öne çıkarmakta hem de Geç Senozoyik boyunca havzaya taşınan klastik malzeme için ana kaynak alanı (provenans) görevi görmektedir.

Güneyde ise havza, 3500 metreyi aşan zirveleriyle Toros Karbonat Platformu'nun parçası olan Bolkar Dağları ile sınırlanmaktadır. Doğuda Aladağlar ve Ecemiş Koridoru gibi devasa morfo-tektonik hatlarla çevrili olan Ulukışla Havzası, bu izole topoğrafik yapısı sayesinde sediman birikimi ve paleogöl gelişimi için kusursuz bir kapalı havza oluşturmuştur.

Havzanın Geç Senozoyik dönemindeki ilerleyici gelişimi, tekrarlayan kurak fazlar ve buna eşlik eden iklimsel dalgalanmalar altında geniş kuru göl düzlüklerinden yerel playa göllerine doğru evrilen bir sedimentasyon karakteri sunar. Bu evrimin en karakteristik litostratigrafik birimi, Üst Miyosen–Pliyosen yaşlı Katrandedetepe Formasyonu'dur. İstif içerisinde dikey ve yanal olarak geçişler sunan bitümlü şeyl ve evaporit ardalanmaları, havzanın paleocoğrafik ve paleoclimate koşullarının çözülmesi açısından anahtar bir role sahiptir. Bu çalışmanın amacı, Niğde-Ulukışla Havzası'nın bu ilerleyici tektono-sedimanter gelişim mekanizmasını, Katrandedetepe Formasyonu özelinde litofasiyes analizleri ve saha verileri ışığında bütüncül bir havza analizi yaklaşımıyla ortaya koymaktır.



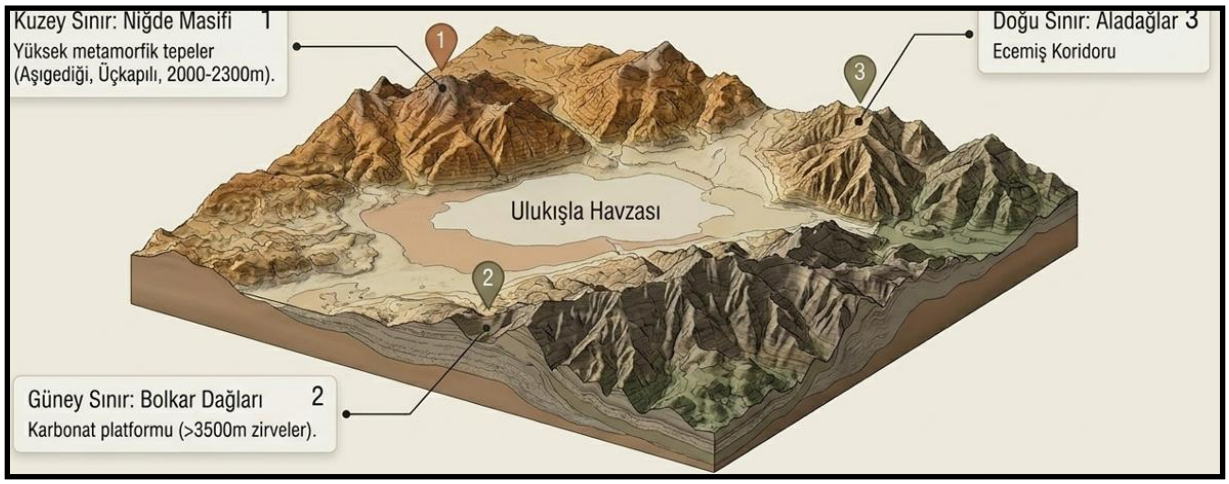
Şekil 1. Çalışma alanının konum haritası: (a) Türkiye içindeki konumu; (b) Bor–Ulukışla Havzası'nda Katrandedetepe Formasyonu yüzlekleri, başlıca yerleşimler, havza sınırları (havza sınırları ve formasyon dağılımı Altay vd., 2010; Görücü ve Bargu, 2015)

ARAŞTIRMA VE BULGULAR

Saha çalışmaları, ölçülü stratigrafi kesitleri ve bölgesel jeolojik korelasyonlar neticesinde, Ulukışla Havzası'nın Neojen dönemindeki dolgusu iki temel alt havza yapısı ve bunlara bağlı farklı sedimentasyon karakterleri ile temsil edilmektedir. Havzanın batı kesiminde evaporitlerin ve playa göl çökellerinin baskın olduğu Aktoprak yer alırken, doğu kesiminde geniş kuru göl düzlükleri, kırmızımsı kireçtaşı konglomerası ve daha kırıntılı (klastik) karakter sunan Hacıbekirli-Tepeköy gelişim göstermiştir. Bu iki alt sistem, havzanın morfolojik asimetrisini ve beslenme kaynaklarının dağılımını doğrudan yansıtmaktadır.

Katrandedetepe Formasyonu, bu iki asimetrik alt havzanın Geç Miyosen sonrasındaki kapanma ve kuruma evrelerinde ortak bir playa-lakustrin sisteme dönüşmesiyle çökelmiştir. Formasyonun litofasiyes özellikleri incelendiğinde, taban seviyelerinde masif klastikler ve ince katmanlı killi kireçtaşları ile başlayan istif, üste doğru sodyum sülfat (glauberit, tenardit) ve halit gibi özgün evaporit parajenezleri içeren ardalanmalara bırakmaktadır. Bu evaporitik matris içerisinde mercekler ve sürekli tabakalar halinde gözlenen koyu gri-siyah renkli, organik maddece zengin bitümlü şeyl seviyeleri saptanmıştır. Söz konusu bitümlü şeyller, göl seviyesinin görece yükseldiği, dip sularında anoksik/duraylı (stratifiye) koşulların hâkim olduğu dönemleri temsil etmektedir. Gölün büzülme ve aşırı buharlaşma evrelerinde ise evaporit çökelimi hız kazanmıştır.

Niğde Masifi (kuzey sınır) ile güneydeki Toros Karbonat Platformu (Bolkar Dağları) arasındaki *Havza Geçiş Kuşağı*, sediman dağılımını yönlendiren ana yapısal kontrol mekanizmasıdır. Niğde Masifi'nin Geç Miyosen-Pliyosen boyunca tektonik olarak yükselmesi, güneye doğru klastik kama geometrilerinin gelişmesine neden olurken, asimetrik havza geometrisi nedeniyle organik madde birikimi için gerekli olan sakin ve derin göl ortamı havzanın nispeten korunaklı zonlarında konumlanmıştır. Sodyum sülfat ve halit mineralojisi, paleogöl suyunun yüksek alkalin karaktere ve kapalı drenaj sistemine sahip olduğunu, karasal alterasyon ürünlerinin kapalı havzada depolanarak kusursuz bir jeokimyasal havza oluşturduğunu kanıtlamaktadır (Şekil 2).



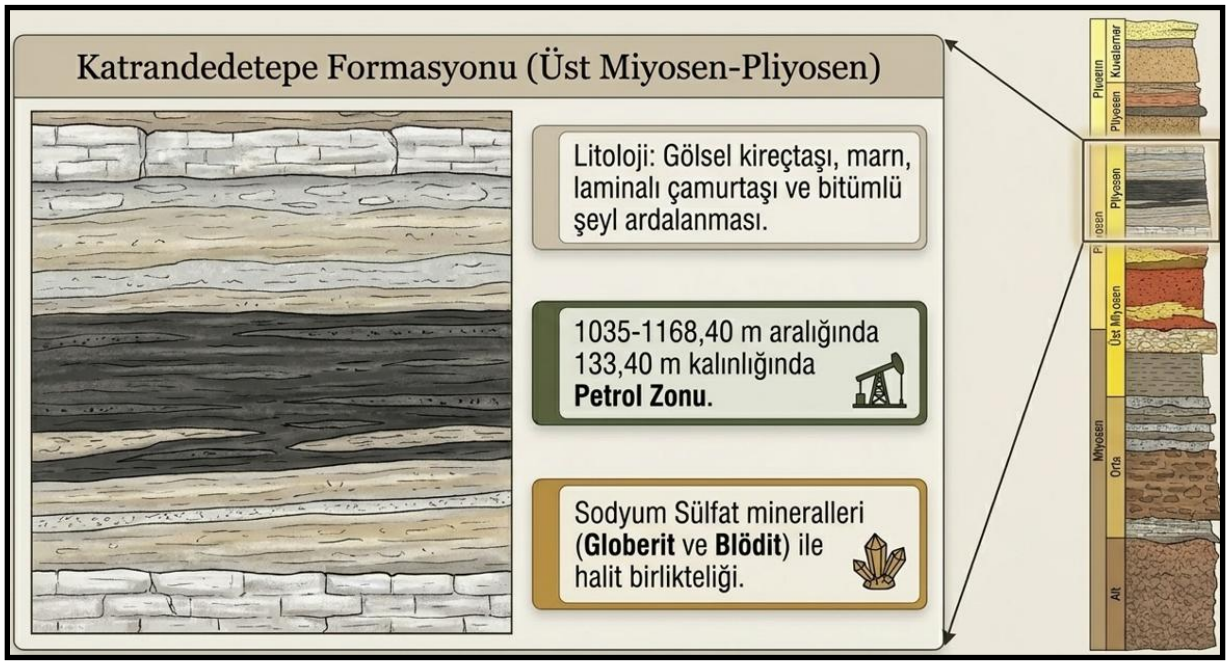
Şekil-2. Ulukışla havzasının sediman birikimi ve paleogöl gelişimi (Esirtgen ve Işık 2021 den düzenlenmiştir).

SONUÇ

Bu çalışma kapsamında elde edilen stratigrafik, yapısal ve sedimentolojik veriler, Bor-Ulukışla Neojen Havzası'nın evrimine dair şu temel sonuçları ortaya koymaktadır:

1. Ulukışla Havzası, etrafını çevreleyen yüksek topoğrafik bariyerler (Niğde Masifi, Bolkar Dağları ve Aladağlar) nedeniyle Neojen döneminde izole ve kapalı bir havza karakteri kazanmıştır. Bu morfolojik konumu paleogöl ve kalın evaporit istiflerinin gelişimi için ideal bir kapan görevi görmüştür.
2. Havza dolgusu batıda klastik-evaporit baskın Aktoprak (AT) alt havzası ve doğuda kuru göl düzlüğü-klastik baskın Hacıbekirli-Tepeköy (HT) alt havzası olarak iki farklı dinamikle kontrol edilmiştir. Geç Senozoyik'teki ilerleyici gelişimle birlikte bu sistem yerel playa göllerine ve neticesinde Katrandedetepe Formasyonu'na evrilmiştir.

3. Katrandedetepe Formasyonu içerisindeki bitümlü şeyller, iklimsel dalgalanmalar ve göl seviyesi salınımları altında, gölün duraylı ve anoksik olduğu dönemlerde organik madde korunumu ile organize olmuştur. Sodyum sülfat ve halit varlığı, havzanın aşırı kurak fazlar geçirdiğini ve yüksek evaporit konsantrasyonuna ulaştığını göstermektedir (Şekil 3).



Şekil 3. Ulukışla havzası içindeki Katrandedetepe formasyonun oluşumu (Esirtgen and Işık, 2021; Altay vd. 2010; Görücü and Bargu, 2015; Helvacı vd. 2017 ve Kadınkız vd. 2017'den düzenlenmiştir).

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AGRO-ENDÜSTRİYEL BİTKİ YAN ÜRÜNLERİNİN HAYVANSAL ÜRETİMDE ALTERNATİF YEM KAYNAĞI OLARAK DEĞERLENDİRİLMESİ

EVALUATION OF AGRO-INDUSTRIAL PLANT BY PRODUCTS AS ALTERNATIVE FEED SOURCES IN ANIMAL PRODUCTION

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ÖZET

Artan dünya nüfusu, değişen beslenme alışkanlıkları ve hayvansal ürünlere olan talebin yükselmesi, hayvansal üretimde kullanılan yem kaynakları üzerinde ciddi bir baskı oluşturmaktadır. Bu durum, özellikle protein ve enerji açısından zengin geleneksel yem hammaddelerinin sürdürülebilirliğini tartışmalı hale getirmiş ve alternatif yem kaynaklarının araştırılmasını hızlandırmıştır. Bu bağlamda agro-endüstriyel bitki yan ürünleri, düşük maliyetli, bol bulunabilir ve besin değeri açısından zengin olmaları nedeniyle önemli bir potansiyel alternatif olarak öne çıkmaktadır. Özellikle yağlı tohumlu bitkilerin işlenmesi sonucu elde edilen kolza, ayçiçeği ve soya küspeleri; yüksek ham protein içerikleri ve sindirilebilirlik özellikleri ile ruminant ve monogastrik hayvan beslemede yaygın şekilde değerlendirilmektedir. Bunun yanı sıra şeker pancarı posası gibi şeker endüstrisi yan ürünleri, yüksek fermente olabilir lif içeriği sayesinde rumen mikrobiyal aktiviteyi destekleyerek enerji kaynağı olarak önemli katkı sağlamaktadır. Nişasta ve lif bazlı endüstriyel artıklar ise uygun işleme teknikleri ile yem değerine kazandırılabilmektedir. Bu derlemede agro-endüstriyel bitki yan ürünlerinin kimyasal kompozisyonu, besleyici özellikleri, hayvan beslemede kullanım alanları ve sürdürülebilir yem üretimine katkıları literatür ışığında değerlendirilmiştir. Elde edilen bulgular, bu yan ürünlerin doğru muhafaza, işlem (fermantasyon, kurutma, peletleme) ve rasyon formülasyonu ile hem ruminant hem de monogastrik hayvanlar için etkili alternatif yem kaynaklarına dönüştürülebileceğini göstermektedir. Ayrıca bu kaynakların kullanımı, yem maliyetlerinin azaltılması ve tarımsal atık yönetiminin iyileştirilmesi açısından döngüsel ekonomi yaklaşımına önemli katkılar sunmaktadır.

Anahtar Kelimeler: agro-endüstri, yan ürün, hayvan besleme, kolza küspesi, ayçiçeği küspesi, sürdürülebilir yem.

ABSTRACT

The growing global population, changing dietary patterns, and increasing demand for animal-derived products have placed significant pressure on feed resources used in animal production systems. This situation has raised concerns regarding the sustainability of conventional feed ingredients, particularly those rich in protein and energy, and has accelerated the search for alternative feed sources. In this context, agro-industrial plant by products have emerged as promising alternatives due to their low cost, wide availability, and considerable nutritional value.

In particular, oilseed processing by-products such as rapeseed, sunflower, and soybean meals are widely utilized in both ruminant and monogastric animal nutrition due to their high crude protein content and favorable digestibility characteristics. Similarly, sugar industry by-products such as sugar beet pulp contribute significantly to animal diets by providing highly fermentable fiber, which supports rumen microbial activity and serves as an important energy source. Starch and fiber based industrial residues can also be converted into valuable feed resources through appropriate processing techniques. This review evaluates the chemical composition, nutritional properties, and application areas of agro-industrial plant by products in animal feeding systems, as well as their contribution to sustainable feed production. The findings indicate that, with proper preservation methods, processing techniques (such as fermentation, drying, and pelleting), and balanced ration formulation, these by-products can be effectively transformed into valuable alternative feed sources for both ruminant and monogastric animals.

Furthermore, their utilization contributes to feed cost reduction and improves agricultural waste management, aligning with the principles of circular economy and environmental sustainability.
Keywords: Agro-industry, by products, animal nutrition, rapeseed meal, sunflower meal, sustainable feed

GİRİŞ

Küresel olarak hayvansal üretim sektöründe görülen büyüme, başta nüfus artışı olmak üzere gelir seviyelerindeki iyileşme, şehirleşme ve değişen tüketim alışkanlıkları gibi faktörlerle paralel şekilde sürekli artış göstermektedir. Birleşmiş Milletler Gıda ve Tarım Örgütü (FAO) raporlarına göre, 2050 yılına kadar dünya nüfusunun yaklaşık 9.7 milyara ulaşması beklenmekte olup, bu durum hayvansal protein talebinde yüzde 70'e varan bir artışa işaret etmektedir. Bu gelişmeler, hayvancılık sektöründe kullanılan yem hammaddeleri üzerindeki baskıyı artırmakta ve özellikle yüksek kaliteli protein kaynaklarının sürdürülebilir temininde ciddi zorluklar ortaya çıkarmaktadır (Ajila ve ark., 2012).

Günümüzde hayvan beslemede yaygın şekilde kullanılan soya küspesi, mısır gibi ürünler, üretim maliyetlerinin giderek yükselmesi, üretim alanlarının sınırlı olması ve küresel iklim değişikliğinin etkileri nedeniyle arz açısından kırılganlık göstermektedir. Üstelik, bu geleneksel yem hammaddelerinin üretimi sırasında oluşan çevresel etkiler (örneğin ormansızlaşma, su kaynaklarının aşırı kullanımı ve karbon ayak izi) ekolojik sürdürülebilirliği tehdit etmekte, dolayısıyla alternatif kaynakların araştırılmasını zorunlu kılmaktadır (Yang ve ark., 2022). Bu kapsamda, agro-endüstriyel yan ürünlerin ve tarımsal atıkların hayvan beslemede daha etkin kullanımı, sürdürülebilir ve çevreci bir hayvancılık sistemine geçişte kritik bir adım olarak görülmektedir.

Agro-endüstriyel yan ürünler, tarımsal işleme süreçleri sırasında ortaya çıkan, genellikle ekonomik değeri düşük veya atık olarak değerlendirilen materyallerdir. Ancak bu ürünler, zengin protein, lif, mineral ve çeşitli biyoaktif bileşen içerikleri sayesinde hayvan beslenmesinde hem besin değeri hem de fonksiyonel açıdan önemli potansiyeller barındırmaktadır (Moreno-González & Ottens, 2021). Özellikle yağlı tohum küspeleri hem protein kaynağı olarak hem de hayvan sağlığını destekleyici nitelikleriyle yaygın bir şekilde kullanılmaktadır (Ajila ve ark., 2012; Yang ve ark., 2022). Bu alternatif yem kaynaklarının değerlendirilmesi, sadece yem maliyetlerini düşürmekle kalmayıp aynı zamanda hayvancılığın ekolojik etkilerini azaltarak sürdürülebilir kalkınmaya katkıda bulunmaktadır.

Bu çalışma, agro-endüstriyel bitki yan ürünlerinin hayvan beslemede kullanımına ilişkin güncel literatürün sistematik olarak incelenmesiyle hazırlanmış bir derlemedir. Web of Science, Scopus ve Google Scholar veri tabanlarında "oilseed meal", "agro-industrial by-products", "animal feed", "rapeseed meal", "sunflower meal" ve "sugar beet pulp" anahtar kelimeleri kullanılarak çalışmalar taranmıştır. Son 15 yıl içinde yayımlanan hakemli makaleler ve derleme çalışmaları değerlendirilmiştir.

YAĞLI TOHUM KÜSPELERİ

Yağlı tohum küspeleri, bitkisel yağ üretimi sonrasında elde edilen ve yüksek protein içerikleri nedeniyle hayvan beslemede yaygın olarak kullanılan agro-endüstriyel yan ürünlerdir. Bu ürünler özellikle protein açığının kapatılması, yem maliyetlerinin azaltılması ve sürdürülebilir hayvancılık sistemlerinin desteklenmesi açısından büyük önem taşımaktadır. Günümüzde soya fasulyesi küspesi en yaygın protein kaynağı olmakla birlikte, fiyat dalgalanmaları ve dışa bağımlılık nedeniyle alternatif protein kaynaklarına olan ilgi giderek artmaktadır (Ravindran ve Blair, 1992).

Kolza (*Brassica napus* L.) küspesi, ham protein içeriğinin %30-40 arasında değişmesi ve dengeli amino asit profiline sahip olması nedeniyle ruminant ve kanatlı rasyonlarında önemli bir yer tutmaktadır. Özellikle metiyonin ve sistein gibi kükürtlü amino asitler bakımından zengin olması, süt ve et veriminin artırılmasında avantaj sağlamaktadır (Khajali ve Slominski, 2012). Bununla birlikte kolza küspesinde bulunan glukosinolatlar, fitatlar ve tanenler gibi antinutrisyonel bileşikler kullanım düzeyini sınırlandırabilmektedir. Glukosinolatların parçalanması sonucu oluşan metabolitler tiroid fonksiyonlarını etkileyebilmekte, yem tüketimini azaltabilmekte ve büyüme performansını olumsuz yönde etkileyebilmektedir. Ancak düşük glukosinolat içeren "canola" çeşitlerinin geliştirilmesi ve uygulanan ısıl işlemler sayesinde bu olumsuzluklar büyük ölçüde azaltılmıştır (Tripathi ve Mishra, 2007).

Ayçiçeği (*Helianthus annuus* L.) küspesi ise yüksek ham protein (%20-45) ve lif içeriği ile dikkat çekmektedir. Özellikle kabuk oranına bağlı olarak besin değeri değişmekte olup, dekortike edilmiş

(kabuksuzlaştırılmış) ayçiçeği küspelerinde protein oranı önemli ölçüde artmaktadır (Senkoylu ve Dale, 2007). Ayçiçeği küspesi, rumen fermentasyonunu olumlu yönde etkileyen yapısal karbonhidratlar içermekte ve süt sığırı rasyonlarında başarılı şekilde kullanılabilmektedir. Ancak yüksek selüloz ve lignin içeriği, monogastrik hayvanlarda sindirilebilirliği sınırlandırmaktadır. Bu nedenle enzim uygulamaları, mikrobiyal fermentasyon ve fiziksel işlemler gibi yöntemlerle besin değerinin artırılması hedeflenmektedir.
Son yıllarda pamuk tohumu küspesi, keten tohumu küspesi ve aspir küspesi gibi diğer yağlı tohum yan ürünlerinin de alternatif protein kaynağı olarak değerlendirilmesine yönelik çalışmalar artmıştır. Özellikle omega-3 yağ asitleri bakımından zengin keten tohumu küspesinin süt ve et ürünlerinin besinsel kalitesini iyileştirebildiği bildirilmektedir (Maddock ve ark., 2006).

ŞEKER ENDÜSTRİSİ YAN ÜRÜNLERİ

Şeker endüstrisi tarafından üretilen yan ürünler, hayvancılık sektöründe enerji ve lif kaynağı olarak önemli bir potansiyele sahiptir. Bunların başında şeker pancarı posası, melas ve filtre çamuru gelmektedir. Şeker pancarı posası, şeker ekstraksiyonu sonrasında geriye kalan ve yüksek düzeyde sindirilebilir lif içeren bir yan üründür. Kuru maddede yaklaşık %18-25 ham selüloz ve %20-30 pektin içermektedir (Voelker ve Allen, 2003). Pektin bakımından zengin olması nedeniyle rumende hızlı fermantasyona uğramakta ve uçucu yağ asitlerinin oluşumunu destekleyerek enerji kaynağı görevi görmektedir. Ayrıca nişasta bakımından fakir olması, rumen asidozu riskini azaltmaktadır. Bu nedenle süt sığırları ve besi sığırlarında güvenli bir enerji kaynağı olarak kullanılabilmektedir.

Şeker pancarı posasının silolanarak muhafaza edilmesi yaygın bir uygulamadır. Silaj formunda kullanımı hem depolama kayıplarını azaltmakta hem de yıl boyunca yem kaynağı olarak değerlendirilmesine olanak sağlamaktadır. Yapılan araştırmalar, şeker pancarı posasının süt verimi ve süt yağ oranı üzerinde olumlu etkiler oluşturduğunu göstermektedir (Firkins, 1997).
Şeker endüstrisinin bir diğer önemli yan ürünü olan melas ise şeker üretimi sırasında kristalize edilemeyen şekerlerin yoğunlaştırılmasıyla elde edilmektedir. Yaklaşık %45-55 oranında şeker içeren melas, yüksek enerji değeri sayesinde özellikle ruminant rasyonlarında lezzetlendirici ve enerji kaynağı olarak kullanılmaktadır. Ayrıca silaj katkı maddesi olarak fermantasyon kalitesini artırdığı bilinmektedir (Mullan ve ark., 2009).

AGRO-ENDÜSTRİYEL YAN ÜRÜNLERİN DEĞERLENDİRİLMESİ

Dünya genelinde yem maliyetlerinin toplam üretim giderlerinin %60-70'ine ulaşabilmesi nedeniyle agro-endüstriyel yan ürünlerin değerlendirilmesi stratejik önem taşımaktadır. Bu yan ürünlerin doğrudan kullanımı bazı durumlarda besin madde sınırlılıkları ve antinutrisyonel faktörler nedeniyle kısıtlanmaktadır. Bu nedenle biyoteknolojik işlemlerle besin değerlerinin artırılması son yıllarda yoğun araştırmalara konu olmaktadır.
Katı faz fermentasyonu (solid-state fermentation), maya ve mantar kültürleri kullanılarak protein içeriğinin artırılması ve sindirilebilirliğin geliştirilmesi amacıyla yaygın şekilde uygulanmaktadır. Aspergillus niger, Saccharomyces cerevisiae ve Trichoderma spp. gibi mikroorganizmalar kullanılarak gerçekleştirilen fermentasyon uygulamalarının ham protein içeriğini artırdığı ve lif fraksiyonlarını azalttığı bildirilmektedir (Lateef ve ark., 2008).
Enzim teknolojileri de agro-endüstriyel yan ürünlerin değerlendirilmesinde önemli rol oynamaktadır. Selülaz, ksilanaz ve fitaz gibi enzimlerin kullanımıyla hücre duvarı bileşenlerinin parçalanması sağlanmakta ve besin maddelerinin biyoyararlanımı artırılmaktadır. Özellikle kanatlı ve domuz beslemede enzim uygulamalarının yemden yararlanmayı önemli ölçüde artırdığı belirtilmektedir (Bedford ve Partridge, 2010). Ayrıca silajlama teknikleri sayesinde yüksek nem içeren yan ürünler uzun süre muhafaza edilebilmekte ve besin kayıpları azaltılabilmektedir. Fermente edilmiş yemlerin rumen mikrobiyal faaliyetlerini desteklediği, bağışıklık sistemini olumlu etkilediği ve hayvan performansını geliştirdiği bildirilmektedir (Kung ve Shaver, 2001).
Agro-endüstriyel yan ürünlerin etkin şekilde değerlendirilmesi yalnızca yem maliyetlerini azaltmakla kalmamakta, aynı zamanda döngüsel ekonomi ve sürdürülebilir tarım hedeflerine de katkı sağlamaktadır. Bu yaklaşım, atıkların çevreye olan olumsuz etkilerinin azaltılması ve sera gazı emisyonlarının düşürülmesi açısından önemli avantajlar sunmaktadır.

SONUÇ

Agro-endüstriyel bitki yan ürünleri, artan yem maliyetleri ve sürdürülebilir üretim gereksinimleri doğrultusunda hayvansal üretim sistemlerinde önemli alternatif yem kaynakları olarak öne çıkmaktadır. Özellikle yağlı tohum küspeleri ve şeker endüstrisi yan ürünleri, yüksek protein ve sindirilebilir lif içerikleri sayesinde ruminant ve monogastrik hayvanların beslenmesinde önemli potansiyele sahiptir.

Kolza ve ayçiçeği küspeleri gibi yağlı tohum yan ürünleri kaliteli protein kaynakları sağlarken, şeker pancarı posası ve melas gibi ürünler enerji ve lif kaynağı olarak değerlendirilmektedir. Bununla birlikte antinutrisyonel faktörler, yüksek lif içeriği ve depolama sorunları gibi sınırlamalar uygun işleme teknolojileri ile büyük ölçüde giderilebilmektedir. Fermentasyon, enzim uygulamaları ve silajlama gibi biyoteknolojik yaklaşımlar, bu materyallerin besin değerini artırmakta ve kullanım alanlarını genişletmektedir. Gelecekte yürütülecek araştırmaların; farklı yan ürünlerin kombinasyonları, biyoteknolojik işlem optimizasyonları, hayvan performansı üzerine uzun dönem etkiler, ürün kalitesi ve ekonomik analizler üzerine yoğunlaşması gerekmektedir. Böylece agro-endüstriyel yan ürünlerin hayvancılık sektöründe daha etkin kullanımı sağlanarak hem çevresel sürdürülebilirlik hem de ekonomik verimlilik artırılabilecektir.

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A CONCEPTUAL ANALYSIS OF THE BINARY OPPOSITION "TRUTH/LIE" IN ENGLISH LITERATURE: FROM METAPHYSICAL ABSOLUTE TO POSTMODERN DECONSTRUCTION

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Abstract
This article presents a comprehensive, in-depth conceptual analysis of the representation of the fundamental binary opposition "truth/lie" in English literary discourse. The study spans a broad chronological period, from the Renaissance to early 21st-century postmodernism. Using works by William Shakespeare, John Swift, Charles Brontë, Oscar Wilde, William Woolf, John Fowles, and Ian McEwan, the historical evolution of the dichotomy is traced.
The transition from ontological absolutism, where truth was understood as a sacred cosmic order, to total postmodern relativism, deconstruction, and the dominance of simulacra is demonstrated. Particular attention is paid to the cognitive metaphors of the concepts TRUTH and LIE, the mechanisms of "unreliable narration" and the ethical potential of fiction as a tool for searching for existential truth.
Key words: conceptual analysis, binary opposition**,** English Literature, the concepts TRUTH and LIE, literary development.

The relevance of this study stems from the radical value shift that occurred in the culture of the turn of the 20th and 21st centuries and that became fully formed by the beginning of the post-truth era. In the history of the Western European intellectual tradition, binary oppositions have traditionally served as a fundamental conceptual framework organizing human cognition, culture, and language. Cartesian dualism, Hegelian dialectic, and, most notably, Ferdinand de Saussure's structural linguistics affirmed the idea that meaning is formed not in isolation, but exclusively through a system of differences and oppositions.
As Saussure asserted, "in language there is nothing but differences". One such fundamental, structure-forming opposition, defining both the moral and ethical matrix of society and the artistic and aesthetic space of literature, is the dichotomy of "truth" and "lie". In English linguistic culture and literary tradition, the lexemes "truth" and "lie" possess a profound conceptual ambivalence. The concept of "truth" traces back to Proto-Germanic 'trew' (loyalty, devotion, agreement), which initially associated truth not so much with abstract logical correspondence to facts (the Aristotelian concept of correspondence) as with categories of trust, existential fidelity, and the inviolability of words [6].
In turn, "lie" (from Proto-Germanic 'lugiz') is historically associated with concepts of concealment, distortion, and the weaving of a false web.
In literary texts, this opposition goes far beyond the purely linguistic or logical opposition of 'True – Lie' is transformed into a global metanarrative, serving as the main tool:
1. For constructing dramatic and psychological conflict.
2. Revealing implicit motives and the internal evolution of characters.
3. Exploring the epistemological boundaries of human cognition and the nature of fiction itself.
Contemporary literary development demonstrates the blurring of rigid ontological boundaries between the true and the lie, the real and the simulated. The concepts of "fact" and "interpretation" are swapped, and the classical hierarchy, in which truth a priori occupied a privileged, sacred position, and falsehood a marginal and destructive one, is being completely dismantled [8].
The problem is that the concepts of "truth" and "lie" in English literary discourse have never been static. At every historical literary stage - from the Renaissance drama of William Shakespeare to the

modernism of Virginia Woolf and the postmodern experiments of John Fowles this opposition has been reimagined.

The aim of this paper is to conduct a comprehensive, in-depth conceptual analysis of the representation of the binary opposition "true/lie" in English literature, as well as to explicate the evolution of this structure from a rigid hierarchical dichotomy to rhizomatic ambivalence.

To ensure a multi-perspective and in-depth analysis, this article employs a comprehensive philological approach, combining the principles of structuralism, post-structuralism (deconstruction), and cognitive-conceptual analysis.

Within the structuralist paradigm (F. de Saussure, C. Lévi-Strauss, A. Greimas), binary opposition is viewed as a universal mechanism for meaning generation. This method allows us to identify the basic semantic markers of "truth" and "lie" as mutually exclusive elements of a textual system [9]. Drawing on A. Greimas's semiotic square, the opposition is expanded to four poles:

- Truth: Being + Manifestation (that which actually exists and which manifests itself).
- Lie: Non-being + Manifestation (that which does not exist, but which simulates its presence).

This approach allows us to analyze the dynamics of the plot as the movement of characters or concepts between these four quadrants [4].

Since any binary opposition in culture is ideological and hierarchical (where one member of the pair is always recognized as "superior", "pure", and the other as "secondary", "corrupt"), Jacques Derrida's method (1967) of deconstruction becomes key to the practical part of the study. The deconstruction procedure involves two steps:

1. Revealing and reversing the hierarchy: demonstrating how the text covertly or explicitly undermines the superiority of "truth" over "lie", revealing that "truth" itself depends on the mechanisms of fiction, language, and interpretation.
2. Neutralizing Opposition: Moving beyond binary boundaries, discovering a third space (the space of différance, trace, simulacrum) where opposition loses its power [3].

Cognitive-Conceptual Analysis aims to reconstruct the mental models of the concepts of TRUTH and LIE in the English linguistic worldview and their specific actualizations in the idiostyles of specific authors. The metaphorical models through which these concepts are verbalized in texts are analyzed:

The integration of these methods allows for a transition from superficial linguistic description to a profound philosophical and literary generalization.

The Renaissance and the Enlightenment: Truth as a Cosmic Order and Ontological Tragedy William Shakespeare: "Othello" and "Hamlet" –Tragedies of the Distortion of Truth In Renaissance consciousness, the opposition "truth/lie" has a clearly cosmological character. Truth is identical to the Divine Order, to Being as such. A lie is not simply disinformation; it is an ontological hole, a fall from grace, chaos that destroys the fabric of the universe [11]. In the tragedy "Othello", Shakespeare constructs a complex architecture of lies. The character of Iago is the archetype of the absolute liar, whose ontological position is formulated in the famous phrase: "*I am not what I am*" – a direct demonic inversion of the biblical Divine self-definition "*I am that I* am". Iago constructs a false reality by exploiting Othello's cognitive vulnerabilities. From a conceptual perspective, Iago subverts conceptual metaphors. He transforms Desdemona's purity and fidelity (associated with whiteness, light, and precious stones) into their opposite, using the metaphors of dirt and animality. Iago's lie triumphs not because it is logical, but because it parasitizes on the semiotic codes of "credibility" (the notorious handkerchief becomes a material sign, a false testimony accepted by Othello as absolute truth). The opposition here is tragically asymmetrical: truth is defenseless in its innocence and silence, while lies are hyperactive, narrative, and performative [9]. Hamlet, striving to uncover the truth ("to find where truth is hidden, though it were hidden indeed within the center"), is forced to resort to simulation– the mask of madness. Thus, Shakespeare demonstrates the paradoxical collapse of binaries: to reveal the truth, Hamlet must entrench himself in a lie (madness) and stage a metatextual lie – the play "The Mousetrap". The Mousetrap is pure fiction (fiction/lie), which nevertheless produces the therapeutic and revealing effect of a true trial. The Age of Enlightenment and Jonathan Swift: A Satire on Rational Truth In the 18th century, a time of triumphant rationalism and empiricism, the concept of truth began to be associated with scientific fact and mathematical precision [13]. However, Jonathan Swift, in Gulliver's Travels, subjects this paradigm shift to harsh satire. In his fourth voyage (to the land of the Houyhnhnms), Gulliver encounters creatures whose language omits the concept of "lie". The

Houyhnhnms use the descriptive phrase “the thing which is not”. In their ideal rational society, truth is as natural as breathing, because reason leaves no room for distortion. Swift demonstrates that for the Houyhnhnms, language is a mirror of reality. However, by introducing this utopian absolute, Swift carries out a subtle deconstruction: deprived of the ability to lie (and, consequently, the capacity for imagination, metaphor, and fiction), the Houyhnhnms are revealed as hard, cold, and empathetic creatures, ready to castrate or destroy the Yahoos solely for reasons of “reasonable expediency”. Swift, for the first time in the English tradition, demonstrates that absolute, sterile truth, purged of human subjectivity, can be as destructive as deliberate villainy.

The Victorian Novel: Ethical Dichotomy and the Social Mask can be revealed in Charlotte Brontë: “Jane Eyre”. Here the Truth is considered as an Inner Imperative.

The Victorian era rigidly codified the “truth/lie” opposition, translating it into the realm of Puritan morality and social contract. Lying was perceived as a social sin, threatening the stability of bourgeois society. In the novel Jane Eyre, the concept of truth is central to the formation of the protagonist’s identity. From childhood, in Mrs. Reed’s home, Jane rebels against the stigma of “liar” imposed upon her by her aunt and the hypocritical trustee of Lowood, Mr.

Brocklehurst. Brocklehurst represents the Victorian model of institutional, self-righteous “truth”, which, when exposed, turns out to be a profound lie and oppression.

For Jane Eyre, truth is fidelity to one’s inner self, God, and the voice of one’s conscience, even in defiance of social conventions. The crucial moment of this test of opposition occurs when Jane learns of the existence of Bertha Mason, Edward Rochester’s mad wife.

Rochester offers Jane a compromise based on a noble, salutary lie: flee with him to France and live as a married couple. Rochester argues that their spiritual marriage is true before God, while his official union is a legal fiction and a nightmare.

Jane faces a profound cognitive dissonance: Jane’s choice to leave Rochester is an affirmation of the absolute primacy of Truth over illusory and sinful happiness. Brontë demonstrates that the Victorian subject attains wholeness only through a painful purge of any form of compromising falsehood.

At the end of the 19th century, aestheticism and decadence dealt a crushing blow to Victorian moralizing, completely inverting the hierarchy within the analyzed binary. In the essay “The Decay of Lying”, Oscar Wilde proclaims a manifesto in which “lying” (understood as art, beautiful fiction, stylization) is declared the highest form of human activity, while “truth” (understood as vulgar, gray fact, the imitation of nature) is dethroned. In The Picture of Dorian Gray, this philosophy finds its tragic novelistic embodiment. Wilde deconstructs this opposition through the separation of appearance and essence.

The paradox constructed by Wilde is profound: a living person becomes a walking lie, an artifact, a simulacrum, while an inanimate object (a painting) takes on the function of holding the Truth. Dorian’s attempt to destroy the portrait at the end is an attempt to finally destroy Truth in favor of Lie, but this act leads to the immediate collapse of the entire system: the lie crumbles, the mask falls, and the corpse regains its true, terrifying appearance, returning the binary opposition to its original metaphysical balance at the cost of the hero’s life.

With the advent of the 20th century, under the influence of the philosophy of Bergson, Nietzsche, and Freudian psychoanalysis, English-language literature loses faith in the existence of a single, objective, knowable Truth with a capital T. Modernism shifts the focus of inquiry from the external world to the internal world of human consciousness. Objective fact gives way to subjective experience [5].

In Virginia Woolf’s novel “To the Lighthouse”, the opposition “truth/lie” is transferred to the realm of epistemology and gender. The male type of cognition, represented by Mr. Ramsay (a philosophy professor), is oriented toward rigid, linear, rational truth. Mr. Ramsay’s thinking is likened to an alphabet: he tries to get from point A to point Z, but gets stuck at the letter R. His “truth” is the truth of fact, impartial, dry, and essentially dead, sowing despondency and fear around him.

In contrast, the female type of being, embodied in Mrs. Ramsay, operates with an entirely different category of the truth of intuition, the truth of an instantaneous emotional fusion with the world. Mrs. Ramsay often resorts to what her husband considers “untruths” or exaggerations: she softens the sharp edges of reality, assures her young son James that the weather will be fine tomorrow (even though the barometer is falling), and creates the illusion of harmony at the dinner table.

Woolf deconstructs the classical opposition, showing that Mrs. Ramsay's "lie" is not a deception but a saving myth, a creative act that creates life. The truth is revealed not as a dry fact from a philosophy professor, but as the fleeting insight of the artist Lily Briscoe ("I have had my vision"), connecting past and present, subject and object. Truth in modernism becomes multiple, shimmering, and deeply individual.

Postmodernism takes the process of relativizing truth to its logical extreme, proclaiming the death of metanarratives (Jacques-François Lyotard) and the triumph of simulacra (Jacques Baudrillard). Literature begins to openly reflect on its own conventionality, turning the "truth/fiction" opposition into the main theme of metatextual play. In John Fowles's novel "The French Lieutenant's Woman", deconstruction unfolds on two levels: plot and narrative.

On the plot level, the heroine, Sarah Woodruff, consciously constructs a grandiose myth (a lie) around herself that she was seduced and abandoned by a French officer. She voluntarily accepts the social stigma of "fallen woman", marginalizing herself in the eyes of Blyme's Victorian society. The protagonist, Charles Smithson, attempts to unravel Sarah, seeing her as a riddle that demands the extraction of the "truth". However, the paradox is that Sarah's "lie" (she confesses to Charles that she is, in fact, a virgin and that the officer did not touch her) was necessary to her as a tool for radical liberation from the stifling grip of Victorian gender and social roles. Her lie was an act of existential choice, the creation of her own sovereign truth.

Thirteen-year-old Bryony Tallis, possessed of a hyperactive writer's imagination, makes a fatal mistake (or crime): she interprets the complex, incomprehensible ambivalent signs of the adult relationship between her sister Cecilia and the cleaner's son, Robbie Turner, through the prism of Gothic novels. Confronted with a real act of violence in the darkness of a park (committed by Paul Marshall), Briony, driven by childhood resentment, jealousy, and a thirst for narrative closure, gives false testimony to the police, blaming Robbie.

This lie shatters lives: Robbie ends up in prison, then on the battlefields of World War II, and Cecilia severing ties with her family. McEwan explores in detail the mechanics of transforming subjective fiction into hard legal and social fact. A lie, recorded in a report, acquires the status of official "truth".

The novel's final section delivers the reader a profound postmodern shock. It is revealed that the entire second and third parts of the book (where Robbie escapes Dunkirk, returns to Cecilia, and Briony comes to them to ask for forgiveness) are a novel written by the elderly Briony, dying of vascular dementia. In reality, Robbie died of septicemia in Dunkirk, and Cecilia died in the bombing of Balham tube station.

Brioni used fiction (or lie) as the only possible means of metaphysically "atonement" for her guilt toward the dead. She gave them the happy truth of life that she herself had taken from them with her childish lies. McEwan poses an insoluble ethical and conceptual question to the reader: can total literary falsehood serve as a tool for restoring the highest spiritual truth?

This in-depth conceptual analysis of the binary opposition "truth/lie" in the context of the English literary tradition allows us to formulate several fundamental conclusions.

Firstly, the evolution of this dichotomy represents a global historical shift in human consciousness from ontological absolutism to epistemological skepticism and relativism. While during the Renaissance and Enlightenment, truth was conceived as an objective given (Divine or Rational), opposing falsehood as chaotic non-existence, by the end of the 20th century, it had completely lost its transcendent status, becoming a product of linguistic and narrative construction.

Secondly, English literature clearly demonstrates a phenomenon that, in Derrida's terms, can be called the "collapse of the privileged pole". Attempts to isolate "pure truth" from the mechanisms of fiction, language, and interpretation have invariably failed.

As illustrated by examples ranging from Shakespeare's "The Mousetrap" to McEwan's "Atonement", "lies" (in the sense of artistic imagination, fiction) often prove to be the only medium available to humans for articulating and comprehending profound existential, psychological, and ethical truths.

Thirdly, the institution of "unreliable narration" has become the most important mechanism for transforming this opposition in contemporary prose.

The shift in emphasis from deliberate deception (the classic lie) to cognitive distortions of memory and narrative autopsychotherapy (as in McEwan) has finally shifted the opposition from a moral to a cognitive-psychological realm. In this space, the boundary between truth and lie becomes not a rigid dividing line, but a fractal zone of diffusion of meanings.

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DENDRO-ECOLOGICAL ZONING FOR SEMI-ARID RESTORATION: A DATA-DRIVEN SPECIES SELECTION FRAMEWORK FOR THE BARIND TRACT, BANGLADESH

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Abstract
The Barind Tract in northwestern Bangladesh is a fragile Pleistocene terrace marked by high temperatures, poor rainfall infiltration, and steadily declining soil organic matter. The Barind Multipurpose Development Authority (BMDA) has run large afforestation campaigns across the region, but its heavy reliance on fast-growing exotics such as Eucalyptus camaldulensis and Acacia auriculiformis has drawn growing concern over what these monocultures are doing to the area's hydrological balance and long-term soil health. This paper puts forward a Dendro-Ecological Zoning (DEZ) model that combines fifteen years of climatic records (2002–2017) from three sub-zones—Puthia, Paba, and Godagari—with species performance data. Using Paterson's (1956) Climate Vegetation and Productivity (CVP) Index, site potential is estimated and habitat suitability shifts are projected for the year 2100. The data point to a sharp rainfall decline in Puthia, from 1321.9 mm in 2002 down to 871.0 mm by 2017, tracking closely with groundwater depletion to a depth of 14.20 m. Exotic species still post the highest survival rates (98%), yet contribute comparatively little to soil restoration next to nitrogen-fixing species such as Albizia lebbeck, which is projected to lose nearly 40% of its suitable habitat by 2100. The findings suggest that restoration planning in the Barind needs to move from "rapid greening" toward climate-resilient indexing, favoring species such as Shorea robusta and Terminalia arjuna, projected to gain 34% and 25.5% in suitable area respectively under future climate conditions.
Keywords: Barind Tract; CVP Index; Dendro-Ecological Zoning; Soil Restoration; Climate Resilience; Species Selection.

SUMMARY

This study examines how climatic stress and current afforestation choices are reshaping the long-term prospects for ecological restoration in the Barind Tract of northwestern Bangladesh. Fifteen years of rainfall and groundwater records from three sub-zones — Puthia, Paba, and Godagari — were combined with species performance data and Paterson's Climate Vegetation and Productivity (CVP) Index to project habitat suitability through to the year 2100. The results show that fast-growing exotic species, while reliable for quick canopy establishment, do little to repair the region's degraded soils and may be worsening water stress in already-vulnerable zones such as Puthia. Nitrogen-fixing species offer real soil benefits but are themselves projected to lose substantial habitat under future climate conditions, while species such as Shorea robusta and Terminalia arjuna are projected to gain ground. The study concludes that restoration planning in the Barind needs to move away from rapid, exotic-led greening and toward a mixed-species, climate-resilient model guided by sub-zonal CVP indexing.

INTRODUCTION

Background

The Barind Tract ranks among the most drought-prone agro-ecological zones in Bangladesh, sitting on elevated, hard-pan clay terraces that hold water poorly (Hossain, 2016). Decades of intensive monoculture rice farming, paired with heavy groundwater extraction, have left the land visibly degraded. In response, the country's plantation forestry approach has increasingly favored clearing existing growing stock and replacing it with faster-growing, more commercially valuable species (Hossain, 2016).

Literature Synthesis

Most current afforestation work in the region leans on Eucalyptus camaldulensis and Acacia auriculiformis to establish canopy cover quickly. Foresters favor these species partly because they double as "biodrains" on waterlogged land and tolerate difficult planting sites well (Ram et al., 2011). Yet a growing body of research suggests these same fast-growing exotics may be worsening water stress

in semi-arid zones rather than relieving it (Ram et al., 2011). Nitrogen-fixing trees (NFTs) and deep-rooting species such as Dalbergia sissoo and Albizia lebbeck tell a different story — studies consistently link them to gains in soil organic carbon, aggregate stability, and microbial activity, all of which matter for rehabilitating the Barind's depleted soils (Saha et al., 2022).

Research Gap and Objectives

Broad species distribution models, including national-scale applications of the CVP Index, have already been used to project habitat loss out to 2100 (Rahman, 2011). What is missing is finer-grained, sub-zonal modeling that ties those projections to real climatic trends on the ground in the Barind sub-zones. There is also a tendency in the literature to judge species purely on survival or purely on soil benefit, rarely both at once. This study therefore sets out to:

- Examine localized rainfall and groundwater level (GWL) trends across the Barind sub-zones.
- Apply the CVP Index to determine site productivity at the sub-zonal level.
- Propose a Dendro-Ecological Zoning model that weighs near-term soil restoration against long-term (2100) habitat resilience.

RESEARCH AND FINDINGS

Study Area

The study covers three contrasting zones within the Rajshahi district portion of the Barind Tract: Puthia, which sees the widest rainfall swings; Paba, a moderate lowland area; and Godagari, characterized by hilly, sloped terrain.

Data Collection and Experimental Logic

Annual rainfall and temperature records spanning 2002 to 2017 were drawn from BMDA zonal archives. Alongside this, performance data — survival rates and soil-feedback indicators such as organic matter and pH — were compiled for five candidate species: Acacia auriculiformis, Dalbergia sissoo, Eucalyptus camaldulensis, Azadirachta indica, and Albizia lebbeck.

CVP Calculation and GIS Suitability Overlay

Each zone's productivity potential was calculated using Paterson's (1956) CVP Index formula, $I = (Tv \times P \times G \times E) / (Ta \times 12)$. The calculation proceeded in four steps.

First, Tv (mean maximum temperature) and Ta (annual temperature range) were drawn from zonal weather station records. Second, P (mean annual precipitation) was derived from the fifteen-year dataset described above. Third, G (growing period) was determined using De Martonne's index. Finally, E (the evapotranspiration/light factor) was standardized for the Rajshahi region's latitude of 24°N.

Spatial suitability zones were then mapped by overlaying climatic layers (mean annual temperature and rainfall) onto edaphic soil-tract layers, for both present-day conditions and a projected 2100 scenario assuming a 4°C temperature rise and a 100 cm shift in precipitation.

Zonal Climatic Fragility

Of the three sub-zones, Puthia stands out as the most climate-vulnerable. Its annual rainfall fell from 1321.9 mm in 2002 to as low as 528.7 mm in 2012, and groundwater followed suit, dropping to a maximum depth of 14.20 m in April 2010. Godagari, despite being roughly 80% hilly and sloped, showed steadier rainfall over the same period — though it remains, on the whole, a low-moisture environment.

Calculated Site Productivity (CVP)

For the central Barind, within the High Ganges river floodplain, the current CVP value works out to 1280, placing it in the "Moist and Dry Sal" productivity class. Puthia's rainfall trajectory, however, points toward a drop below the 1000 threshold by 2100 — a shift that would favor drier, scrub-like vegetation over the timber stands the region currently supports.

Spatio-Temporal Species Shifts

GIS modeling points to substantial habitat loss for several restoration species by 2100, summarized in Table 1 below.

Table 1. Projected Area Shifts for Key Restoration Species (2011–2100)

Species	Present Area (million ha)	Area in 2100 (million ha)	Loss/Gain (%)
Albizia lebbeck	2.33	1.40	-39.91%
Eucalyptus camaldulensis	1.34	1.13	-14.92%
Shorea robusta	0.15	0.60	+34.09%
Terminalia arjuna	0.12	0.60	+25.53%
Heritiera fomes	0.34	0	-100.0%

The Growth-Restoration Trade-off

The data point to a real trade-off in how Barind restoration is currently being done. Eucalyptus and similar exotics establish at rates near 98%, which explains their popularity for quick greening. But that speed comes at a cost: transpiration rates as high as 73.8 L/day per tree under some planting geometries can intensify water stress in already-strained zones like Puthia. Nitrogen-fixing trees grow more slowly at first, but they do the quieter, longer-term work of repairing the Barind's hard-pan soils (Saha et al., 2022).

Resilience of the Mixed-Species Model

The 2100 projections make one thing fairly clear: habitat loss is coming for several of the species currently treated as restoration priorities. Under the DEZ model, zones under heavy stress — Puthia in particular — would be better served moving away from Albizia lebbeck (facing a projected 40% loss) and toward Shorea robusta (a projected 34% gain) and Terminalia arjuna.

Multistoried agroforestry systems, which stack species across different vertical layers, also help here: they raise land-use efficiency (LER greater than 1), boost nutrient cycling through litterfall, and offer some buffer against hailstorms and extreme heat (Banyal et al., 2017).

Significance of Sub-Zonal Indexing

National-level models miss this kind of detail because they do not track localized rainfall trends the way this DEZ model does. Puthia's steep decline is a clear signal that blanket afforestation policies will not hold up across the region. Zoning decisions need to reflect the fact that Paba's groundwater stays comparatively stable thanks to its lowland position, while Puthia needs drought-tolerant "nurse trees" to give soil-building species a chance to establish (Reza et al., 2020).

CONCLUSION

This study points to a fairly clear conclusion: restoration in the Barind Tract cannot keep relying on survival rates alone as its yardstick. Future-oriented climatic suitability indexing needs to take that role instead. The rainfall decline already underway in zones like Puthia means species choices have to be made with 2100 CVP projections in view, not just current performance. A Mixed-Species Dendro-Ecological Model is recommended: fast-growing exotics should be used sparingly, as transitional buffers rather than the backbone of restoration, while the long-term effort is anchored with soil-building nitrogen-fixing trees and climate-resilient species such as Shorea robusta.

Three practical recommendations follow from these findings. First, new deep tube-well installations should be halted in favor of rainwater harvesting and the re-excavation of surface water bodies, as BMDA has already begun doing, to take pressure off the Barind aquifer. Second, the DEZ model should be implemented by using CVP-based habitat projections to guide species distribution decisions in the next phase of BMDA afforestation work. Third, SDG-aligned social forestry should be pursued by encouraging homestead agroforestry built around locally favored species such as mango, mahogany, and coconut, supporting poverty and hunger reduction targets alongside restoration goals (Ruba & Talucder, 2023).

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MACAR FİĞİ (*VİCİA PANNONİCA* CRANTZ) ÇEŞİTLERİNİN TOHUM YAĞ KALİTESİ: HAM YAĞ ORANI VE YAĞ ASİDİ BİLEŞİMİ

SEED OIL QUALITY OF HUNGARIAN VETCH (VICIA PANNONICA CRANTZ) CULTIVARS: CRUDE OIL CONTENT AND FATTY ACID COMPOSITION

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ÖZET

Bu çalışmada, üç Macar fiği (*Vicia pannonica* Crantz) çeşidinin (Ege Beyazı, Göksun Beyazı ve Kral Kızı) tohumlarında ham yağ oranı ile yağ asidi bileşiminin belirlenmesi amaçlanmıştır. Bu kapsamda, çeşitlere ait tohum örneklerinde ham yağ oranı ve on bir yağ asidi (butirik, miristik, miristoleik, palmitik, palmitoleik, stearik, oleik, linoleik, γ-linolenik, lignoserik ve nervonik asit) içeriği üç tekerrürlü olarak saptanmış; veriler tek yönlü varyans analizi (ANOVA) ve Tukey HSD çoklu karşılaştırma testi ile değerlendirilmiştir. İncelenen özelliklerin tamamı bakımından çeşitler arasındaki farklılıklar istatistiksel olarak çok önemli bulunmuştur ($p<0.001$). Ham yağ oranı en yüksek Göksun Beyazı çeşidinde (%2.19) belirlenmiş; Ege Beyazı (%1.70) ile Kral Kızı (%1.66) çeşitleri aynı istatistiksel grupta yer almıştır. Tüm çeşitlerde baskın yağ asidi linoleik asit olmuş, bunu oleik ve palmitik asitler izlemiştir; bu durum Macar fiği tohum yağının doymamış yağ asitlerince zengin olduğunu göstermektedir. Linoleik asit içeriği en yüksek Kral Kızı (%76.07), en düşük ise Göksun Beyazı (%57.35) çeşidinde saptanmıştır. Buna karşılık oleik ve palmitik asit içerikleri en yüksek Göksun Beyazı çeşidinde ölçülürken; γ-linolenik, lignoserik ve nervonik asit içerikleri bakımından Ege Beyazı çeşidi öne çıkmıştır. Sonuç olarak, incelenen Macar fiği çeşitleri ham yağ ve yağ asidi bileşimi yönünden belirgin farklılıklar göstermiş ve her çeşit kendine özgü bir yağ asidi profili sergilemiştir. Elde edilen bulgular, Macar fiği genetik kaynaklarının besinsel değerlendirilmesi ve tohum kalitesi ıslahı açısından değerli bir varyasyon sunduğunu ortaya koymaktadır.

Anahtar Kelimeler: Macar fiği, ham yağ, yağ asidi bileşimi, linoleik asit, çeşit Seed Oil Quality of Hungarian Vetch (*Vicia pannonica* Crantz) Cultivars: Crude Oil Content and Fatty Acid Composition

ABSTRACT

This study aimed to determine the crude oil content and fatty acid composition in the seeds of three Hungarian vetch (*Vicia pannonica* Crantz) cultivars (Ege Beyazı, Göksun Beyazı, and Kral Kızı). Within this scope, the crude oil ratio and the content of eleven fatty acids (butyric, myristic, myristoleic, palmitic, palmitoleic, stearic, oleic, linoleic, γ-linolenic, lignoceric, and nervonic acid) in the seed samples of the cultivars were determined in three replicates; the data were evaluated using one-way analysis of variance (ANOVA) and Tukey's HSD multiple comparison test.

Differences among the cultivars were found to be statistically highly significant for all investigated characteristics ($p<0.001$). The highest crude oil content was determined in the Göksun Beyazı cultivar (2.19%), while the Ege Beyazı (1.70%) and Kral Kızı (1.66%) cultivars were placed in the same statistical group.

Linoleic acid was the predominant fatty acid in all cultivars, followed by oleic and palmitic acids; this indicates that Hungarian vetch seed oil is rich in unsaturated fatty acids. The highest linoleic acid content was detected in the Kral Kızı cultivar (76.07%), whereas the lowest was found in the Göksun Beyazı cultivar (57.35%). Conversely, the highest oleic and palmitic acid contents were measured in the Göksun Beyazı cultivar, while the Ege Beyazı cultivar stood out in terms of γ-linolenic, lignoceric, and nervonic acid contents. In conclusion, the investigated Hungarian vetch cultivars exhibited distinct variations regarding crude oil and fatty acid composition, with each cultivar displaying a specific fatty acid profile.

The findings demonstrate that Hungarian vetch genetic resources offer a valuable variation for nutritional evaluation and seed quality breeding.
Keywords: Hungarian vetch, crude oil, fatty acid composition, linoleic acid, cultivar

Giriş

Macar fiği (*Vicia pannonica* Crantz), soğuğa ve kuraklığa dayanıklı, tek yıllık bir baklagil yem bitkisidir. Yüksek yem verimi, marjinal koşullara uyum yeteneği ve biyolojik azot fiksasyonu yoluyla toprak verimliliğine katkısı nedeniyle yarı kurak ve ılıman bölgelerde yaygın olarak yetiştirilmekte ve sürdürülebilir tarım sistemlerinin önemli bir bileşeni olarak kabul edilmektedir (Kızıl Aydemir vd., 2025; Yılmaz vd., 2015). Türkiye'nin farklı bölgelerinde yürütülen tarla çalışmaları, Macar fiği genotipleri arasında bitki başına bakla sayısı, bin tohum ağırlığı, biyolojik verim, tohum verimi ve hasat indeksi gibi agronomik özellikler bakımından önemli farklılıklar bulunduğunu ortaya koymuş; bu durum, değişken iklim koşulları altında yüksek performanslı genotiplerin seçilmesinde genotip-çevre etkileşimlerinin belirleyici olduğunu göstermiştir (Kızıl Aydemir vd., 2025).

Yem değerinin yanı sıra Macar fiğinin tohum kalitesi özellikleri de giderek daha fazla ilgi görmektedir. Tohum bileşimine ilişkin ayrıntılı çalışmaların büyük bölümü, yakın akraba tür olan yaygın fiğ (*Vicia sativa* L.) üzerinde yoğunlaşmıştır. Bu araştırmalar, yaygın fiğ tohumlarının yüksek ham protein içeriğine; lizin, lösin ve arginin gibi amino asitlerce zengin bir profile ve dengeli bir mineral bileşimine sahip olduğunu, ayrıca uygun işleme koşullarında kanatlı rasyonlarında tahılların bir bölümünün yerini olumsuz etki oluşturmaksızın alabildiğini göstermiştir (Darre vd., 1998a, 1998b). Tohum kalitesinin genotip, kuraklık gibi çevresel etmenler ve rizobiyumlarla kurulan simbiyotik ilişkilerden etkilendiği; bu nedenle ıslah çalışmalarında stres toleransının ve besinsel özelliklerin birlikte değerlendirilmesi gerektiği bildirilmiştir (López-Román vd., 2026).

Vicia cinsi de dâhil olmak üzere baklagil tohum yağları, başta linoleik, α-linolenik ve oleik asit olmak üzere yüksek oranda doymamış yağ asitleri içermeleriyle karakterize edilir. Bu yağ asitleri, hücre zarı bütünlüğünün korunması, bağışıklık işlevlerinin desteklenmesi ve temel metabolik süreçler açısından hem insan hem de hayvan sağlığı için önem taşımaktadır. Dolayısıyla yağ asidi bileşimi, tohum kalitesinin iyileştirilmesini amaçlayan genetik kaynak karakterizasyonu ve ıslah programlarında önemli bir seçim ölçütü olarak kullanılmaktadır (Avramidou vd., 2024; Ramírez-Parra ve De La Rosa, 2023). Yaygın fiğ üzerinde yürütülen çalışmalar, tohum yağı içeriği ve yağ asidi profili bakımından genotipler arasında belirgin bir genetik çeşitlilik bulunduğunu ortaya koymuştur (Avramidou vd., 2024).

Benzer şekilde, genotip-çevre etkileşimlerinin tohum verimi ve besinsel özellikler üzerinde güçlü bir etkiye sahip olduğu ve yüksek verim ile elverişli besinsel nitelikleri bir arada bulunduran kararlı genotiplerin belirlenebildiği gösterilmiştir (Parissi vd., 2022).

Yaygın fiğe kıyasla Macar fiği (*Vicia pannonica* Crantz) tohumlarının ham yağ içeriği ve yağ asidi bileşimi yeterince incelenmemiştir. Bu bilgi eksikliği, türün besinsel potansiyelinin bütüncül biçimde değerlendirilmesini ve tohum kalitesinin iyileştirilmesine yönelik ıslah programlarında kullanımını sınırlandırmaktadır (Ramírez-Parra ve De La Rosa, 2023). Bu çalışmada, üç Macar fiği (*Vicia pannonica* Crantz) genotipinde ham yağ oranı ile yağ asidi bileşiminin belirlenmesi amaçlanmıştır. Elde edilen bulguların, Macar fiği tohumlarının besinsel değerinin ortaya konmasına ve tür içi genetik çeşitliliğin tohum kalitesi ıslahında değerlendirilmesine katkı sağlaması beklenmektedir.

Materyal ve Yöntem

Araştırmada bitkisel materyal olarak üç farklı Macar fiği (*Vicia pannonica* Crantz) genotipi kullanılmıştır. Tarla denemesi, Doğu Akdeniz Geçit Kuşağı Tarımsal Araştırma Enstitüsü Müdürlüğü deneme alanlarında tesadüf blokları deneme desenine göre üç tekerrürlü olarak yürütülmüştür. Ekim işlemi Kasım ayında, hasat ise bitkilerin fizyolojik olgunluğa ulaştığı Haziran ayında gerçekleştirilmiştir. Parseller 1.0 m × 4.0 m (4.0 m²) boyutlarında düzenlenmiş olup, her parsel 25 cm sıra aralığına sahip dört sıradan oluşturulmuştur. Ekimde dekara 10 kg tohumluk kullanılmış ve tohumlar markörle açılan sıralara elle ekilmiştir. Ekimle birlikte dekara 4.5 kg saf azot (N) ve 8.0 kg fosfor (P_2O_5) gübresi uygulanmıştır. Vejetasyon süresince yabancı ot kontrolü el çapası ve elle yolma yöntemleriyle sağlanmıştır. Hasatta kenar etkisini ortadan kaldırmak amacıyla her parselin başlangıç ve bitiş kısımlarından 50'şer cm ile kenarlardaki birer sıra değerlendirme dışı bırakılmış, kalan orta kısım hasat edilerek analizlerde kullanılmıştır.

Deneme Alanının Toprak ve İklim Özellikleri

Deneme alanına ait toprak özellikleri Tablo 1'de verilmiştir. Topraklar her iki derinlikte de tınlı bünyeye sahip olup, hafif alkali (pH 7.51-7.53), yüksek kireç içerikli (%26.71-26.90) ve organik madde (%1.83-1.91) ile alınabilir fosfor bakımından düşük düzeydedir. Alınabilir potasyumun yeterli düzeyde olduğu belirlenmiştir.

Çizelge 1. Deneme alanı topraklarının bazı fiziksel ve kimyasal özellikleri

Derinlik (cm)	Tekstür sınıfı	pH	$CaCO_3$ (%)	P_2O_5 (kg da^{-1})	K_2O (kg da^{-1})	Organik madde (%)
0-30	Tınlı	7.51	26.90	4.85	40.15	1.83
30-60	Tınlı	7.53	26.71	4.55	68.21	1.91

Yetişme dönemine ait iklim verileri Tablo 2'te sunulmuştur. Ortalama sıcaklık (13.05 °C) ve nispi nem (%66.9) değerleri uzun yıllar ortalamalarına oldukça yakın gerçekleşmiştir. Buna karşılık toplam yağış (542.8 mm), uzun yıllar ortalamasından (490.6 mm) daha yüksek olmuş, yağışın önemli bir kısmı Ocak ve Mart aylarında yoğunlaşırken, bitkilerin generatif gelişme dönemine rastlayan Nisan-Haziran aylarında yağışlar uzun yıllar ortalamasının altında kalmıştır.

Tablo 2. Deneme dönemi (2020-2021) ve uzun yıllar (1980-2021) iklim verileri

Aylar	Sıcaklık (°C)		Nispi Nem (%)		Yağış (mm)	
	2020-2021	1980-2021	2020-2021	1980-2021	2020-2021	1980-2021
Kasım	11.39	12.08	73.50	69.40	57.60	57.37
Aralık	7.31	6.70	84.58	78.05	62.60	79.26
Ocak	5.58	5.70	78.70	81.31	226.60	126
Şubat	6.97	7.20	70.04	74.03	32.60	59.37
Mart	10.33	10.50	69.03	71.59	135.20	91.19
Nisan	16.27	16.70	63.49	63.44	16.20	32.62
Mayıs	20.35	20.90	47.76	55.95	12.00	43.84
Haziran	26.17	26.80	48.12	47.63	0.00	0.92
Toplam					542.80	490.57
Ortalama	13.05	13.32	66.9	67.68		

İstatistiksel Analiz

Çalışmada incelenen ham yağ oranı ve yağ asidi bileşimine ait veriler, üç tekerrür (n = 3) esas alınarak değerlendirilmiştir. Her bir özellik için çeşit faktör olacak şekilde tek yönlü varyans analizi (ANOVA) uygulanmış ve çeşitler arasındaki farklılıkların önemliliği F testi ile belirlenmiştir. Varyans analizi sonucunda önemli bulunan özelliklerde ortalamaların karşılaştırılması amacıyla Tukey çoklu karşılaştırma testi kullanılmıştır. Sonuçlar ortalama ± standart sapma olarak verilmiştir (SAS, 1999).

Bulgular

Üç Macar fiği çeşidine ait ham yağ oranı ve yağ asidi bileşimine ilişkin varyans analizi (ANOVA) sonuçları ile Tukey HSD çoklu karşılaştırma testine göre oluşturulan ortalama değerler Tablo 1'de verilmiştir. İncelenen ham yağ ve on bir yağ asidi özelliğinin tamamı bakımından çeşitler arasındaki farklılıklar istatistiksel olarak çok önemli bulunmuştur ($p \leq 0.001$).

Ham yağ oranı bakımından en yüksek değer %2.19 ile Göksun Beyazı çeşidinde belirlenmiş olup, bu değer Ege Beyazı (%1.70) ve Kral Kızı (%1,66) çeşitlerinden önemli ölçüde yüksektir. Ege Beyazı ile Kral Kızı çeşitleri ham yağ oranı yönünden istatistiksel olarak aynı grupta yer almıştır. Yağ asidi bileşiminde tüm çeşitlerde baskın bileşen linoleik asit olmuştur; bunu oleik ve palmitik asitler izlemiştir. Bu durum, Macar fiği tohum yağının doymamış yağ asitleri açısından zengin olduğunu göstermektedir. Linoleik asit içeriği en yüksek Kral Kızı çeşidinde (%76.07), en düşük ise Göksun Beyazı çeşidinde (%57.35) saptanmış; Ege Beyazı (%63.95) ara değer göstermiştir. Buna karşılık, oleik asit en yüksek

Göksun Beyazı (%21.70), en düşük ise Kral Kızı (%13.07) çeşidinde ölçülmüştür. Başlıca doymuş yağ asidi olan palmitik asit bakımından çeşitler belirgin biçimde ayrışmış; en yüksek değer Göksun Beyazı (%12.21), en düşük değer ise Kral Kızı (%3.44) çeşidinde belirlenmiştir. Stearik asit en yüksek miktarda Göksun Beyazı (%1.63) çeşidinde bulunmuştur. γ-Linolenik asit içeriği en yüksek Ege Beyazı çeşidinde (%6.31) saptanmıştır. Uzun zincirli yağ asitlerinden lignoserik asit (%0.419) ve nervonik asit (%0.662) bakımından en yüksek değerler Ege Beyazı çeşidinde ölçülmüştür. Genel olarak, incelenen özelliklerin tamamında çeşitler arasında istatistiksel açıdan önemli farklılıkların bulunması, Macar fiği genetik kaynaklarında ham yağ ve yağ asidi bileşimi yönünden kayda değer bir çeşitlilik olduğunu ve her çeşidin kendine özgü bir yağ asidi profili taşıdığını ortaya koymaktadır.

Tablo 3. Macar fiği çeşitlerinin ham yağ oranı ve yağ asidi bileşimi (%) ile önemlilik düzeyleri

Özellikler (%)	Ege Beyazı	Göksun Beyazı	Kral Kızı	Önem
Ham yağ	1.70 ± 0.01^{b}	2.19 ± 0.04^{a}	1.66 ± 0.02^{b}	***
Butirik asit (C4:0)	0.222 ± 0.002^{b}	0.122 ± 0.002^{c}	0.330 ± 0.003^{a}	***
Miristik asit (C14:0)	0.179 ± 0.002^{b}	0.473 ± 0.009^{a}	0.185 ± 0.002^{b}	***
Miristoleik asit (C14:1)	0.239 ± 0.002^{a}	0.134 ± 0.003^{b}	0.110 ± 0.001^{c}	***
Palmitik asit (C16:0)	8.61 ± 0.09^{b}	12.21 ± 0.24^{a}	3.44 ± 0.03^{c}	***
Palmitoleik asit (C16:1)	0.079 ± 0.001^{c}	0.270 ± 0.005^{a}	0.154 ± 0.002^{b}	***
Stearik asit (C18:0)	1.42 ± 0.01^{b}	1.63 ± 0.03^{a}	1.23 ± 0.01^{c}	***
Oleik asit (C18:1)	17.91 ± 0.18^{b}	21.70 ± 0.43^{a}	13.07 ± 0.13^{c}	***
Linoleik asit (C18:2)	63.95 ± 0.64^{b}	57.35 ± 1.15^{c}	76.07 ± 0.76^{a}	***
γ-Linolenik asit (C18:3)	6.31 ± 0.06^{a}	5.87 ± 0.12^{b}	4.99 ± 0.05^{c}	***
Lignoserik asit (C24:0)	0.419 ± 0.004^{a}	0.111 ± 0.002^{b}	0.110 ± 0.001^{b}	***
Nervonik asit (C24:1)	0.662 ± 0.007^{a}	0.122 ± 0.002^{c}	0.309 ± 0.003^{b}	***

*Değerler ortalama ± standart sapma (n=3) olarak verilmiştir. Aynı satırda farklı üst simge harfleri taşıyan ortalamalar arasındaki fark Tukey HSD testine göre önemlidir. Ham yağ oranı tohumdaki % ağırlık, yağ asitleri ise toplam yağ asitleri içindeki % oranı olarak ifade edilmiştir. ***: $p<0.001$.*

Tartışma

Bu çalışmada, üç Macar fiği (*Vicia pannonica* Crantz) çeşidinin ham yağ oranı ve yağ asidi bileşimi bakımından istatistiksel olarak çok önemli düzeyde ($p \leq 0.001$) farklılaştığı belirlenmiştir. Ham yağ oranı %1.66-2.19 arasında değişmiş ve en yüksek değer Göksun Beyazı çeşidinde saptanmıştır. Baklagil tohumlarında yağ birikiminin genotip, çevre koşulları ve yetiştirme uygulamalarının ortak etkisiyle şekillendiği bilindiğinden, aynı çevre koşullarında yetiştirilen çeşitler arasında gözlenen bu farklılık büyük ölçüde genotipik kaynaklıdır ve Macar fiğinde yağ verimi yönünden genotip seçiminin belirleyici olabileceğini göstermektedir.

İncelenen tüm çeşitlerde baskın yağ asidi linoleik asit (C18:2) olmuş, bunu oleik (C18:1) ve palmitik asit (C16:0) izlemiştir. Doymamış yağ asitlerinin toplam yağ asitlerinin büyük bölümünü oluşturması, *Vicia* türlerinin tohum yağlarında linoleik ve oleik asidin baskın bileşenler olduğunu bildiren önceki çalışmalarla (Pastor-Cavada vd., 2009; Renna vd., 2014) genel olarak uyumludur. Bununla birlikte, çeşitler arasında ve söz konusu çalışmalardaki yabani *Vicia* taksonlarına kıyasla gözlenen oransal farklılıklar, yağ asidi bileşiminin tür, genotip ve çevre etkileşimine bağlı olarak değişebileceğini göstermektedir. Linoleik asit, insan ve hayvan beslenmesinde esansiyel bir omega-6 yağ asidi olup hücre zarı bütünlüğü, büyüme ve bağışıklık işlevlerinde rol oynamaktadır; bu nedenle Kral Kızı çeşidinde belirlenen yüksek linoleik asit oranı (%76.07), bu çeşidin beslenme kalitesi açısından öne çıkan bir potansiyel taşıdığını göstermektedir.

Oleik asit bakımından ise Göksun Beyazı çeşidi (%21.70) diğer çeşitlerden önemli ölçüde yüksek değer vermiştir. Tekli doymamış bir yağ asidi olan oleik asit, tohum yağının oksidatif stabilitesini artırarak raf ömrünü uzatmakta ve depolama niteliklerini iyileştirmektedir; bu avantaj yer fıstığı ve mısır gibi yağlı tohumlarda da iyi bilinmektedir (Otyama vd., 2021; Wassom vd., 2008). Çeşitler arasında linoleik ve oleik asit içerikleri arasında gözlenen ters yönlü değişim (Kral Kızı'nda yüksek linoleik–düşük oleik, Göksun Beyazı'nda düşük linoleik–yüksek oleik), oleik asidi linoleik aside dönüştüren Δ12-desatüraz

(FAD2) enzimindeki genotipik farklılıklarla açıklanabilir. Bu enzim aktivitesinin yüksek olduğu genotiplerde oleik asit linoleik aside daha fazla dönüştürülmekte ve dolayısıyla linoleik asit birikmektedir. Benzer genetik kontrol örüntüleri çeşitli baklagil ve yağlı tohum türlerinde de bildirilmiş olup (Wang vd., 2015; Wassom vd., 2008), bulgularımız bu çalışmalarla uyumludur.

Palmitik ve stearik asit gibi doymuş yağ asitleri de çeşitlere bağlı olarak önemli farklılık göstermiş; ancak toplam yağ asitleri içinde doymamış yağ asitlerine kıyasla daha düşük bir oran oluşturmuştur. Doymamış yağ asitlerinin baskın olması, lipid profili ve kardiyovasküler sağlık üzerindeki olumlu etkileri nedeniyle Macar fiği tohumlarının besinsel değerini artıran arzu edilen bir özelliktir (Renna vd., 2014).

Öte yandan, Ege Beyazı çeşidinde belirlenen yüksek γ-linolenik asit (%6.31), lignoserik asit (%0,419) ve nervonik asit (%0.662) içerikleri, bu çeşidin yalnızca temel yağ asitleri bakımından değil, biyolojik öneme sahip uzun zincirli yağ asitleri açısından da öne çıktığını göstermektedir. γ-Linolenik asit, anti-enflamatuar ve sağlığı destekleyici özellikleriyle; nervonik asit ise sinir dokusu gelişimi ve işleviyle ilişkilendirilmektedir. Bu yağ asitlerinin varlığı, Macar fiği tohumlarının temel besin değerinin ötesinde işlevsel (fonksiyonel) özellikler de sunabileceğine işaret etmektedir. Söz konusu yağ asitlerinin biyosentezi de genetik düzenleme altında olup, yağ asidi sentezini yönlendiren transkripsiyon faktörleri ve ilgili genlerin bu birikimde belirleyici olduğu bildirilmektedir (Li vd., 2026).

İncelenen tüm özelliklerde çeşitler arasındaki farklılıkların istatistiksel olarak çok önemli bulunması ($p \leq 0.001$), yağ asidi bileşiminin büyük ölçüde genetik kontrol altında olduğunu güçlü biçimde ortaya koymaktadır. Bu durum, ilgili türlerde yürütülen moleküler genetik ve QTL haritalama çalışmalarıyla da uyumlu olup (Otyama vd., 2021; Wang vd., 2015), söz konusu genetik değişkenliğin tohum yağı kalitesini artırmayı amaçlayan ıslah programları için değerli bir kaynak oluşturduğunu göstermektedir.

Sonuç olarak, Macar fiği çeşitleri yağ asidi bileşimi bakımından belirgin genetik farklılıklar sergilemiş; Kral Kızı yüksek linoleik asit, Göksun Beyazı yüksek ham yağ ve oleik asit, Ege Beyazı ise γ-linolenik, lignoserik ve nervonik asit içerikleriyle öne çıkmıştır. Bu bulgular, Macar fiğinde yağ asidi bileşiminin çeşit seçiminde dikkate alınabilecek önemli bir kalite kriteri olduğunu ve besinsel değeri yüksek yeni çeşitlerin geliştirilmesine yönelik ıslah çalışmalarına katkı sağlayabileceğini göstermektedir.

Sonuç ve Öneriler

Bu çalışmada üç Macar fiği çeşidi, ham yağ oranı ve yağ asidi bileşimi bakımından istatistiksel olarak önemli düzeyde farklılaşmış ve her çeşit kendine özgü bir profil sergilemiştir. Ham yağ oranı en yüksek Göksun Beyazı çeşidinde belirlenirken, tüm çeşitlerde yağ asidi bileşiminde linoleik asit başta olmak üzere doymamış yağ asitleri egemen olmuştur. Buna göre, yüksek çoklu doymamış yağ asidi içeriği için Kral Kızı, yüksek ham yağ ve oleik asit içeriği için Göksun Beyazı, uzun zincirli ve γ-linolenik asitçe zengin bir profil için ise Ege Beyazı öne çıkmakta; bu durum, Macar fiği genetik kaynaklarının tohum kalitesi ıslahında değerlendirilebilecek önemli bir çeşitlilik taşıdığını göstermektedir.

Bununla birlikte, sonuçların sınırlı sayıda çeşitten ve tek bir üretim koşulundan elde edildiği göz önünde bulundurulmalıdır. Yağ asidi bileşimi genotipin yanında çevresel etmenlerden de etkilendiğinden, bulguların farklı lokasyon ve yıllarda tekrarlanarak kararlı çeşitlerin belirlenmesi ve daha geniş bir genetik kaynağın taranması yararlı olacaktır. Bu tür çalışmaların yaygınlaştırılması, Macar fiğinin besinsel değerinin ortaya konmasına ve yem, gıda ve endüstriyel açıdan kaliteli bir baklagil tohumu kaynağı olarak kullanım potansiyelinin genişlemesine katkı sağlayacaktır.

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KAHRAMANMARAŞ DOĞAL FLORASINDAN TOPLANAN EŞEK GÜRÜLÜ (*VİCİA SATİVA* SUBSP. *NİGRA* (L.) EHRH.) GENOTİPLERİNİN BAZI MORFOLOJİK VE TOHUM ÖZELLİKLERİ BAKIMINDAN KARAKTERİZASYONU

CHARACTERIZATION OF NARROW-LEAVED VETCH (VICIA SATIVA SUBSP. NIGRA (L.) EHRH.) GENOTYPES COLLECTED FROM KAHRAMANMARAŞ NATURAL FLORA IN TERMS OF SOME MORPHOLOGICAL AND SEED CHARACTERISTICS

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ÖZET

Bu araştırmada, Kahramanmaraş doğal florasından toplanan üç Eşek gürülü (*Vicia sativa* subsp. *nigra* (L.) Ehrh.) genotipinin bazı morfolojik ve tohum özellikleri bakımından karakterizasyonu amaçlanmıştır. Çalışmada B19, B27 ve B51 genotipleri kullanılmış; bitki boyu, sap kalınlığı, yan dal sayısı, çiçek sayısı, yaprakçık boyu, yaprakçık eni, yaprakçık sayısı, çimlenme oranı, bakla boyu, bakla eni, baklada tohum sayısı ve bin tane ağırlığı incelenmiştir. Ölçüm ve gözlemler her genotipte 10 bitki üzerinden gerçekleştirilmiş elde edilen veriler ortalama, minimum, maksimum ve standart sapma değerleri kullanılarak değerlendirilmiştir.

Genotipler arasında incelenen tüm özellikler bakımından önemli düzeyde morfolojik varyasyon belirlenmiştir. B27 genotipi bitki boyu (92.20 cm), sap kalınlığı (3.46 mm), yan dal sayısı (3.60 adet), çiçek sayısı (18.30 adet), yaprakçık eni (0.91 cm), çimlenme oranı (%84), bakla boyu (6.44 cm) ve bakla eni (0.73 cm) bakımından en yüksek ortalama değerlere sahip olmuştur. B51 genotipi yaprakçık boyu (2.18 cm), yaprakçık sayısı (258.80 adet) ve bin tane ağırlığında (58.35 g) öne çıkarken, B19 genotipi baklada tohum sayısı bakımından (5.80 adet) en yüksek değeri göstermiştir. Sonuç olarak, doğal floradan toplanan Eşek gürülü genotipleri arasında önemli düzeyde morfolojik çeşitlilik bulunduğu belirlenmiştir. Özellikle B27 ve B51 genotiplerinin üstün performans gösteren özellikleri nedeniyle fiğ ıslah programlarında ebeveyn materyali olarak değerlendirilme potansiyeline sahip olduğu sonucuna varılmıştır.

Anahtar Kelimeler: *Vicia sativa* subsp. *nigra*, genetik kaynak, morfolojik karakterizasyon, doğal flora, tohum özellikleri

ABSTRACT

This study aimed to characterize three narrow-leaved vetch (*Vicia sativa* subsp. *nigra* (L.) Ehrh.) genotypes collected from the natural flora of Kahramanmaraş in terms of some morphological and seed characteristics. Genotypes B19, B27, and B51 were utilized in the study; and plant height, stem thickness, number of lateral branches, number of flowers, leaflet length, leaflet width, number of leaflets, germination rate, pod length, pod width, number of seeds per pod, and thousand-seed weight were investigated. Measurements and observations were performed on 10 plants for each genotype, and the obtained data were evaluated using mean, minimum, maximum, and standard deviation values.

A significant level of morphological variation was determined among the genotypes for all investigated characteristics. The B27 genotype exhibited the highest mean values for plant height (92.20 cm), stem thickness (3.46 mm), number of lateral branches (3.60), number of flowers (18.30), leaflet width (0.91 cm), germination rate (84%), pod length (6.44 cm), and pod width (0.73 cm). While the B51 genotype stood out in terms of leaflet length (2.18 cm), number of leaflets (258.80), and thousand-seed weight (58.35 g), the B19 genotype showed the highest value for the number of seeds per pod (5.80). In conclusion, it was determined that there is a significant level of morphological diversity among the

narrow-leaved vetch genotypes collected from the natural flora. It was concluded that particularly genotypes B27 and B51 have the potential to be evaluated as parental material in vetch breeding programs due to their superior performing characteristics.
Keywords: *Vicia sativa* subsp. *nigra*, genetic resource, morphological characterization, natural flora, seed characteristics

Giriş

Yem bitkileri, hayvancılıkta gereksinim duyulan yüksek kaliteli kaba yemin başlıca kaynağını oluşturarak sürdürülebilir üretim sistemlerinin temelini oluşturmaktadır. Baklagil yem bitkileri, yüksek protein içeriği ve simbiyotik azot fiksasyonu yoluyla toprak verimliliğine sağladıkları katkı nedeniyle bu grup içinde ayrı bir öneme sahiptir. *Vicia* cinsine ait fiğ türleri, özellikle adi fiğ (*Vicia sativa* L.), yüksek besin değeri, azot bağlama kapasitesi ve farklı ekolojik koşullara uyum yeteneği sayesinde dünya genelinde yaygın olarak yetiştirilmektedir (Avramidou vd., 2024; De La Rosa vd., 2021). Bu tür içinde yer alan *Vicia sativa* subsp. *nigra* (L.) Ehrh. (eşek gürülü), Türkiye'nin farklı yükselti ve ekolojik bölgelerinde doğal olarak yayılış gösteren tek yıllık bir baklagildir. Türkiye, geniş ancak büyük ölçüde karakterize edilmemiş bir *Vicia* çeşitliliğine sahip önemli bir gen merkezi konumundadır (Cil & Tiryaki, 2015; Kim vd., 2015).

Kültür bitkilerinin yabani akrabaları ve doğal popülasyonları, biyotik ve abiyotik streslere karşı adaptasyon sağlayan geniş bir alel çeşitliliği barındırdıklarından, iklim değişikliği koşullarında dayanıklı çeşitlerin geliştirilmesi için değerli genetik kaynaklar olarak kabul edilmektedir (Kapazoglou vd., 2023; Prohens vd., 2017). Fiğde son yıllarda referans genom düzeyinde dizilerin ve moleküler işaretleyicilerin geliştirilmesi bu kaynaklardan yararlanma olanaklarını artırmış olsa da (Xi vd., 2022), mevcut çeşitliliğin ıslahda etkin kullanımı öncelikle bu materyallerin ayrıntılı biçimde tanımlanmasına bağlıdır. Nitekim farklı *Vicia sativa* genotiplerinin nodülasyon ve azot fiksasyon kapasitelerinde önemli varyasyon bulunması, üstün genotiplerin seçiminin hem yem verimi hem de sürdürülebilir üretim açısından taşıdığı değeri ortaya koymaktadır (López-Román vd., 2025).

Bitki genetik kaynaklarının morfolojik ve agronomik karakterizasyonu, bu kaynakların korunması ve ıslah programlarında etkin kullanımı için kritik bir ilk adımdır (Flores-Sánchez vd., 2025; Salgotra & Chauhan, 2023). Sap kalınlığı, yan dal sayısı, yaprakçık özellikleri, çiçek sayısı ile bakla ve tohuma ilişkin özellikler gibi bitkisel karakterlerin değerlendirilmesi, genetik varyasyonun belirlenmesini ve üstün genotiplerin seçilmesini sağlamaktadır. Türkiye'nin doğal florasından toplanan genetik materyaller üzerinde yürütülen benzer karakterizasyon çalışmaları hem tür içi varyasyonun belgelenmesinde hem de ıslah için umut vadeden ebeveynlerin belirlenmesinde bu yaklaşımın etkinliğini göstermiştir (Bozokalfa & Eşiyok, 2011; Karaköy vd., 2013; Yılmaz vd., 2017).

Bununla birlikte, Türkiye florasında doğal olarak bulunan *Vicia sativa* subsp. *nigra* (L.) genotiplerine yönelik çalışmaların büyük bölümü taksonomik tanımlama ve floristik kayıtlarla sınırlı kalmış; farklı lokasyonlardan toplanan genotiplerin morfolojik özellikleri arasındaki varyasyonu ortaya koyan kapsamlı araştırmaların sayısı ise oldukça yetersiz kalmıştır. Bu durum, mevcut genetik kaynakların ıslah programlarında etkin biçimde değerlendirilmesini sınırlamaktadır.

Bu çalışmada, Kahramanmaraş'ın doğal florasından toplanan üç *Vicia sativa* subsp. *nigra* (L.) Ehrh. genotipinin; sap kalınlığı (mm), yan dal sayısı (adet), çiçek sayısı (adet), yaprakçık boyu (cm), yaprakçık eni (cm), yaprakçık sayısı (adet), çimlenme oranı (%), bakla boyu (cm), bakla eni (cm), baklada tohum sayısı (adet) ve bin tane ağırlığı (g) gibi bazı morfolojik ve tohum özellikleri bakımından karakterize edilmesi amaçlanmıştır. Elde edilecek bulguların, doğal genetik kaynaklardaki varyasyonun ortaya konulmasına, üstün özelliklere sahip genotiplerin belirlenmesine ve gelecekte yürütülecek fiğ ıslah programlarına genetik materyal sağlanmasına katkıda bulunacağı düşünülmektedir.

Materyal ve Yöntem

Materyal

Bu çalışmanın materyalini, Kahramanmaraş ilinin doğal florasından toplanan üç *Vicia sativa* subsp. *nigra* (L.) Ehrh. (eşek gürülü) genotipi (B19, B27 ve B51) oluşturmuştur. Genotipler, Doğu Akdeniz Geçit Kuşağı Tarımsal Araştırma Enstitüsü Müdürlüğü'nün görev ve sorumluluk alanına giren bölgelerde yürütülen survey ve toplama çalışmaları sırasında, doğal yayılış gösterdikleri alanlardan elde edilmiştir. Materyal toplanan alanların yöre adı, yükseklik ve hâkim bitki örtüsü gibi ekolojik verileri

belirlenmiş; her bir örneğe ait rakım, enlem ve boylam değerleri GPS cihazı kullanılarak kaydedilmiştir. Genotiplere ait konum bilgileri ve mevkileri Tablo 1'de verilmiştir. Genotiplerin tamamı Kahramanmaraş ili sınırları içerisinde, 855–1407 m arasında değişen rakımlardaki doğal alanlardan toplanmıştır.

Tablo 1. Vicia sativa subsp. nigra (L.) Ehrh. genotiplerinin toplandığı alanların konum bilgileri

Genotip	Koordinatlar (Kuzey – Doğu)	Mevkii	İlçe	Rakım (m)
B19	37° 58′ 30.26″ K – 36° 27′ 13.61″ D	Kabaklar	Andırın	855
B27	38° 05′ 09.90″ K – 36° 24′ 25.36″ D	Andırın Yolu	Andırın	1275
B51	37° 31′ 35.12″ K – 36° 28′ 33.68″ D	Değirmendere	Göksun	1407

Yöntem

Doğal floradan ilk toplandıklarında tohum miktarı sınırlı olduğundan, her bir genotipe ait tohumlar öncelikle saksılarda çoğaltılmıştır. Bu amaçla 25 cm çapında ve 35 cm yüksekliğindeki saksılara 3/5 oranında tarla toprağı, 1/5 oranında torf ve 1/5 oranında perlit doldurulmuş; her saksıya eşit aralıklarla 5'er tohum ekilmiş ve çıkış tamamlandıktan sonra her saksıda iyi gelişmiş 3'er bitki bırakılmıştır. Bakla bağlama dönemine kadar düzenli sulama ve yabancı ot temizliği yapılmış, olgunlaşan baklalardaki tohumlar dökülmeden hasat edilerek tarla ekimine hazır hâle getirilmiştir.

Tarla çalışmaları, Kahramanmaraş ili Merkez ilçesinde Enstitü arazisinde yürütülmüştür. Deneme alanı Türkiye'nin Doğu Akdeniz Bölgesi'nde, 37° 38′ kuzey enlemi ile 36° 37′ doğu boylamı arasında yer almakta olup ortalama rakımı 568 metredir. Yörede esas itibarıyla Akdeniz iklimi etkili olup gece-gündüz arası sıcaklık farkı düşüktür; mevsimler arası sıcaklık farkı ise yüksektir; kışlar genellikle ılık ve yağışlı, yazlar ise sıcak ve kuraktır. Ekim öncesi tarla sürülüp bastırılarak iyi bir tohum yatağı hazırlanmış; her genotip için birer metre uzunluğunda sıralar oluşturularak tohumlar sıralara eşit şekilde yayılmış ve sıralar üzeri kapatılmıştır. Ekim 2018 yılının Ocak ayı ortasında gerçekleştirilmiş, ölçüm ve gözlemlere Mart ayında başlanmış, hasat ise Haziran ayında başlamış ve Temmuz ayında tamamlanmıştır.

Toprak analiz sonuçları dikkate alınarak, çalışmanın yürütüldüğü topraklara diamonyum fosfat (18-46-0) kimyevi gübresi 5 kg/da N ve 12 kg/da P_2O_5 olacak şekilde, açılan sıraların yanına homojen olarak verilip toprakla karıştırılmıştır. Deneme alanının 2018 yılına ait toprak analiz sonuçları Tablo 2'de sunulmuştur. Buna göre deneme toprağı killi-tınlı bünyede, hafif alkali (pH 7.84), tuzsuz, kireç oranı yüksek, organik madde bakımından fakir, yarayışlı fosfor bakımından az, yarayışlı potasyum bakımından orta düzeydedir (Anonim, 2018a).

Tablo 2. Deneme yerine ait 2018 toprak analiz sonuçları

Ölçülen Değer	Sonuçlar	Değerlendirme
Saturasyon (su ile doygunluk) %	69	Killi-Tınlı
pH	7.84	Hafif Alkali
EC (dS m^{-1})	0.89	Tuzsuz
Kireç %	22.33	Fazla Kireçli
Organik Madde %	1.32	Az
Yarayışlı Fosfor (P_2O_5) (kg da^{-1})	3.77	Az
Yarayışlı Potasyum (K_2O) (kg da^{-1})	16.9	Orta
Ca (ppm)	8814	İyi
Mg (ppm)	336	İyi
Cu (ppm)	2.67	Yeterli
Fe (ppm)	4.10	İyi
Mn (ppm)	2.98	Çok Az
Zn (ppm)	1.46	Yeterli

Deneme alanına ait 2018 yılı ve uzun yıllar (1930-2018) iklim verileri Çizelge 3'te sunulmuştur. Denemenin yürütüldüğü 2018 yılında ortalama sıcaklık (17.62 °C), uzun yıllar ortalamasından (15.93 °C) daha yüksek; toplam yağış (356.60 mm), uzun yıllar ortalamasından (459.40 mm) daha yüksek; ortalama nispi nem (%65.62) ise uzun yıllar ortalamasından (%58.60) daha yüksek gerçekleşmiştir (Anonim, 2018b).

Çizelge 3. Deneme yerine ait 2018 yılı ve uzun yıllar (1930-2018) iklim verileri

Aylar	Sıcaklık (°C)		Yağış (mm)		Nispi Nem (%)	
	2018	1930-2018	2018	1930-2018	2018	1930-2018
Ocak	6.76	4.90	164.60	130.00	81.14	70.30
Şubat	9.01	6.50	68.20	109.90	81.60	66.70
Mart	13.79	10.70	54.20	96.30	72.08	60.60
Nisan	17.89	15.50	48.80	72.80	54.67	58.00
Mayıs	21.44	20.30	1.60	41.90	61.71	54.70
Haziran	25.52	25.20	17.00	7.40	56.13	49.20
Temmuz	28.90	28.40	2.20	1.10	52.01	50.70
Toplam	**-**	**-**	**356.60**	**459.40**	**-**	**-**
Ortalama	**17.62**	**15.9**	**-**	**-**	**65.62**	**58.60**

İncelenen Özellikler

Genotiplerde morfolojik, tohum ve çimlenme özelliklerinin belirlenmesine yönelik ölçüm ve gözlemler her sıradan 10'ar bitki üzerinden yapılmıştır (Tokluoğlu, 1979; Sağsöz, 1995). Araştırmada incelenen özelliklerden sap kalınlığı, örnek alınan bitkilerde ana dalın orta kısmından kumpas yardımıyla milimetre (mm) cinsinden ölçülmüştür. Yan dal sayısı, bitkiler çiçeklenme dönemine ulaştığında kök boğazından çıkan ana dal dışında kalan dalların sayılmasıyla belirlenmiştir. Çiçek sayısı ise örneklenen her bir bitki üzerindeki tüm çiçek ve çiçekçiklerin sayılmasıyla adet olarak tespit edilmiştir. Yaprak özelliklerinin belirlenmesinde her bitkinin alt yarısından rastgele seçilen 10 yaprak kullanılmıştır. Yaprakçık boyu ve yaprakçık eni cetvel yardımıyla santimetre (cm) cinsinden ölçülmüş, yaprakçık sayısı ise örnek alınan bitkilerdeki toplam yaprakçıkların sayılmasıyla adet olarak belirlenmiştir. Meyve (bakla) özelliklerinin belirlenmesi amacıyla olgunlaşma öncesinde örnek alınan bitkilerden seçilen 10 baklada ölçümler yapılmıştır. Bakla boyu ve bakla eni santimetre (cm) cinsinden ölçülmüş; baklalar çatlamadan önce her bir örnek bitkiden alınan 10 bakladaki tohumlar sayılmak suretiyle baklada tohum sayısı adet olarak belirlenmiştir. Bin tane ağırlığının belirlenmesinde, hasat sonrası her genotipe ait tohumlardan dört tekerrürlü olarak 100'er adet tohum sayılmış; elde edilen değerler 10 ile çarpılarak bin tane ağırlığı hesaplanmış ve sonuçlar gram (g) cinsinden ifade edilmiştir. Çimlenme testi için her genotipten dört tekerrürlü olacak şekilde 100'er tohum kurutma kâğıdı üzerinde çimlendirmeye alınmıştır. Çimlenen tohumlar iki gün arayla sayılmış ve sayımlar tohumlar canlılığını yitirinceye kadar sürdürülmüştür. Elde edilen sonuçlar kullanılarak çimlenme oranı yüzde (%) olarak hesaplanmıştır.

Elde edilen verilerden her bir genotip ve özellik için ortalama, en düşük (minimum), en yüksek (maksimum) değerler ile standart sapma hesaplanmış ve genotipler arasındaki morfolojik varyasyon tanımlayıcı istatistikler yardımıyla değerlendirilmiştir.

Bulgular

Tablo 1'de Eşek gürülü (*Vicia sativa* subsp. *nigra* (L.) Ehrh.) genotiplerine ait bazı morfolojik özelliklerin ortalama, minimum, maksimum ve standart sapma değerleri verilmiştir. İncelenen özellikler bakımından genotipler arasında belirgin farklılıklar olduğu görülmüştür.

Bitki boyu bakımından en yüksek ortalama değer B27 genotipinde 92.20 cm, en düşük değer ise B19 genotipinde 58.60 cm olarak belirlenmiştir. B51 genotipi ise 65.00 cm bitki boyu ile bu iki genotip arasında yer almıştır. Sap kalınlığı 3.16-3.46 mm arasında değişmiş olup en yüksek ortalama değer B27 genotipinde, en düşük değer ise B51 genotipinde saptanmıştır. Yan dal sayısı bakımından da B27 genotipi (3.60 adet) ilk sırada yer alırken, bunu B51 (3.20 adet) ve B19 (2.40 adet) genotipleri izlemiştir. Çiçek sayısı bakımından en yüksek ortalama değer 18.30 adet ile B27 genotipinde belirlenmiş, B51

genotipi (17.90 adet) benzer değer gösterirken, en düşük çiçek sayısı 14.20 adet ile B19 genotipinde tespit edilmiştir. Yaprak özellikleri incelendiğinde, yaprakçık boyu 1.98-2.18 cm arasında değişmiş ve en yüksek ortalama değer B51 genotipinde belirlenmiştir. Yaprakçık eni bakımından ise B27 genotipi (0.91 cm) diğer genotiplerden daha yüksek değer göstermiştir. Yaprakçık sayısı bakımından genotipler arasında oldukça belirgin farklılıklar bulunmuş; en yüksek ortalama 258.80 adet ile B51 genotipinde, en düşük değer ise 98.00 adet ile B19 genotipinde belirlenmiştir. Çimlenme oranı %74.00-84.00 arasında değişmiş olup en yüksek değer B27, en düşük değer ise B19 genotipinde saptanmıştır.
Meyve (bakla) özellikleri bakımından da genotipler arasında önemli farklılıklar gözlenmiştir. En uzun bakla 6.44 cm ile B27 genotipinde belirlenirken, en kısa bakla 2.72 cm ile B19 genotipinde ölçülmüştür. Benzer şekilde, bakla eni bakımından da en yüksek ortalama değer 0.73 cm ile B27 genotipinde, en düşük değer ise 0.32 cm ile B19 genotipinde belirlenmiştir. Baklada tohum sayısı 4.00-5.80 adet arasında değişmiş, en yüksek ortalama B19 genotipinde (5.80 adet), en düşük değer ise B51 genotipinde (4.00 adet) tespit edilmiştir. Bin tane ağırlığı bakımından ise B51 genotipi 58.35 g ile en yüksek değere sahip olurken, B19 (51.66 g) ve B27 (51.91 g) genotipleri birbirine oldukça yakın değerler göstermiştir. Genotipler içerisinde B27, bitki boyu, sap kalınlığı, yan dal sayısı, çiçek sayısı, yaprakçık eni, çimlenme oranı ile bakla boyu ve bakla eni bakımından öne çıkarken, B51 yaprakçık boyu, yaprakçık sayısı ve bin tane ağırlığı bakımından üstünlük göstermiştir. Buna karşılık B19 genotipi incelenen birçok morfolojik özellik bakımından daha düşük değerlere sahip olmasına rağmen baklada tohum sayısı açısından diğer genotiplerden daha yüksek performans sergilemiştir.

Tablo 1. Eşek Gürülü (Vicia Sativa Subsp. Nigra (L.) Ehrh.) Genotiplerinin Bazı Morfolojik Özelliklerine Ait Ortalama, Minimum, Maksimum Ve Standart Sapma Değerleri

POP. NO.	**Bitki boyu (cm)**				**Sap kalınlığı (mm)**				**Yan dal sayısı (adet)**				**Çiçek sayısı (adet)**			
Ort.	**Min.**	**Mak.**	**S. sapma**	**Ort.**	**Min.**	**Mak.**	**S. sapma**	**Ort.**	**Min.**	**Mak.**	**S. sapma**	**Ort.**	**Min.**	**Mak.**	**S. sapma**	
B19	58.60	45.00	69.00	8.78	3.26	2.90	3.60	0.29	2.40	1.00	4.00	1.07	14.20	11.00	17.00	1.87
B27	92.20	83.00	100.00	5.61	3.46	2.90	4.00	0.38	3.60	2.00	5.00	1.07	18.30	15.00	22.00	2.54
B51	65.00	50.00	75.00	8.72	3.16	2.90	3.50	0.25	3.20	2.00	4.00	0.79	17.90	14.00	22.00	2.81

Pop. No.	**Yaprakçık boyu (cm)**				**Yaprakçık eni (cm)**				**Yaprakçık sayısı (adet)**				**Çimlenme testi (%)**			
Ort.	**Min.**	**Mak.**	**S. sapma**	**Ort.**	**Min.**	**Mak.**	**S. sapma**	**Ort.**	**Min.**	**Mak.**	**S. sapma**	**Ort.**	**Min.**	**Mak.**	**S. sapma**	
B19	1.98	1.80	2.20	0.15	0.62	0.60	0.65	0.02	98.00	90.00	106.00	5.50	74.00	69.00	80.00	5.35
B27	2.14	1.80	2.40	0.25	0.91	0.85	0.95	0.04	166.40	156.00	180.00	8.78	84.00	79.00	89.00	5.23
B51	2.18	1.90	2.40	0.18	0.54	0.49	0.60	0.04	258.80	240.00	280.00	14.21	76.50	70.00	84.00	6.61

Pop. No.	**Meyve (bakla) boyu (cm)**				**Meyve (bakla) eni (cm)**				**Meyvede (baklada) tohum sayısı (adet)**				**Bin tane ağırlığı (g)**			
Ort.	**Min.**	**Mak.**	**S. sapma**	**Ort.**	**Min.**	**Mak.**	**S. sapma**	**Ort.**	**Min.**	**Mak.**	**S. sapma**	**Ort.**	**Min.**	**Mak.**	**S. sapma**	
B19	2.72	2.50	3.00	0.18	0.32	0.28	0.39	0.04	5.80	4.00	7.00	0.92	51.66	48.69	55.52	2.89
B27	6.44	6.00	6.70	0.25	0.73	0.69	0.80	0.04	5.40	3.00	7.00	1.07	51.91	46.97	57.69	4.55

B51	4.28	4.00	4.50	0.18	0.41	0.39	0.45	0.02	4.00	3.00	5.00	0.82	58.35	55.52	61.74	2.56

TARTIŞMA

Doğal popülasyonların karakterizasyonu, uzun süre çevresel baskılar altında doğal seçilimle şekillenmiş genetik değişkenliği ortaya koyduğundan, ıslahta kullanılabilecek üstün genotiplerin belirlenmesinde temel bir adımdır. Bu çalışmada eşek gürülü (vicia sativa subsp. Nigra) genotipleri arasında incelenen tüm özellikler bakımından belirlenen farklılıklar, önemli düzeyde genetik varyasyona işaret etmektedir. Genotiplerin 855–1407 m arasında değişen farklı rakımlardan toplanmış olması, bu varyasyonun hem genetik hem de ekolojik kökenli olabileceğini düşündürmektedir. Elde edilen bulgular, v. Sativa'nın 537 genetik materyalinde nigra alt türünün tohum boyutu ve şekli bakımından oldukça çeşitli olduğunu bildiren dong vd. (2016) ile örtüşmektedir. Değişkenlik morfolojik düzeyle de sınırlı değildir; alt türler arasındaki karyotip asimetrileri ve kromozom sayısı farklılıkları (2n = 10–12) çeşitliliğe sitogenetik bir boyut katmakta (benlioglu, 2020), depo proteinleri ve izoenzim modellerinde coğrafi kökenle ilişkili varyasyon ise farklı habitatlardan gelen popülasyonların zengin bir genetik materyal deposu olduğunu doğrulamaktadır (haider & el-shanshoury, 2000).

Bitki boyunun 58.60 cm (B19) ile 92.20 cm (B27), sap kalınlığının 3.16–3.46 mm ve yan dal sayısının 2.40–3.60 adet arasında değişmesi, büyüme özellikleri bakımından belirgin farklılıklar bulunduğunu göstermektedir. Hem en yüksek bitki boyuna, hem en kalın gövdeye (3.46 mm) hem de en fazla yan dala (3.60 adet) sahip olan B27 genotipi, yem verimine dönüşebilecek güçlü bir vejetatif büyüme potansiyeli sergilemektedir. Bu bulgular, gövde kalınlığı ile vejetatif büyüme arasında olumlu ilişkiler bildiren ve daha kalın gövdeli genotiplerin daha güçlü biyokütle birikimini desteklediğini ortaya koyan önceki fiğ araştırmalarıyla uyumludur (Avramidou vd., 2024; Çakmakçı & Açıkgöz, 1994). Genom çapında ilişkilendirme çalışmalarının bitki boyu ile taze ve kuru ağırlık gibi biyokütle özelliklerine bağlı lokusları belirlemiş olması da, bu fenotipik varyasyonun genetik temelini ve seleksiyonda kullanılabilecek belirteçleri ortaya koymaktadır (Jin vd., 2025).

Çiçek sayısı üreme gelişiminin temel göstergesi olmakla birlikte, tohum verimiyle her zaman doğrudan ilişkili değildir; çiçek dökülmesi, tozlaşma başarısı ve çevresel stresler bakla oluşum oranını belirlemektedir. Nitekim bu çalışmada en yüksek çiçek sayısına sahip B27 (18.30 adet) ve B51 (17.90 adet) genotipleri baklada en fazla tohumu vermemiş; en düşük çiçek sayısına sahip B19 genotipi (14.20 adet) baklada en yüksek tohum sayısına (5.80 adet) ulaşmıştır. Bu sonuç, tohum veriminin yalnızca çiçek ve bakla sayısına değil, üreme verimliliğini içeren karmaşık etkileşimlere de bağlı olduğunu bildiren çalışmalarla tutarlıdır (Çakmakçı vd., 2006; Çakmakçı & Açıkgöz, 1994). Yaprak özellikleri bakımından ise B51 genotipinin dikkat çekici yaprakçık sayısı (258.80 adet) daha geniş bir fotosentetik yüzey alanına, B27 genotipinin daha geniş yaprakçıkları (0.91 cm) ise farklı bir uyum stratejisine işaret etmektedir; yani fotosentetik kapasite kimi genotipte yaprakçık sayısının, kimisinde ise yaprakçık boyutunun artırılmasıyla optimize edilmektedir. Yaprakçık sayısının B19'da 98.00 adetten B51'de 258.80 adede yükselmesi, tür içi varyasyonun genişliğini açıkça ortaya koymaktadır. Yaprak fotosentezinin bakla oluşumu ve tohum gelişimindeki belirleyici rolü dikkate alındığında (Ramana & Ghildiyal, 1997), bu özelliklerin üreme başarısını dolaylı olarak etkilediği anlaşılmaktadır (Dong vd., 2016).

Çimlenme oranının %74.00 ile %84.00 arasında değişmesi, doğal popülasyonlardan elde edilen tohum materyalinin yüksek canlılığa sahip olduğunu göstermektedir.

En yüksek değere ulaşan B27 genotipi (%84.00) tohum kalitesi bakımından üstün kabul edilebilir; bu durum güçlü fide oluşumu potansiyelinin yanı sıra gen bankalarında daha kolay korunma ve çoğaltılma olanağını da ifade etmektedir (Çakmakçı & Açıkgöz, 1994). Bakla özellikleri bakımından B27 genotipi en uzun (6.44 cm) ve en geniş (0.73 cm) baklaları oluşturmuş; ancak en büyük baklalara sahip genotip baklada en fazla tohumu vermemiştir. Nitekim en kısa (2.72 cm) ve en dar (0.32 cm) baklalara sahip B19 genotipi baklada en yüksek tohum sayısına ulaşmıştır. Benzer bir ödünleşim bin tane ağırlığında da görülmüştür: 58.35 g ile en iri tohumlara sahip B51 genotipi, baklada en düşük tohum sayısını (4.00 adet) vermiştir. Bakla boyutu ve tohum iriliği ile tohum sayısı arasındaki bu ayrışma, söz konusu özelliklerin doğrudan bir boyut–sayı ilişkisinden ziyade farklı genetik mekanizmalar tarafından kontrol edildiğini düşündürmekte ve fiğde üreme özelliklerinin kalıtımındaki karmaşıklığı pekiştirmektedir (Açıkgöz & Rumbaugh, 1979; Tsialtas vd., 2018). Bununla birlikte, bin tane ağırlığı ve baklada tohum

sayısı gibi özellikler için bildirilen yüksek geniş anlamda kalıtım dereceleri, bu özelliklerin seleksiyona uygunluğunu doğrulamaktadır (Çakmakçı & Açıkgöz, 1994).

Genel olarak, incelenen genotiplerin farklı özellikler bakımından öne çıkması ve tek bir genotipin tüm özellikler yönünden üstünlük göstermemesi dikkat çekicidir: B27 bitki gelişimi, çimlenme ve bakla özellikleri; B51 yaprakçık boyu, yaprakçık sayısı ve bin tane ağırlığı; B19 ise baklada tohum sayısı bakımından üstünlük sergilemiştir. Bu durum, genotip iyileştirmede çoklu özellik seçimine dayalı stratejilerin daha etkili olacağını göstermektedir. Gözlemlenen morfolojik varyasyon, *Vicia* türlerinde genetik çeşitliliğin belirlenmesinde etkinliği kanıtlanmış SSR ve SCoT gibi moleküler belirteçlerle bütünleştirildiğinde, verim artışı, stres direnci ve adaptasyona yönelik ıslah programları için önemli bir potansiyel sunmaktadır (Chai vd., 2017; Raveendar vd., 2015; López-Román vd., 2024). *V. sativa* alt türlerinin yalnızca değerli yem bitkileri olmayıp azot fiksasyonu ve streslere direnç yoluyla sürdürülebilir tarımda üstlendiği rol de göz önüne alındığında, doğal olarak adapte olmuş bu genetik kaynakların morfolojik, sitogenetik ve moleküler yöntemlerle bütüncül biçimde karakterize edilmesi, belirli ortamlara uyum sağlamış üstün genotiplerin tanımlanması ve ıslahta değerlendirilmesi açısından büyük önem taşımaktadır (Benlioglu, 2020; Dong vd., 2016; Haider & El-Shanshoury, 2000).

Sonuç ve Öneriler

Bu çalışma, Kahramanmaraş doğal florasından toplanan Eşek gürülü (*Vicia sativa* subsp. *nigra* (L.) Ehrh.) genotiplerinin önemli düzeyde morfolojik çeşitlilik gösterdiğini ortaya koymuştur. İncelenen özellikler bakımından genotipler arasında belirgin farklılıkların bulunması, doğal popülasyonların zengin bir genetik varyasyona sahip olduğunu göstermektedir.

Araştırmada B27 genotipi, bitki gelişmesi ve bakla özellikleri bakımından; B51 genotipi ise yaprakçık özellikleri ve bin tane ağırlığı bakımından öne çıkmıştır. Buna karşılık, B19 genotipi baklada tohum sayısı bakımından diğer genotiplerden daha yüksek değer göstermiştir. Bu durum, farklı genotiplerin farklı özellikler bakımından üstünlük taşıdığını ve tek bir genotipin tüm özellikler bakımından üstün olmadığını ortaya koymaktadır.

Elde edilen bulgular, doğal florada bulunan Eşek gürülü genotiplerinin fiğ ıslah çalışmalarında değerlendirilebilecek önemli genetik kaynaklar olduğunu göstermektedir. Özellikle yüksek bitki gelişimi, iri tohum yapısı ve yüksek çimlenme oranına sahip genotiplerin kültür çeşitlerinin geliştirilmesinde ebeveyn materyali olarak kullanılabileceği değerlendirilmektedir.

Bununla birlikte, araştırma yalnızca 3 genotip ile yürütülmüştür. Gelecekte daha fazla genotipin farklı ekolojik bölgelerden toplanarak çok yıllı ve çok lokasyonlu denemelerde değerlendirilmesi, yem verimi ve kalite özelliklerinin belirlenmesi ile moleküler karakterizasyon çalışmalarının birlikte yürütülmesi, doğal genetik kaynakların korunmasına ve ıslah programlarında etkin kullanılmasına önemli katkılar sağlayacaktır.

Teşekkür

TAGEM/TBAD/14/A01/P01/008 proje numaralı bu çalışma, Tarım ve Orman Bakanlığı Tarımsal Araştırmalar ve Politikalar Genel Müdürlüğü (TAGEM) tarafından desteklenmiştir. Proje ekibinde yer alarak çalışmalarda önemli bir paya sahip olan ve 30.01.2025 tarihinde vefat eden Doç. Dr. Rukiye KARA'yı rahmet ve minnetle yad ederiz. Yazarlar, çalışmanın gerçekleştirilmesine sağladığı katkı ve destek için Tarım ve Orman Bakanlığı Tarımsal Araştırmalar ve Politikalar Genel Müdürlüğü'ne (TAGEM) teşekkürlerini sunarlar.

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JEOLOJİK KAYNAKLARDAN İLERİ TEKNOLOJİYE: NADİR TOPRAK ELEMENTLERİNİN NANOTEKNOLOJİK UYGULAMALARI

FROM GEOLOGICAL RESOURCES TO ADVANCED TECHNOLOGY: NANOTECHNOLOGICAL APPLICATIONS OF RARE EARTH ELEMENTS

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ÖZET

Nadir Toprak Elementleri (NTE), yerkabuğundaki jeokimyasal davranışları, birincil cevherleşme mekanizmaları ve kendilerine özgü fotofiziksel karakteristikleri doğrultusunda, geleneksel hammadde algısının ötesine geçerek modern nanoteknolojik ve kuantum uygulamalarının stratejik odağı haline gelmiştir. Bu çalışma, magmatik, hidrotermal ve sedanter süreçlerle şekillendirilmiş birincil NTE yataklarından (bastnasit, monazit vb.) başlanarak ileri teknoloji nano-malzeme matrislerine uzanan disiplinlerarası dönüşüm zincirini jeolojik ve jeokimyasal bir bakış açısıyla incelemektedir. NTE'lerin nanoteknolojik sistemlerdeki vazgeçilmezliğini sağlayan 4f iç kabuk elektronlarının perdeleme (kalkan) etkisi, kristal kafes yapısı içindeki iyonik yer değiştirmeler ve izomorfizm kuralları çerçevesinde ele alınmıştır. Jeolojik kaynaklardan elde edilen NTE iyonlarının fonksiyonelliği; mikro-lazer sistemleri ve fotovoltaik hücre katmanlarındaki kritik rolleri üzerinden analiz edilmektedir. Sonuç olarak makro ölçekteki jeolojik süreçlerin, nano ölçekteki ışık-madde etkileşimini doğrudan şekillendirerek geleceğin yeşil enerji ve kuantum teknolojilerine nasıl yön verebileceği tartışılmaktadır.
Anahtar Kelimeler: Nadir Toprak Elementleri, Hammadde Jeolojisi, Jeokimyasal Fraksiyonlaşma, Nanoteknoloji, Disiplinlerarası Jeokimya.

ABSTRACT

Rare Earth Elements (REEs) have transcended the traditional perception of raw materials to become the strategic focus of modern nanotechnological and quantum applications. This study examines the interdisciplinary transformation chain extending from primary REE deposits (bastnäsite, monazite, etc.) to advanced technological nanomaterial matrices. The shielding effect of 4f inner-shell electrons is evaluated within the framework of ionic substitutions within the crystal lattice structure. The functionality of REE ions in advanced technological structures, such as micro-laser systems and photovoltaic cell layers, is of vital importance. Consequently, it is crucial to understand how macro-scale geological processes can directly shape nano-scale light-matter interactions, thereby steering the green energy and quantum technologies of the future.
Keywords: Rare Earth Elements, Raw Material Geology, Geochemical Fractionation, Nanotechnology, Interdisciplinary Geochemistry.

GİRİŞ

Nadir Toprak Elementleri (NTE), periyodik tablonun lantanitler serisi (atom numarası 57'den 71'e kadar) ile birlikte kimyasal benzerlikleri nedeniyle Skandiyum (Sc) ve İtriyum (Y) elementlerini içeren 17 üyeli stratejik bir grubu temsil eder. Modern dünyada "Teknolojinin Vitaminleri" olarak adlandırılan bu elementler, düşük miktarlarda kullanılmalarına rağmen eklendikleri malzemeye kazandırdıkları manyetik, optik ve katalitik özelliklerle vazgeçilmezdirler. NTE'ler yer kabuğunda bakır veya çinkodan daha yaygın bulunabilmelerine rağmen, ekonomik yoğunlukta birikmeleri ve birbirlerinden ayrıştırılmaları karmaşık jeolojik ve metalurjik süreçler gerektirdiği için "nadir" olarak tanımlanırlar.

Günümüzde yeşil enerji dönüşümü, savunma sanayii ve dijitalleşme süreçlerinin tamamı NTE kaynaklarına bağımlıdır. Elektrikli araçların motorlarından rüzgâr türbinlerine, fiber optik kablolardan akıllı telefon ekranlarına kadar her alanda bu elementlerin imzası bulunmaktadır. Bu çalışma, doğal laboratuvar olan yer kabuğundan elde edilen bu stratejik cevherlerin nano-boyuttaki teknolojik evrimini ve Türkiye'nin bu denklemdeki yerini ele almaktadır.

ARAŞTIRMA VE BULGULAR

1. NTE'lerin Jeokimyasal Özellikleri ve Kristal Kimyası

NTE'lerin teknolojik üstünlüğü, atomik yapılarındaki 4f orbitallerinin karakteristik özelliklerinden kaynaklanır. 4f iç kabuk elektronlarının dış kabuklar tarafından perdelenmesi (shielding effect), bu iyonların kristal kafes yapıları içinde kararlı ve özgün bir luminesans emisyonu sergilemesine olanak tanır. Jeokimyasal olarak "uyumsuz elementler" sınıfında yer alan NTE'ler, magmatik farklılaşma sırasında ana minerallerin yapısına girmeyerek kalan sıvıda zenginleşme eğilimi gösterirler. Bu süreçte iyonik yarıçapların atom numarası arttıkça küçülmesi (Lantanit Büzülmesi), elementlerin hafif (LREE) ve ağır (HREE) olarak fraksiyonlaşmasına yol açar (Henderson, 1984; Miyawaki, and Nakai, 1996).

2. Jeolojik Oluşum Modelleri ve Yatak Tipleri

NTE zenginleşmeleri üç temel jeolojik model çerçevesinde gerçekleşmektedir:

Magmatik Model: Alkali magmaların soğuması sırasında NTE'lerin kristal kafese sığamayarak en son sıvıda birikmesiyle oluşur. Karbonatitler ve alkali siyenitler bu modelin en önemli örnekleridir (Örn: Eskişehir-Beylikova).

Hidrotermal Model: Sıcak akışkanların derinlerden çözdüğü NTE'leri çatlak ve kırık hatları boyunca taşıyarak damar tipi yataklar oluşturmasıdır (Örn: Malatya-Kuluncak).

Yüzeysel Süreçler (Aşınma ve Killeşme): Tropikal ve nemli iklimlerde granitlerin aşınmasıyla NTE'lerin serbest kalarak kil mineralleri yüzeyine yapışmasıdır (İyon emilimli killer). Bu yataklar, işlenmesi en kolay ve Ağır NTE (HREE) bakımından en zengin kaynaklardır (Robb, 2005).

3. Küresel Rezervler ve Türkiye'nin Potansiyeli

Dünya NTE rezervleri yaklaşık 121 milyon ton olarak tahmin edilmektedir. Çin, 44 milyon tonluk rezervi ve pazarın %80'inden fazlasını kontrol eden üretim kapasitesiyle lider konumdadır. Onu Brezilya ve Vietnam takip etmektedir. Türkiye, Eskişehir-Beylikova (Kızılcaören) sahasında keşfedilen 12.5 milyon tonluk REO (Nadir Toprak Oksit) kapasiteli karbonatit yatağı ile küresel ölçekte ikinci büyük rezerv kapasitesine sahip olmuştur. Bu yatak sadece NTE değil, aynı zamanda stratejik bir enerji hammaddesi olan Toryum (Th), Florit ve Barit içeriğiyle de "kompleks yatak" statüsündedir. Ayrıca Malatya (Kuluncak), Sivas (Kangal), Burdur (Çanaklı) ve Manisa çevresindeki farklı jeolojik ortamlarda NTE potansiyelleri tespit edilmiştir.

4. Nanoteknolojik Uygulamalar ve Element Bazlı Fonksiyonlar

NTE'lerin nano-ölçekteki uygulamaları, her bir elementin kendine özgü "süper gücü" üzerine inşa edilmiştir (Tablo 1).

Manyetik Uygulamalar (Nd, Pr, Dy, Tb): Neodimyum (Nd) mıknatıslar dünyanın en güçlü kalıcı mıknatıslarıdır. Elektrikli araçların (TOGG gibi) motorlarında ve rüzgâr türbinlerinde yüksek verimlilik sağlar. Disprosiyum (Dy) ve Terbiyum (Tb), bu mıknatısların yüksek sıcaklıklarda güç kaybetmesini önleyen nano-koruyuculardır.

Optik ve Fotonik (Eu, Er, Ho, Tm): Evropiyum (Eu) ekranlarda canlı renkleri üretirken, Erbiyum (Er) okyanus altı fiber optik internet kablolarındaki ışık sinyalini nano-yükseltici olarak güçlendirir. Holmiyum (Ho) ise tıp alanında kullanılan mikroskobik lazer cerrahisinin temelidir.

Savunma ve Enerji (Sm, Lu, Ce, Sc): Samaryum (Sm) jet motorları ve füzelerde yüksek ısıya dayanıklı mıknatıslar oluşturur. Skandiyum (Sc), alüminyum alaşımlarına nano-ölçekte eklendiğinde uçak gövdelerini çok daha hafif ve dayanıklı hale getirir.

Tablo 1. Nadir Toprak Elementlerin Nanoteknolojideki Görevi (Panichev, 2015; Balaram, 2019 Yavuz Pehlivanlı, 2025; Yavuz Pehlivanlı ve Kanbur Çavuş, 2025).

Atom No	Element	Süper Gücü	Nanoteknolojideki Görevi
57	**Lantan (La)**	Süzer ve Korur	Gece görüş kameralarının merceklerinde ışığı kusursuz iletir; petrol rafinerilerinde üretimi hızlandırır.
58	**Seryum (Ce)**	Hava Temizleyici	Arabaların egzozlarında zehirli gazları temiz havaya dönüştürür; ekranları mikroskobik seviyede pürüzsüzleştirir.

59	**Praseodim (Pr)**	Göz Koruyucu	Kaynakçı gözlüklerinde zararlı ışınları süzer; uçak motorlarının yüksek ısıda çatlamasını önler.
60	**Neodimyum (Nd)**	Mıknatısların Kralı	Elektrikli araç (TOGG) motorlarını, rüzgar türbinlerini ve kulaklıkları çalıştıran dünyanın en güçlü mıknatıslarını oluşturur.
61	**Prometyum (Pm)**	Sonsuz Pil	Doğada bulunmaz; uzay araçlarında ve kalp pillerinde onlarca yıl bitmeyen nano-nükleer pillerin kalbidir.
62	**Samaryum (Sm)**	Isıya Dayanıklı Şövalye	Füzeler ve jet motorları gibi aşırı sıcak askeri teknolojilerde gücünü kaybetmeyen özel mıknatıslar yapar.
63	**Evropiyum (Eu)**	Renklerin Ustası	Ekranlardaki canlı kırmızı ve mavi renkleri üretir; paralardaki mor ışıkta parlayan gizli güvenlik şeritlerini oluşturur.
64	**Gadolinyum (Gd)**	Kanser Dedektörü	MR (Emar) çekiminde damardan verilen sıvıyla kanserli tümörlerin bir lamba gibi parlamasını sağlar.
65	**Terbiyum (Tb)**	Kuantum Hafıza	Ekranlarda kusursuz yeşil rengi verir; geleceğin kuantum bilgisayarlarında veriyi dondurup saklayan hafıza kartıdır.
66	**Disprosiyum (Dy)**	Mıknatıs Koruyucusu	Neodimyum mıknatıslarının içine eklenerek, elektrikli araç motorları aşırı ısınsa bile mıknatısın gücünün bitmesini engeller.
67	**Holmiyum (Ho)**	Lazer Cerrahı	Göz çizme, böbrek taşı kırma ve tümör eritme ameliyatlarında nokta atışı yapan mikroskobik lazerler üretir.
68	**Erbiyum (Er)**	İnternetin Kalbi	Okyanus altındaki fiber optik internet kablolarında zayıflayan ışığı (veriyi) otomatik olarak güçlendirip hızlandırır.
69	**Tuliyum (Tm)**	Taşınabilir Röntgen	Ambulanslarda ve savaş alanlarında kullanılabilecek, pille çalışan küçük el röntgen cihazlarının yapılmasını sağlar.
70	**İterbiyum (Yb)**	Enerji Hasatçısı	Görünmez kızılötesi ışığı yakalar; güneş panellerine kaplandığında panellerin elektrik üretme verimini ikiye katlar.
71	**Lutetyum (Lu)**	Kanser Savaşçısı	Akıllı nano-taşıyıcılarla doğrudan kanserli hücrenin içine girerek sadece o hücreyi yok eden radyasyon yayar.

SONUÇLAR

Nadir Toprak Elementleri, makro ölçekli jeolojik süreçlerin milyarlarca yıllık birikimi olan bir mirasın, nano ölçekli ileri teknolojiyle buluştuğu noktadır. Türkiye'nin sahip olduğu Beylikova gibi devasa rezervler, ülkemizi sadece hammadde ihracatçısı değil, aynı zamanda yüksek teknoloji üreticisi yapma potansiyeline sahiptir. Ancak asıl başarı, bu cevheri topraktan "taş" olarak çıkarmak değil, nanoteknolojik yöntemlerle rafine ederek %99,999 (5N) ve üzeri saflığa ulaştırmaktır. Saflaştırma ve metalurji alanındaki yerli know-how kapasitesinin artırılması, savunma sanayii ve yeşil enerji dönüşümünde teknolojik bağımsızlığın mutlak anahtarıdır. Sonuç olarak, yer bilimleri ve nanoteknolojinin disiplinlerarası entegrasyonu, Türkiye'nin gelecekteki "milli güvenlik ve tam bağımsızlık" stratejisinin temel taşı olacaktır (Balaram 2019; Yavuz Pehlivanlı, 2025).

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AN ANALYSİS OF MAY DAY POSTERS WİTHİN THE FRAMEWORK OF POSTCOLONİAL THEORY

POSTKOLONYAL TEORİ ÇERÇEVESİNDE 1 MAYIS AFİŞLERİNİN ÇÖZÜMLENMESİ

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ÖZET
Bu çalışma, 1 Mayıs (Uluslararası Emek ve Dayanışma Günü) afişlerinin postkolonyal teori çerçevesinde kültürel ve ideolojik çözümlemesini amaçlamaktadır. Araştırmanın yöntemi, nitel içerik çözümlemesi ve görsel söylem çözümlemesi yöntemlerinin bir kombinasyonu olarak tasarlanmıştır. Çalışmada, 1 Mayıs afişlerinde yer alan görsel temsiller, renk kullanımı, tipografi, beden imgesi ve ideolojik anlatı unsurları olarak yorumlanmıştır. Çalışmada, afişlerin içerdiği temsillerin Batı-merkezci modernlik, güzellik ve ilerleme anlayışlarını nasıl yeniden ürettikleri sorgulanmaktadır. Postkolonyal teori, özellikle Edward Said'in Oryantalizm (1978) kavramı, Gayatri Chakravorty Spivak'ın subaltern özne tartışması (1988) ve Homi K. Bhabha'nın kültürel melezlik (1994) yaklaşımı üzerinden ele alınmıştır. Bu çerçevede rastgele, 1953 tarihli Doğu Almanya (DDR) afişi ve 1970'ler Türkiye'sinden beş adet afiş seçilmiş 1 Mayıs afişleri karşılaştırmalı olarak incelenmiştir. Bulgular, afişlerin ideolojik olarak Batı kapitalizmine karşı bir direniş söylemi üretmelerine rağmen, estetik düzlemde Batı'nın modernlik ve "evrensel insan" ideallerini yeniden ürettiklerini göstermektedir. Bu durum, postkolonyal kuramın "merkez–çevre" ilişkilerinin sadece politik değil, estetik bir düzlemde de sürdüğüne işaret etmektedir.
Anahtar Kelimeler: Postkolonyal teori, Bir Mayıs afişleri, temsil, modernlik, ideoloji, görsel kültür.

ABSTRACT
This study aims to analyze the cultural and ideological dimensions of May Day (International Workers' Day) posters within the framework of postcolonial theory. The research adopts a combined methodological approach of qualitative content analysis and visual discourse analysis. The visual representations, color schemes, typography, body imagery, and ideological narratives in the posters are interpreted through this lens. The study questions how the representations within these posters reproduce Western-centric notions of modernity, beauty, and progress. The theoretical framework draws upon Edward Said's concept of Orientalism (1978), Gayatri Chakravorty Spivak's discussion of the subaltern subject (1988), and Homi K. Bhabha's notion of cultural hybridity (1994). Within this framework, a total of six posters the 1953 East German (DDR) poster and five Turkish posters from the 1970s were randomly selected and analyzed comparatively. The findings indicate that although these posters construct an ideological discourse of resistance against Western capitalism, they simultaneously reproduce the aesthetic norms and ideals of Western modernity and the concept of the "universal human." This reveals that the "center–periphery" relations identified by postcolonial theory persist not only on a political level but also within aesthetic and visual dimensions.
Keywords: Postcolonial theory, May Day posters, representation, modernity, ideology, visual culture.

GİRİŞ

Toplumsal hareketlerin tarihsel süreç içerisindeki en önemli görsel iletişim araçlarından biri afiştir. Afişler yalnızca belirli bir etkinliği duyuran grafik ürünler değil; aynı zamanda dönemin siyasal, ekonomik ve kültürel ilişkilerini görünür kılan ideolojik metinlerdir. Özellikle işçi

hareketleri, sendikal mücadeleler ve toplumsal muhalefet bağlamında üretilen 1 Mayıs afişleri, emek, sınıf, dayanışma, direniş ve özgürlük gibi kavramları görsel göstergeler aracılığıyla yeniden üretmektedir. Bu nedenle afişler, yalnızca estetik açıdan değil, temsil politikaları ve iktidar ilişkileri açısından da incelenmesi gereken önemli kültürel belgelerdir (Erzincan, 2026). Modern iletişim araştırmaları, görsel kültür ürünlerinin yalnızca tasarım ilkeleri üzerinden değil; aynı zamanda ideoloji, söylem ve temsil bağlamında okunması gerektiğini ortaya koymaktadır. Özellikle postyapısalcı ve kültürel çalışmalar geleneği içerisinde gelişen postkolonyal teori, görsel metinlerin egemen iktidar ilişkileriyle nasıl biçimlendiğini ve bu ilişkileri nasıl yeniden ürettiğini inceleyen önemli kuramsal yaklaşımlardan biri hâline gelmiştir. Postkolonyal yaklaşım, sömürgeciliğin yalnızca siyasal ve ekonomik bir süreç olmadığını; bilgi üretimi, kültür, dil, sanat ve temsil biçimleri aracılığıyla günümüzde de etkisini sürdüren bir iktidar mekanizması olduğunu ileri sürmektedir (Ashcroft, Griffiths & Tiffin, 2002; Loomba, 2005).

Edward Said'in (1978) geliştirdiği Oryantalizm yaklaşımı, Batı'nın Doğu'yu yalnızca coğrafi bir alan olarak değil; aynı zamanda kültürel olarak "öteki" konumunda inşa ettiğini göstermektedir. Said'e göre temsil, iktidardan bağımsız değildir; aksine iktidarın bilgi üretme biçimlerinden biridir. Dolayısıyla görsel imgeler de belirli ideolojik anlamların dolaşıma girdiği söylemsel alanlar olarak değerlendirilmelidir. Bu yaklaşım daha sonra Homi K. Bhabha'nın (1994) melezlik (hybridity), üçüncü mekân (third space) ve taklit (mimicry) kavramlarıyla genişletilmiş; Gayatri Chakravorty Spivak'ın (1988) geliştirdiği "Madun konuşabilir mi?" sorusu ise temsil edilmeyen ya da temsil edilme biçimleri iktidar tarafından belirlenen toplumsal grupların görünürlüğünü tartışmaya açmıştır. Frantz Fanon (1967) ise sömürgeciliğin yalnızca fiziksel değil, psikolojik ve kültürel tahakküm yarattığını vurgulayarak postkolonyal düşüncenin temel kuramsal zeminini oluşturmuştur (Akbaş, 2023).

Her ne kadar Türkiye klasik anlamda sömürge geçmişine sahip ülkeler arasında yer almasa da, postkolonyal teori günümüzde yalnızca sömürge deneyimini açıklayan bir yaklaşım olmaktan çıkmış; küresel kapitalizm, neoliberal ekonomi, kültürel hegemonya, temsil ilişkileri ve emek politikalarının analizinde de kullanılmaya başlanmıştır. Bu nedenle işçi sınıfı hareketleri ve emek mücadeleleri bağlamında üretilen görsel materyaller, postkolonyal kuramın sunduğu kavramsal çerçeve içerisinde yeniden okunabilmektedir. Özellikle küresel sermaye düzeni içerisinde emek sömürüsünün ulusötesi bir nitelik kazanması, postkolonyal eleştiriyi yalnızca ulusal bağımsızlık tartışmalarıyla sınırlı olmaktan çıkarmış; sınıf, kimlik, göç, yoksulluk ve kültürel temsil gibi çok katmanlı meselelerle ilişkilendirmiştir (Loomba, 2005; Ashcroft vd., 2002).

1 Mayıs afişleri bu bağlamda yalnızca işçi sınıfının taleplerini görünür kılan propaganda araçları değildir. Aynı zamanda emekçilerin nasıl temsil edildiğini, hangi kimliklerin merkeze alındığını, hangi toplumsal grupların görünmez bırakıldığını ve iktidar karşısında nasıl bir direniş söylemi üretildiğini gösteren önemli görsel belgelerdir. Kullanılan renkler, semboller, tipografi, figürler ve sloganlar belirli ideolojik kodlar taşımakta; emek-sermaye ilişkilerinin kültürel temsilini yeniden kurmaktadır. Türkiye'de özellikle 1970'lerden itibaren DİSK ve farklı sendikalar tarafından hazırlanan 1 Mayıs afişleri, yalnızca grafik tasarım tarihi açısından değil; toplumsal belleğin oluşumu bakımından da önemli bir arşiv oluşturmaktadır. Günümüzde bu afişlerin önemli bir bölümü araştırmacılara açık dijital arşivlerde korunmaktadır.

Bu çalışmanın temel amacı, farklı dönemlerde üretilmiş 1 Mayıs afişlerini postkolonyal teori çerçevesinde inceleyerek afişlerde kurulan temsil biçimlerini, ötekilik söylemlerini, emek ve iktidar ilişkilerini, direniş pratiklerini ve görsel ideolojileri çözümlemektir. Çalışmada Edward Said'in söylem ve temsil yaklaşımı, Homi Bhabha'nın melezlik ve üçüncü mekân kavramları ile Gayatri Spivak'ın madunluk kuramı temel kuramsal çerçeveyi oluşturacaktır. Böylece 1 Mayıs afişlerinin yalnızca grafik tasarım ürünleri olmadığı; aynı zamanda toplumsal mücadelelerin,

kültürel belleğin ve ideolojik söylemlerin üretildiği görsel metinler olduğu ortaya konulmaya çalışılacaktır.
Bu araştırmanın literatüre katkısı ise Türkiye'de çoğunlukla sanat tarihi, grafik tasarım veya siyasal iletişim perspektifinden değerlendirilen 1 Mayıs afişlerini postkolonyal teori ekseninde ele alarak farklı bir okuma modeli önermesidir. Böylece görsel iletişim çalışmaları ile kültürel çalışmalar arasında disiplinlerarası bir ilişki kurulması hedeflenmektedir. Bu çalışmada, 1 Mayıs (Uluslararası Emek ve Dayanışma Günü) afişlerini, postkolonyal yaklaşım çerçevesinde analiz edilecektir. Özellikle afişlerin görsel-ideolojik kodları, estetik seçimleri ve "evrensel insan" imgesi üzerinden nasıl Batı-merkezci güzellik ve modernlik anlayışlarını yeniden ürettiğini sorgulamaktır. Bu bağlamda, Edward Said'in Oryantalizm kuramı ile Gayatri Chakravorty Spivak'ın subaltern (alt-özne) kavramı ve özneleşme üzerine politik-estetik düşünceleri yöntem bilimsel olarak referans alınacaktır.
Çalışma üç bölümden oluşacaktır:
Bağlamsal ve kuramsal çerçeve,
1 Mayıs afişlerinin biçimsel ve içeriksel çözümlemesi,
Postkolonyal teori açısından bulguların tartışılması ve sonuç.

YÖNTEM

Bu araştırma, nitel içerik çözümlemesi (qualitative content analysis) ve görsel söylem çözümlemesi (visual discourse analysis) yöntemlerinin bir kombinasyonu olarak tasarlanmıştır. Çalışmada, postkolonyal teorinin temel kavramları doğrultusunda 1 Mayıs afişlerinde yer alan görsel temsiller, renk kullanımı, tipografi, beden imgesi ve ideolojik anlatı unsurları yorumlanmıştır.
Araştırma Deseni
Araştırma, betimsel-yorumsal nitelikte bir görsel analizdir. İncelenen afişler, tarihsel ve ideolojik bağlamlarıyla birlikte değerlendirilmiş; her bir afişteki imgelerin taşıdığı anlam katmanları, postkolonyal eleştiri perspektifiyle okunmuştur (Rose, 2016).
Sınırlılıklar
Bu çalışma, dört adet rastgele seçilmiş örneklerle sınırlıdır ve postkolonyal okumanın yalnızca belirli tarihsel afişsel bağlamlara uygulanması mümkündür. Ayrıca, görsel analiz öznel yorumlara açık olduğundan, sonuçlar temsili değil, yorumlayıcı niteliktedir (Hall, 1997).
Örneklem ve Veri Seti
Analiz için iki tarihsel bağlamdan örnekler seçilmiştir:
•Doğu Almanya (DDR) 1953 tarihli 1 Mayıs afişi: Sosyalist gerçekçilik estetiğinin Batı karşısında "yeni insan" idealini nasıl kurduğunu görmek için incelenmiştir.
•Türkiye 1970'ler dönemi 1 Mayıs afişleri: Yerel motiflerle evrensel sosyalist sembollerin nasıl melezleştiğini anlamak amacıyla seçilmiştir.
Bu örneklem, hem postsosyalist hem postkolonyal okuma imkânı sağlamaktadır (Tlostanova, 2017).
Analiz Süreci
Afişler, aşağıdaki beş eksende incelenmiştir:
1.Temsillerin ideolojik işlevi (örneğin, sınıf, cinsiyet, ulus imgeleri),
2.Görsel unsurların (renk, figür, tipografi) anlam üretimi,
3.Batı-merkezci estetik kodların yeniden üretimi,
4.Subaltern öznenin görünürlüğü veya sessizliği (Spivak, 1988),
5.Kültürel melezlik ve kimlik inşası (Bhabha, 1994).
Her afiş, bu kriterler doğrultusunda çözümlenmiş ve tablo biçiminde değerlendirilmiştir.

BULGULAR

Görsel 1. Almanya, 1953

Bu afiş, 1953 yılında Alman Demokratik Cumhuriyeti'nde (Doğu Almanya) 1 Mayıs kutlamaları için üretilmiştir. Sosyalist gerçekçiliğin güçlü olduğu bir dönemde, afiş hem "halkın birliği" hem de "sosyalist ilerleme" mesajı taşır (Bykova, 2018). Almanya 1953 Afişinin Görsel ve İdeolojik Çözümlemesi için tablo 1'e bkz.

Tablo 1. Almanya, 1953 Afişi için Görsel Unsurların Özet tablosu

Görsel Unsur	Açıklama
Figürler	Genç, beyaz tenli, gülen kadın ve erkek; arkalarında işçiler, askerler ve Marx–Engels–Lenin–Stalin portreleri.
Renkler	Kırmızı (devrim, emek), beyaz (saflık, umut), mavi (barış).
Tipografi	Büyük, sans-serif, blok harflerle "1. MAI 1953". Güç, birlik ve kolektifliği simgeler.
Kompozisyon	Yükselen bakışlar ve yukarıya uzanan kollar, "ilerleme" ve "geleceğe yönelme" metaforu yaratır.

Postkolonyal değerlendirmeye baktığımızda;

Batı-merkezli Modernlik ve Evrensellik:

Afiş, Batı kapitalizmine ideolojik olarak karşı görünse de, biçimsel olarak Batı modernizminin estetik kodlarını kullanır (Tlostanova, 2017).

Kadın figürün beyaz teni, düzgün dişleri, açık renk saçları — Batı'nın güzellik normlarını "evrensel insan" imgesi olarak sunar (Thomas, 2023).

Temiz, Aydınlık, Beyaz Beden:

Beyazlık yalnızca etnik değil, ideolojik bir temizlik göstergesidir. Sosyalist ütopya, kolonyal "medenileştirme" misyonunu "yeni insan" üzerinden yeniden üretir (Said, 1978).

Subalternin Sessizliği:

Figürler konuşmaz, sadece güler ve coşku gösterir; onların sesi, devletin ideolojik sesiyle örtüşür (Spivak, 1988).

Bu, öznenin görünür ama sessiz oluşunu — yani Spivak'ın "subaltern konuşamaz" tezini — görsel olarak yansıtır.

Batı'nın Aynasında Doğu:

Afiş Doğu Bloku'na ait olsa da "modernlik"i hâlâ Batı'nın epistemik aynasında tanımlar. Bu nedenle temsil ettiği "Doğu", Batı'nın estetik aynasında şekillenmiş bir Doğu'dur (Said, 1978).

A) B) C)

Görsel 2. A) 1976, Orhan Taylan B) 1977, Emre Çağatay C) 1977, Erkal Yav

1970'lerin Türkiye'sinde 1 Mayıs afişleri, hem sol hareketin yükselişi hem de sendikal örgütlenmenin kamusal alanda görünürleştiği bir dönemde üretildi. Bu afişlerde ulusal motiflerle enternasyonalist semboller (örneğin orak-çekiç, kırmızı bayrak) bir arada kullanılmıştır (Rızvanoğlu & Ataman, 2002).

Türkiye de 1 Mayıs Afişlerini Görsel 2'ye göre, Görsel ve İdeolojik Çözümlemesi için tablo 2'ye bkz.

Tablo 1. Türkiye 1 Mayıs Afişleri için Görsel Unsurların Özet tablosu

Görsel Unsur	Açıklama
Figürler	Emekçi kadın, işçi, köylü, öğrenci figürleri; çoğunlukla kahverengi veya toprak tonlarında ten rengiyle betimlenir.
Renkler	Kırmızı, siyah, sarı; dayanışma, direniş, güç simgesi.
Tipografi	El çizimi yazı karakterleri, slogan tarzı ifadeler: "Yaşasın 1 Mayıs!", "Emek en yüce değerdir!".
Simgesel Unsurlar	Fabrika bacaları, güneş, orak–çekiç, halk zinciri gibi dayanışma ikonları.

Postkolonyal değerlendirmeye baktığımızda;

Batı İkonografisinin Yerelleştirilmesi:

Türkiye'deki 1 Mayıs afişleri, Sovyet estetiğini benimserken yerel kültürel öğeleri (örneğin başörtülü kadın, Anadolu işçisi) ekleyerek hibrit bir kimlik üretir (Bhabha, 1994). Bu hibritlik, Batı modernliğiyle yerel kimliğin müzakere edildiği bir alan yaratır.

Renk ve Beden Politikası:

Toprak tonlarının tercih edilmesi, "yerli halk"ın görünür kılınma çabası olarak okunabilir. Ancak bu bile Batı'nın ilerleme mitine eklemlenen bir "yetişme" anlatısını içerir (Said, 1978).

Subalternin Kısmi Temsili:

Türkiye'deki afişlerde alt-özne (işçi, köylü, kadın) daha aktif görünür — örneğin ellerinde pankartlar veya aletlerle betimlenir. Buna rağmen, temsil dili hâlâ ideolojik merkez tarafından belirlenir (Spivak, 1988).
Evrensel Emek Miti:
Afişlerde "işçi sınıfının evrensel mücadelesi" söylemi baskındır; fakat bu evrensellik, Batı kökenli Marksist estetiğin görsel kodlarına dayanır. Dolayısıyla ulusal direniş bile, Batı kaynaklı bir evrensellik fikrinin yerel varyantı olarak konumlanır (Tlostanova, 2017).

SONUÇ

1 Mayıs afişleri ideolojik olarak Batı kapitalizmine karşı durur; ancak biçimsel ve estetik düzeyde Batı'nın modernlik söylemine bağımlı kalır. Bu durum, Said'in (1978) "Oryantalizmin ters yüz edilmiş biçimi" dediği duruma benzer: Batı'nın estetik sistemine karşıtlık değil, onun yeniden üretimi söz konusudur. Spivak'ın (1988) belirttiği gibi, alt-özneler (işçiler, kadınlar, halk) görünür olsalar bile kendi seslerini kuramazlar — çünkü temsil araçları, kolonyal estetiğin mirasını taşır. Dolayısıyla "görsel sömürgesizleşme" hâlâ tamamlanmamış bir süreçtir. Edward Said'e göre Batı, "Öteki"ni yani "Doğu"yu kurgulayarak kendi kimliğini tanımlar. "Oryantalizm", Batı'nın Doğu'yu geri kalmış, irrasyonel ve egzotik olarak tanımlayıp, kendi ilerlemeci kimliğini bu karşıtlık üzerinden inşa etmesidir. Bu bağlamda, 1 Mayıs afişlerinde yer alan "ilerici toplum", "yeni insan" ve "aydınlık gelecek" imgeleri, Batı'nın ilerleme söylemini sosyalist biçimde yeniden üretmektedir. Afişler, Batı kapitalizmine karşı konumlanmış olsalar da, Batı'nın modernlik, güzellik ve akılcılık kriterlerini içselleştirmiştir. Bu durum, Said'in tanımladığı biçimiyle "Batı'nın aynasında Doğu" olgusunu yansıtır (Said, 1978). Spivak (1988), "Subaltern konuşabilir mi?" sorusuyla sömürge-sonrası toplumlarda "konuşan özne"nin kim olduğunu sorgular. Sömürge edilen ya da merkez-dışı gruplar, Batı'nın belirlediği söylem alanı içinde kendi seslerini tam olarak ifade edemezler. Bu durum 1 Mayıs afişlerinde de gözlemlenir: işçi figürleri coşkulu, güçlü ve umutlu görünseler de kendi sözlerini değil, ideolojik aygıtın dilini dile getirirler. Bu nedenle, afişlerdeki figürler "konuşan özne" değil, "konuşulan özne"dir; yani subaltern hâlindedir (Spivak, 1988). Tlostanova'ya (2017) göre postkolonyal ve postsosyalist alanların kesişimi, modernliğin Batı merkezli epistemolojisinin her iki bağlamda da geçerli olduğunu gösterir. Doğu Bloku propaganda afişleri, Batı'ya karşı bir "evrensel insanlık ideali" sunsa da, bu ideal yine Batı'nın estetik ve epistemolojik ölçütleriyle tanımlanır. Bu nedenle 1 Mayıs afişleri, "alternatif modernlik" iddiasına rağmen Batı modernliğinin görsel kodlarını yeniden üretir (Tlostanova, 2017). Bu afişler, yüzeyde anti-emperyalist ve sosyalist bir dayanışma mesajı taşırken, derin yapısında Batı-merkezci modernlik ideolojisinin yeniden üretimini sürdürür. Postkolonyal okuma bize şunu gösterir:
•Sosyalist gerçekçilik, Batı kapitalizmini reddederken bile Batı'nın ilerleme, güzellik ve insanlık ideallerini ödünç almıştır.
•Kadın ve erkek figürler, kolonyal söylemin "medenileştirilmiş özne"sinin yeni versiyonlarıdır.
•Görsel ve tipografik düzen, ilerleme ve saflık mitini yüceltir — bu da Batı modernitesinin temel ideolojik unsurlarından biridir.

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POTENTIAL UTILIZATION OF HEMP (Cannabis sativa L.) PLANT RESIDUES AS AN ALTERNATIVE FEED RESOURCE IN ANIMAL PRODUCTION

KENEVİR (Cannabis sativa L.) BİTKİ ATIKLARININ HAYVANSAL ÜRETİMDE ALTERNATİF YEM KAYNAĞI OLARAK DEĞERLENDİRİLME POTANSİYELİ

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ÖZET
Hayvansal üretimde yem maliyetlerinin artması, sürdürülebilir ve ekonomik alternatif yem kaynaklarının araştırılmasını zorunlu hale getirmiştir. Kenevir (Cannabis sativa L.), lif, tohum ve yağ üretimi amacıyla yetiştirilen önemli endüstriyel bitkilerden biridir. Hasat ve işleme süreçleri sonrasında ortaya çıkan yaprak, sap, çiçek ve diğer bitkisel artıklar önemli miktarda biyokütle oluşturmaktadır. Bu atıkların değerlendirilmesi, hem çevresel sürdürülebilirliğe katkı sağlamakta hem de hayvancılık sektörüne alternatif yem kaynakları sunmaktadır. Kenevir bitki atıkları; protein, lif, esansiyel yağ asitleri ve çeşitli biyoaktif bileşikler bakımından dikkat çekmektedir. Yapılan çalışmalar, uygun işleme yöntemleri ve rasyon formülasyonları ile bu materyallerin ruminant ve bazı kanatlı türlerinin beslenmesinde kullanılabileceğini göstermektedir. Bununla birlikte, besin madde içeriğinin değişkenliği, antinutrisyonel faktörler ve yasal düzenlemeler gibi hususlar kullanımını sınırlandırabilmektedir. Bu bildiride, kenevir bitki atıklarının hayvansal üretimde yem kaynağı olarak değerlendirilme olanakları, besleme açısından avantajları ve karşılaşılan sınırlamalar güncel literatür ışığında ele alınmıştır.
Anahtar Kelimeler: Kenevir, bitki atıkları, alternatif yem kaynakları, hayvansal üretim, sürdürülebilir tarım.

ABSTRACT
The increasing cost of feed in animal production has intensified the search for sustainable and cost-effective alternative feed resources. Hemp (Cannabis sativa L.) is an important industrial crop cultivated primarily for fiber, seed, and oil production. Following harvesting and processing, substantial amounts of plant residues, including leaves, stems, flowers, and other biomass components, are generated. The utilization of these by-products may contribute to environmental sustainability while providing alternative feed resources for livestock production systems. Hemp plant residues are notable for their content of protein, fiber, essential fatty acids, and various bioactive compounds. Previous studies have indicated that, with appropriate processing techniques and ration formulations, these residues can be incorporated into the diets of ruminants and certain poultry species. However, variations in nutrient composition, the presence of anti-nutritional factors, and regulatory considerations may limit their widespread application. This paper reviews the potential of hemp plant residues as feed resources in animal production, highlighting their nutritional benefits and current limitations based on recent scientific literature.
Keywords: Hemp, plant residues, alternative feed resources, animal production, sustainable agriculture.

GİRİŞ

Dünya nüfusundaki hızlı artışa paralel olarak hayvansal protein kaynaklarına yönelik talep sürekli bir yükseliş göstermektedir (Altman ve ark., 2024). Bu artış, hayvancılıkta kullanılan yem hammaddelerine olan ihtiyacın da önemli ölçüde artmasına neden olmuş ve yem maliyetleri, özellikle küçük ve büyük ölçekli hayvancılık işletmeleri için en yüksek gider kalemlerinden biri haline gelmiştir (Irawan ve ark., 2025). Ekonomik olarak sürdürülebilir ve çevresel açıdan daha sorumlu bir hayvancılık modeli oluşturmak amacıyla, alternatif ve yenilenebilir yem kaynaklarının araştırılması önem kazanmıştır.

Bu bağlamda, tarımsal yan ürünler ile bitkisel atıkların yem hammaddesi olarak değerlendirilmesi, sürdürülebilirlik ve döngüsel ekonomi ilkeleri açısından kritik bir strateji olarak kabul edilmektedir (Kasapidou ve ark., 2020). Kenevir (Cannabis sativa L.), hem biyokütle üretim kapasitesi hem de çok yönlü kullanım alanları bakımından son yıllarda yeniden ön plana çıkmıştır. Endüstriyel kenevir, özellikle lif, tohum ve yağ üretimi için yetiştirilmekte olup, bu süreçte önemli miktarda yan ürün ve biyokütle açığa çıkmaktadır (Mohamed ve ark., 2023).

Kenevirin yan ürünlerinin değerlendirilmesi, yalnızca ekonomik değerin artırılması açısından değil, aynı zamanda çevresel etkilerin azaltılması ve tarım-hayvancılık sektörlerinin entegrasyonuyla kaynak verimliliğinin sağlanması açısından da büyük önem taşımaktadır. Bu nedenle, kenevir bitki atıklarının yem olarak kullanım potansiyelinin kapsamlı bir şekilde incelenmesi gerekmektedir (Bailoni ve ark., 2021).

KENEVİR BİTKİ ATIKLARININ BESİNSEL ÖZELLİKLERİ

Kenevir bitkisinden elde edilen yan ürünler; sap, yaprak, çiçek kalıntıları, tohum küspesi, un ve ekstraksiyon sonrası kalan biyokütleyi kapsamaktadır. Bu materyallerin besin değerleri, bitki varyetesi, yetiştirme koşulları ve kullanılan işleme tekniklerine bağlı olarak değişkenlik göstermektedir (Mohamed ve ark., 2023).

Kenevir tohumları ve küspesi yüksek kaliteli protein içerikleriyle dikkat çekmektedir. Özellikle esansiyel amino asit profili açısından zengin olan bu materyaller, hayvansal beslemede değerli bir protein kaynağı olarak değerlendirilebilir (Bailoni ve ark., 2021). Ayrıca, kenevir tohumlarında bulunan omega-3 ve omega-6 yağ asitleri, hayvansal ürünlerin besin değerini iyileştirmede önemli katkılar sağlamaktadır (Altman ve ark., 2024).

Bunun yanı sıra, kenevir sapı ve yaprakları gibi lifli materyaller selüloz, hemiselüloz ve lignin gibi yapısal karbonhidratlar bakımından yüksektir. Bu içerikler, özellikle ruminantların sindirim sistemi tarafından kısmen fermente edilebilir olup, lif kaynaklarının dengelenmesi açısından önem arz etmektedir (Kasapidou ve ark., 2020). Ancak yüksek lignin içeriği sindirilebilirliği sınırlayabilir ve bu da yem değerini belirleyen önemli bir faktördür. Ayrıca kenevir yan ürünlerinde antioksidan özellik taşıyan fitokimyasal bileşikler ve fenolik maddeler bulunmaktadır ki bu bileşenler hayvan sağlığı ve ürün kalitesine olumlu etkiler yapabilmektedir (Irawan ve ark., 2025).

RUMİNANT BESLEMEDE KULLANIM OLANAKLARI

Ruminantlar, selüloz bakımından zengin yemleri sindirebilme yetenekleriyle kenevir yan ürünlerinden maksimum düzeyde faydalanabilen hayvan grubu olarak öne çıkmaktadır. Araştırmalar, kenevir tohumu küspesinin soya küspesi gibi yaygın protein kaynaklarının bir kısmını ikame etmede etkili olduğunu ve ruminantların performansını olumsuz etkilemediğini göstermiştir (Altman ve ark., 2024).

Süt sığırlarında yapılan çalışmalarda, kenevir yan ürünlerinin süt verimi üzerinde olumsuz etkisi bulunmamış, hatta süt yağ asidi profili omega-3 ve omega-6 bakımından iyileşmiştir. Bu durum, sütün besinsel kalitesinin artırılması açısından önemli bir gelişme olarak değerlendirilmektedir (Bailoni ve ark., 2021). Ayrıca, kenevir bazlı yemlerin rumen mikrobiyal

fermentasyonu üzerindeki etkilerinin sınırlı ve olumlu yönde olduğu da rapor edilmiştir (Kasapidou ve ark., 2020).
Meta-analiz çalışmaları, kenevir yan ürünlerinin ruminant rasyonlarına belirli oranlarda dahil edilmesinin hayvan sağlığı ve performansını desteklediğini, yüksek kaliteli protein ve değerli yağ asidi içeriği nedeniyle umut verici bir yem alternatifini temsil ettiğini ortaya koymaktadır (Irawan ve ark., 2025).

KANATLI VE DİĞER ÇİFTLİK HAYVANLARINDA KULLANIMI

Kanatlı hayvan beslemesinde kenevir tohumu ve yan ürünleri üzerine yapılan araştırmalar umut verici sonuçlar ortaya koymaktadır. Özellikle yumurta tavuklarında kenevir ürünlerinin kullanımı, yumurta sarısının yağ asidi kompozisyonunda olumlu değişikliklere yol açmakta, omega-3 yağ asitlerinin artırılmasıyla besin kalitesi yükselmektedir (Mohamed ve ark., 2023). Ayrıca, kenevir bileşenlerinin bağışıklık sistemini destekleyici etkileri olduğu ve büyüme performansını iyileştirdiği bildirilmektedir.
Bununla birlikte, kenevir bitkisinin yüksek lif içeriğine sahip sap ve diğer biyokütle atıkları, kanatlıların farklı sindirim yapısı nedeniyle sınırlı miktarlarda kullanılabilmektedir. Yüksek selüloz ve lignin oranları, bu materyallerin sindirilebilirliğini düşürmekte ve besin değerini azaltmaktadır (Kasapidou ve ark., 2020). Domuz ve küçükbaş hayvanlarda yapılan çalışmalar da kenevir yan ürünlerinin dikkatli oranlarda rasyonlara dahil edilebileceğini göstermektedir. Ancak, bu tür hayvanlarda kullanım düzeyinin iyi belirlenmesi gerekmekte olup, aşırı kullanımdan kaçınılmalıdır. Çünkü özellikle küçükbaşlarda yüksek lif içeriği ve potansiyel olarak kenevirde bulunan bazı bileşiklerin etkileri daha dikkatli izlenmelidir (Irawan ve ark., 2025).

KULLANIMI SINIRLANDIRAN FAKTÖRLER

Kenevir atıklarının yem olarak kullanımını sınırlayan en önemli faktörlerden biri, kannabinoid bileşiklerin, özellikle Δ9-tetrahidrokannabinol (THC) kalıntılarının hayvansal ürünlere geçme riski ve yasal düzenlemelerdir (Altman ve ark., 2024). Endüstriyel kenevir çeşitlerinde THC oranı oldukça düşük olsa da, farklı ülkelerde bu konuda uygulanan mevzuatlar oldukça katı olup kenevir yan ürünlerinin yem olarak kullanımını sınırlandırmaktadır (Irawan ve ark., 2025). Ayrıca, bitki kısımları arasında besin madde içeriğindeki büyük değişkenlik, standart ve güvenilir bir yem hammaddesi üretimini zorlaştırmaktadır. Örneğin, sap materyallerinin yüksek lignin içeriği sindirilebilirliği düşürürken, tohum küspesi ve un gibi yan ürünler daha yüksek protein içerirken daha az lif barındırmaktadır (Mohamed ve ark., 2023). Bunların yanında, kenevir yan ürünlerinin işlenme süreçleri de yem değerini etkileyebilmektedir. Uygun işleme yöntemlerinin belirlenmesi, hem besin değerini artırmak hem de olası zararlı bileşenlerin etkisini azaltmak açısından önem taşımaktadır (Kasapidou ve ark., 2020).

SONUÇ VE ÖNERİLER

Kenevir bitki atıkları, sürdürülebilir hayvancılık bakımından yüksek potansiyel taşıyan alternatif yem kaynakları arasında yer almaktadır. Özellikle kenevir tohumu küspesi ve ekstraksiyon sonrası biyokütle, yüksek protein ve sağlıklı yağ asidi içeriğiyle ruminant ve belirli kanatlı türlerinin beslenmesinde değerlendirilebilir (Bailoni ve ark., 2021).
Ancak, kannabinoid kalıntıları, besin madde içeriğinde görülen değişkenlikler ve yasal düzenlemeler, kenevir atıklarının daha yaygın olarak yem sektöründe kullanımının önünde önemli engel teşkil etmektedir (Altman ve ark., 2024). Bu nedenle, ileriye dönük araştırmaların güvenli kullanım sınırlarının belirlenmesine, uzun vadeli hayvan performansı ve sağlık üzerindeki etkilerin daha kapsamlı incelenmesine ve farklı işleme tekniklerinin yem değerini artırmadaki etkilerinin ortaya konmasına odaklanması gerekmektedir (Irawan ve ark., 2025). Bu araştırmaların ışığında, kenevir yan ürünlerinin hayvansal üretimde daha etkin ve güvenli

bir şekilde değerlendirilmesi mümkün olacak, hem ekonomik hem de çevresel açıdan hayvancılık sektörüne değerli katkılar sağlanacaktır.

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DIELECTRIC RESPONSE AND CHARGE-CARRIER DYNAMICS IN INGAAS SCHOTTKY BARRIER HETEROSTRUCTURES

InGaAs SCHOTTKY BARİYER HETEROYAPILARINDA DİELEKTRİK YANIT VE YÜK TAŞIYICI DİNAMİKLERİ

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ÖZET
İndiyum Galyum Arsenik (InGaAs) tabanlı heteroyapılar, yüksek elektron mobiliteleri ve dar direkt bant aralıkları sayesinde yeni nesil yüksek hızlı mikroelektronik ve optoelektronik uygulamalar için gelecek vadeden adaylar haline gelmiştir. Bu çalışmada, InGaAs tabanlı Schottky engel hetero yapısının fabrikasyonu gerçekleştirilmiştir. Üretilen aygıtın frekans ve voltaj bağımlı yük taşıyıcı dinamikleri ile kompleks dielektrik relaksasyon profilleri, -10V ile +10V gibi geniş bir voltaj aralığında ve 1kHz ile1MHz frekans spektrumunda sistematik olarak incelenmiştir. Deneysel kapasitans-voltaj (C-V) ve iletkenlik-voltaj (G/w-V) karakteristiklerinden yararlanılarak; kompleks dielektrik sabitinin gerçek (□□) ve sanal (□□□) kısımları, kayıp tanjantı (tan q), kompleks elektriksel modülün gerçek (M') ve sanal (M") bileşenleri ile alternatif akım elektriksel iletkenliği (□ac) elde edilmiştir. Deneysel sonuçlar, incelenen tüm dielektrik modül ve iletim profillerinin hem çalışma frekansına hem de uygulanan bias voltajına karşı güçlü bir duyarlılık sergilediğini göstermiştir. Bu belirgin bağımlılık, temel olarak arayüzey durumlarının (Nss) tuzaklama-salma (trapping-detrapping) kinetiği ve uzaysal yük polarizasyon mekanizmaları tarafından kontrol edilmekte olup, InGaAs Schottky eklemlerindeki yük iletim dinamiklerine dair kapsamlı bir bakış açısı sunmaktadır.
Anahtar Kelimeler: InGaAs Schottky hetero yapıları; Yük taşıyıcı dinamikleri, Dielektrik gevşeme; Elektriksel modül spektrumları, Arayüzey durumları.

ABSTRACT
Indium Gallium Arsenide (InGaAs) based heterostructures have emerged as highly promising candidates for next-generation, high-speed microelectronic and optoelectronic applications due to their superior electron mobility and narrow direct bandgaps. In this study, an InGaAs-based Schottky barrier heterostructure was fabricated. The frequency and voltage-dependent charge carrier dynamics, along with the complex dielectric relaxation profiles of the fabricated device, were systematically investigated over an extended bias voltage sweep from -10V to +10V and across a wide frequency spectrum spanning from 1kHz to 1MHz. Utilizing the experimental capacitance-voltage (C-V) and conductance-voltage (G/w-V) characteristics, key microelectronic parameters-including the real (□□) and imaginary (□□□) parts of the complex dielectric constant, the loss tangent (tan q), the real (M') and imaginary (M") components of the complex electric modulus, and the alternating current electrical conductivity (□ac) were extracted. The experimental results reveal that all investigated dielectric modulus, and transport profiles exhibit a profound susceptibility to both the operational frequency and the applied bias voltage. This distinct dependency is primarily governed by the trapping-detrapping kinetics of interface states (Nss) and spatial charge polarization mechanisms, thereby providing comprehensive insights into the charge transport dynamics within InGaAs Schottky hetero junctions.
Keywords: InGaAs Schottky heterostructures; Charge carrier dynamics; Dielectric relaxation; Electric modulus spectra; Interface states.

GİRİŞ

Yarı iletken teknolojilerindeki hızlı gelişmeler, yeni nesil yüksek performanslı mikroelektronik ve optoelektronik aygıtların tasarımında üstün elektriksel ve optik özelliklere sahip malzemelerin kullanımını zorunlu hale getirmiştir. Bu bağlamda, III-V grubu bileşik yarıiletkenler, özellikle yüksek elektron mobiliteleri ve dar direkt bant aralıkları sayesinde optik haberleşme, fotovoltaik enerji dönüşümü ve yüksek hızlı anahtarlama elemanlarında gelecek vadeden en güçlü adaylar arasında yer almaktadır. Galyum Arsenik (GaAs) tabanlı matrisler içine indiyum (In) katkılanmasıyla elde edilen İndiyum Galyum Arsenik (InGaAs) heteroyapıları, ayarlanabilir bant genişlikleri ve mükemmel yük taşıma kapasiteleriyle optoelektronik endüstrisinde kritik bir öneme sahiptir [1-3].

Bir mikroelektronik aygıtın performansı, güvenilirliği ve çalışma hızı; büyük ölçüde metal-yarıiletken (MS) arayüzeyinde oluşan Schottky engel yüksekliğine, seri dirence ve yük iletim mekanizmalarına bağlıdır. Termiyonik emisyon teorisine göre ideal bir Schottky bariyer yapısında yük iletiminin kararlı olması beklense de deneysel uygulamalarda idealiteden sapmalar (idealite faktörünün birden büyük olması) sıklıkla gözlenmektedir. Bu sapmaların ve yapıdaki potansiyel dalgalanmalarının temel nedenleri arasında arayüzey hazırlama süreçleri, metal ile yarı iletken arasında kaçınılmaz olarak oluşan ince yalıtkan/oksit tabaka ve bu bölgede yoğunlaşan arayüzey durumları (N_{ss}) yer almaktadır. Arayüzey durumlarının tuzaklama ve salma (trapping-detrapping) kinetiği ile uzaysal yük polarizasyon mekanizmaları, aygıtın alternatif akım (AC) altındaki dinamik davranışını doğrudan kontrol eder. Bu nedenle, InGaAs tabanlı Schottky yapılarının geniş bir voltaj sweeps ve frekans spektrumunda dielektrik gevşeme profillerinin, kompleks elektriksel modül spektrumlarının ve alternatif akım iletkenliğinin (□ac) sistematik olarak incelenmesi, yük iletim dinamiklerinin kökenini anlamak açısından büyük bir öneme sahiptir [2-8].

Bu çalışmada, belirtilen arayüzey mekanizmalarını ve yük taşıyıcı dinamiklerini kapsamlı bir şekilde aydınlatmak amacıyla InGaAs tabanlı Schottky engel heteroyapısının fabrikasyonu gerçekleştirilmiştir. Üretilen aygıtın frekans ve voltaj bağımlı dielektrik relaksasyon profilleri, geniş bir elektriksel karakterizasyon spektrumunda sistematik olarak analiz edilmiştir.

DENEYSEL YÖNTEM

Bu çalışmada incelenen İndiyum Galyum Arsenik (InGaAs) tabanlı metal-yarıiletken (MS) Schottky bariyer heteroyapılarının fabrikasyon süreci, alttaş hazırlığı (temizlik), omik kontak oluşumu, Schottky metalizasyonu ve elektriksel karakterizasyon olmak üzere dört temel aşamada gerçekleştirilmiştir. Deneysel süreçte, GaAs matrisi üzerine epitaksiyal olarak büyütülmüş yüksek elektron mobiliteli p-tipi InGaAs yarıiletken tabakaları alttaş olarak kullanılmıştır. Metalizasyon işlemleri öncesinde, numune yüzeyindeki olası organik kirlilikleri ve fabrikasyon kaynaklı kalıntıları uzaklaştırmak amacıyla standart RCA temizlik prosedürü uygulanmıştır. Bu doğrultuda numuneler sırasıyla aseton ve izopropil alkol içerisinde 5'er dakika ultrasonik banyoda temizlenmiş, ardından deiyonize (DI) saf su ile durulanmıştır. Yüzeyde kontrolsüz şekilde oluşan doğal oksit (As_2O_3 ve Ga_2O_3) tabakasını uzaklaştırmak amacıyla numuneler, HF:H_2O (1:10) çözeltisinde kısa bir süre dağlanmış (etching) ve hemen ardından yüksek saflıktaki azot (N_2) gazı altında kurutulmuştur.

Temizleme işleminin ardından, heteroyapının arka yüzeyine düşük dirençli ve kararlı bir omik kontak elde etmek amacıyla yüksek saflıktaki Evaporasyon sistemi kullanılarak Au metal termal buharlaştırma yöntemiyle kaplanmıştır. Omik kontağın kalitesini ve metal-yarıiletken ara yüzeyindeki difüzyonu optimize etmek amacıyla numune, azot atmosferi altında uygun sıcaklıkta 400 derecede ısıl işleme (annealing) tabi tutulmuştur. Schottky bariyer kontağını oluşturmak amacıyla, temizlenmiş ön InGaAs yüzeyine uygun geometrideki gölgeli maskeler (shadow mask) kullanılarak yüksek saflıkta altın (Au) metali termal olarak buharlaştırılmış ve böylece dairesel geometride Au/InGaAs/GaAs Schottky bariyer heteroyapıları başarıyla tamamlanmıştır.

Fabrikasyonu tamamlanan cihazın frekans ve voltaj bağımlı yük iletim mekanizmaları ile dielektrik relaksasyon profilleri, bilgisayar kontrollü bir empedans analizör (LCR metre) yardımıyla oda sıcaklığında (295 K) ölçülmüştür. Elektriksel karakterizasyon işlemleri, -10 V ile $+10$ V gibi geniş bir bias voltaj aralığında (sweep) ve 1 kHz ile 1 MHz frekans spektrumunda sistematik olarak gerçekleştirilmiştir. Deneysel olarak elde edilen kapasitans-voltaj ($C-V$) ve iletkenlik-voltaj ($G/\omega-V$) verilerinden yararlanılarak, yapının kompleks dielektrik sabitinin gerçek (ε') ve sanal (ε'') kısımları,

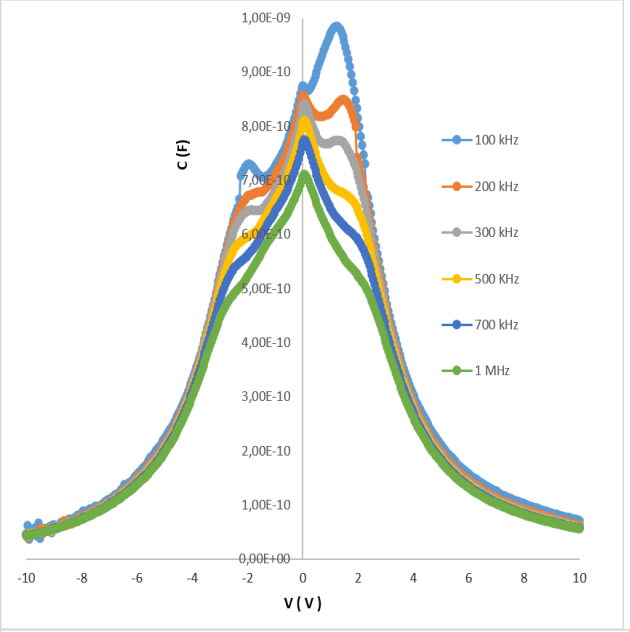
kayıp tanjantı ($\tan\theta$), kompleks elektriksel modülün gerçek (M') ve sanal (M'') bileşenleri ile alternatif akım elektriksel iletkenliği (σ_{ac}) incelenmiştir.

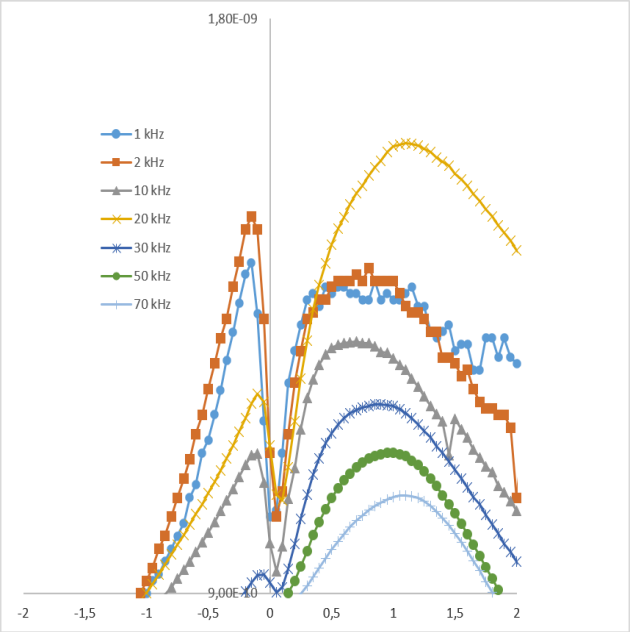
BULGULAR

Bu çalışmada fabrikasyonu gerçekleştirilen Au/InGaAs/GaAs Schottky bariyer heteroyapısının -10 V ile +10 V voltaj aralığında ve 1 kHz ile 1 MHz frekans spektrumunda elde edilen deneysel C-Vverileri sistematik olarak incelenmiştir. C-V eğrilerinde (Şekil 1) uygulanan voltaj ve çalışma frekansına bağlı olarak belirgin değişimler gözlenmiştir. Düşük frekanslarda (örneğin 100 kHz civarında), pozitif beslem bölgesinde kapasitansta keskin tepe noktaları (pikler) oluştuğu tespit edilmiştir. Frekansın artmasıyla (1 MHz değerine doğru) bu kapasitans piklerinin yüksekliğinde belirgin bir azalma meydana gelmektedir. Bu durum, metal ile yarıiletken arayüzeyinde yer alan arayüzey durumlarının (N_{ss}) tuzaklama dinamikleriyle açıklanır. Düşük frekanslarda AC sinyaline yetişebilen arayüzey durumları kapasitansa ekstra katkıda bulunurken, yüksek frekanslarda sinyali takip edemeyerek etkisiz kalmaktadır [2-9].

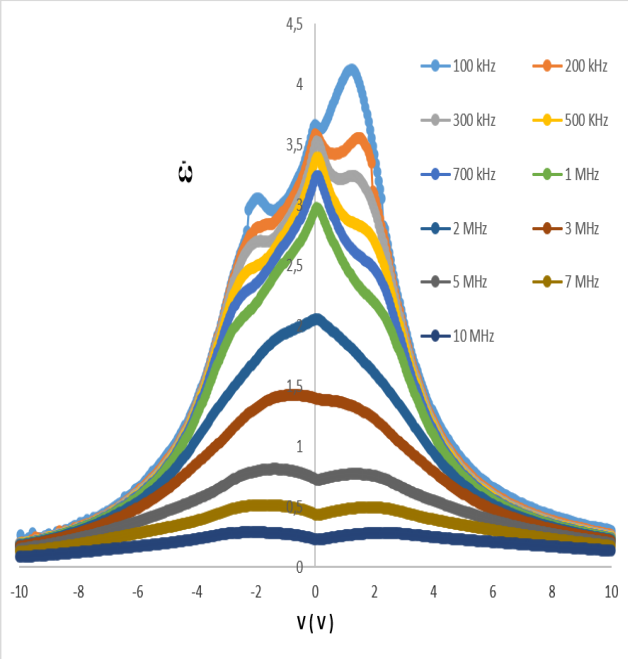
Kapasitans ve iletkenlik verilerinden türetilen kompleks dielektrik sabitinin gerçek (ε') ve sanal (ε'') kısımları frekans ve voltaja karşı güçlü bir duyarlılık sergilemiştir. Pozitif beslem bölgesinde pikler sergileyen ε' eğrileri (Şekil 2), frekans arttıkça sistematik bir düşüş göstermektedir. Bu durum uzaysal yük (arayüzey) polarizasyon mekanizmalarının yüksek frekanslarda sönümlenmesinden kaynaklanmaktadır. Dielektrik Sabitinin İmajiner Kısmı (ε'') ve Kayıp Tanjantı ($\tan\theta$) ise Şekil 3 ve Şekil 4'te görüldüğü üzere, uygulanan voltajının uç değerlerine (özellikle yüksek negatif ve pozitif voltajlara) gidildikten sonra dielektrik kayıpları keskin bir artış göstermektedir. Frekans yükseldikçe ε'' ve $\tan\theta$ değerlerinin azalması, arayüzeydeki yüklerin gevşeme (relaksasyon) sürelerinin sınırlayıcı etkisini ortaya koymaktadır. Yapının alternatif akım elektriksel iletkenliği (σ_{ac}) uygulanan voltaj sweep ve frekansa bağlı olarak Şekil 5'te sunulmuştur. Sıfır bias (0 V) civarında minimum seviyede olan iletkenlik, hem ileri yön (pozitif) hem de ters yön (negatif) bias voltajı arttıkça hızla yükselmektedir. Frekans spektrumunda yukarı doğru gidildikçe AC iletkenliğin genel seviyesinde artış gözlenmiştir. Bu davranış, yük taşıyıcılarının tuzak merkezleri arasında atlama (hopping) iletim mekanizması ile hareket ettiğini desteklemektedir [10-13].

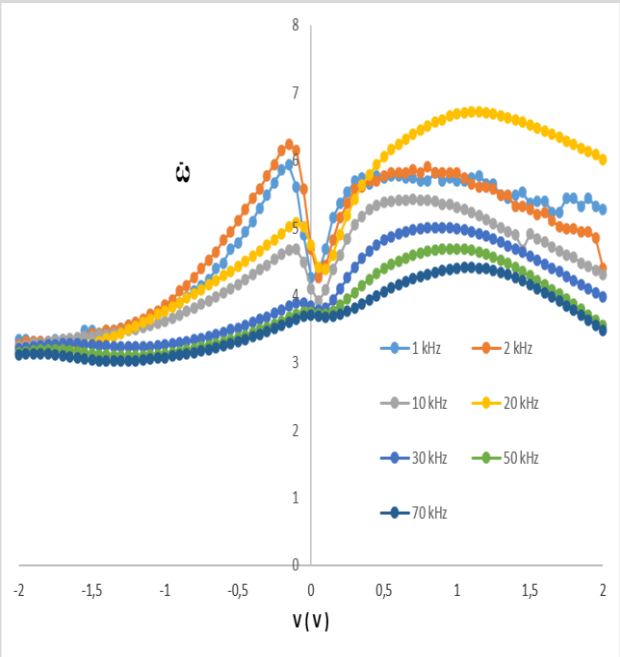
Arayüzey etkilerini ve elektrot polarizasyonunu ayrıştırmak amacıyla incelenen elektriksel modül bileşenleri (Şekil 6 ve Şekil 7) şu bulguları sunmuştur. Gerçek kısım (M'), düşük voltajlarda sıfıra yakın değerler alırken, belirli bias aralıklarında pikler oluşturarak frekansla birlikte yukarı doğru kaymaktadır. Sanal kısım (M'') eğrilerinde gözlenen çift tepe (double-peak) veya asimetrik pik oluşumları, yapıda tek bir gevşeme süresi yerine birden fazla dielektrik relaksasyon mekanizmasının baskın olduğunu göstermektedir [14,15].



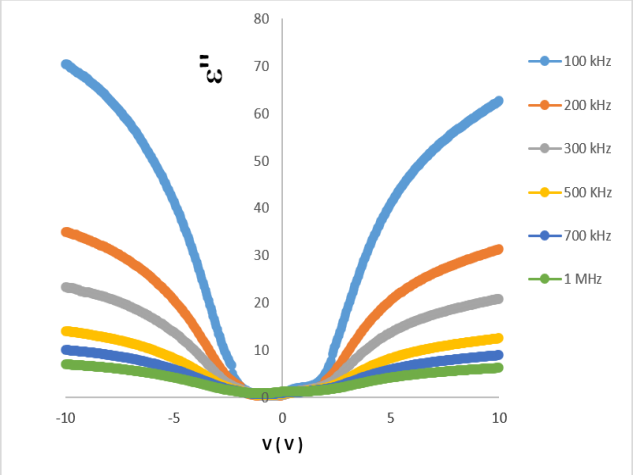


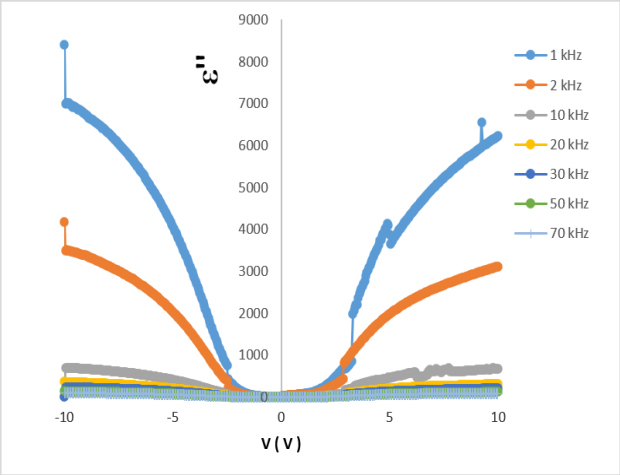
Şekil 1. InGaAs Schottky bariyer heteroyapının farklı frekanslarda C-V eğrileri.



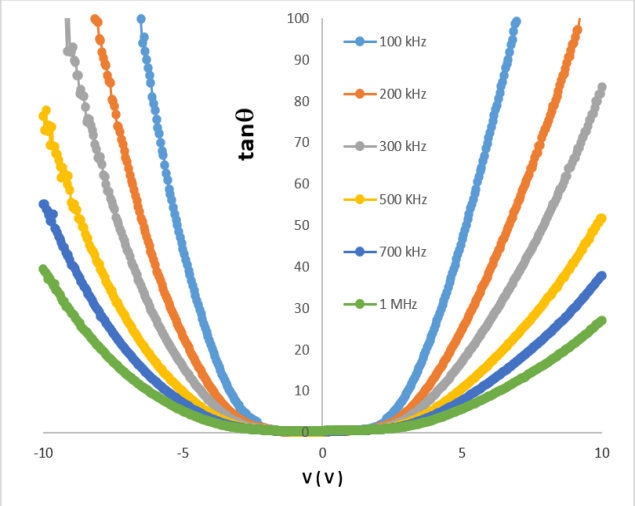


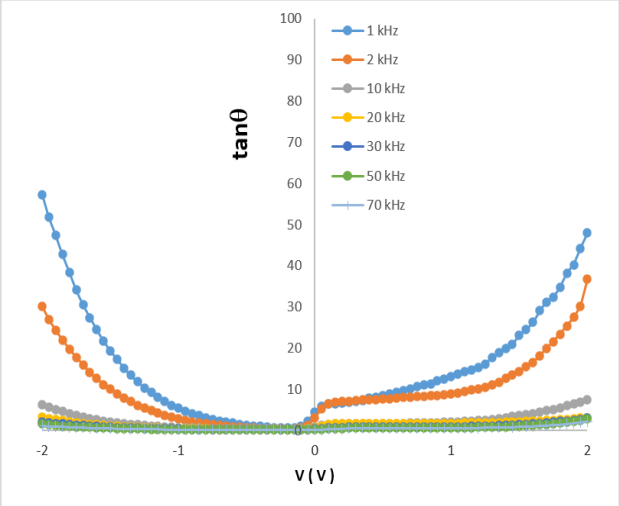
Şekil 2. InGaAs Schottky bariyer heteroyapının farklı frekanslarda dielektrik sabiti eğrileri.



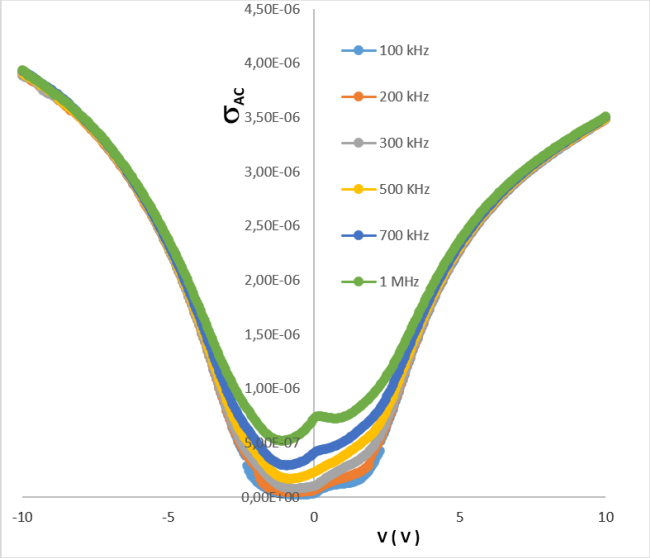


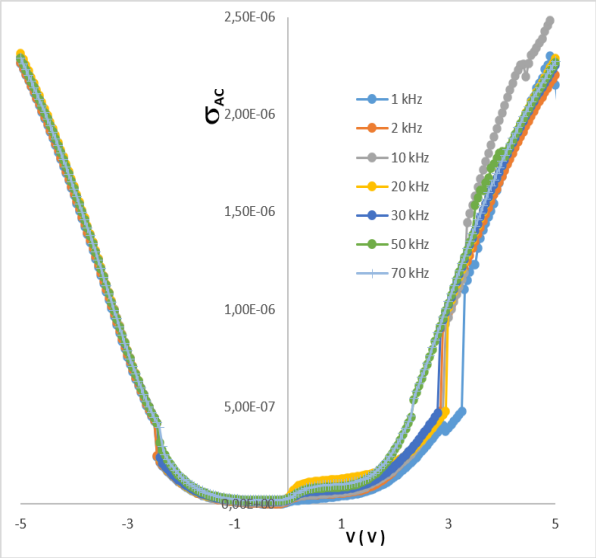
Şekil 3. InGaAs Schottky bariyer heteroyapının farklı frekanslarda dielektrik sabiti imajiner kısım eğrileri.



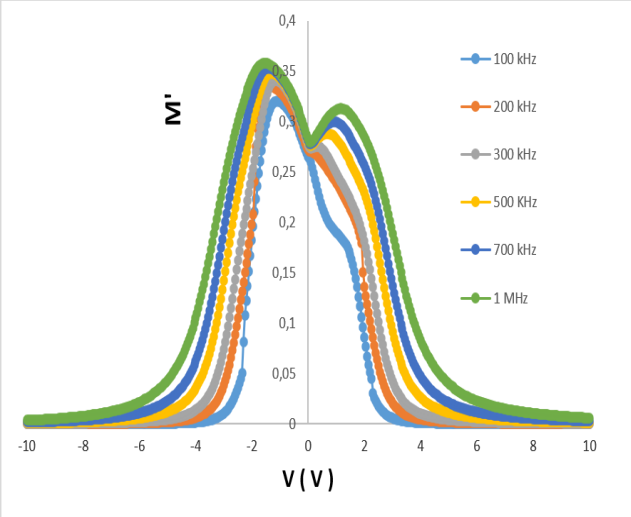


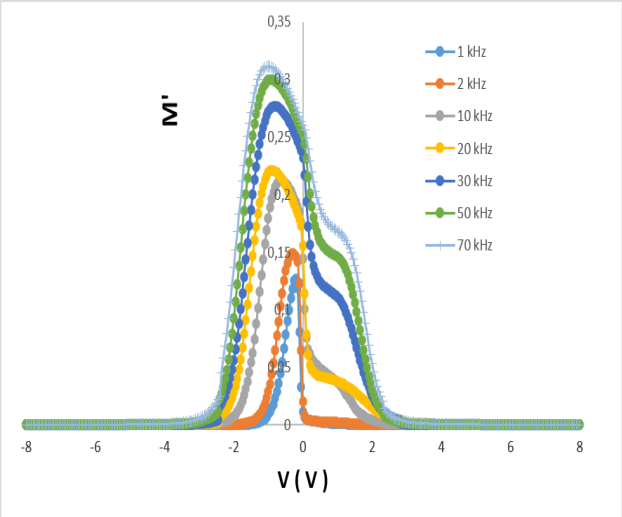
Şekil 4. InGaAs Schottky bariyer heteroyapının farklı frekanslarda tanq eğrileri.



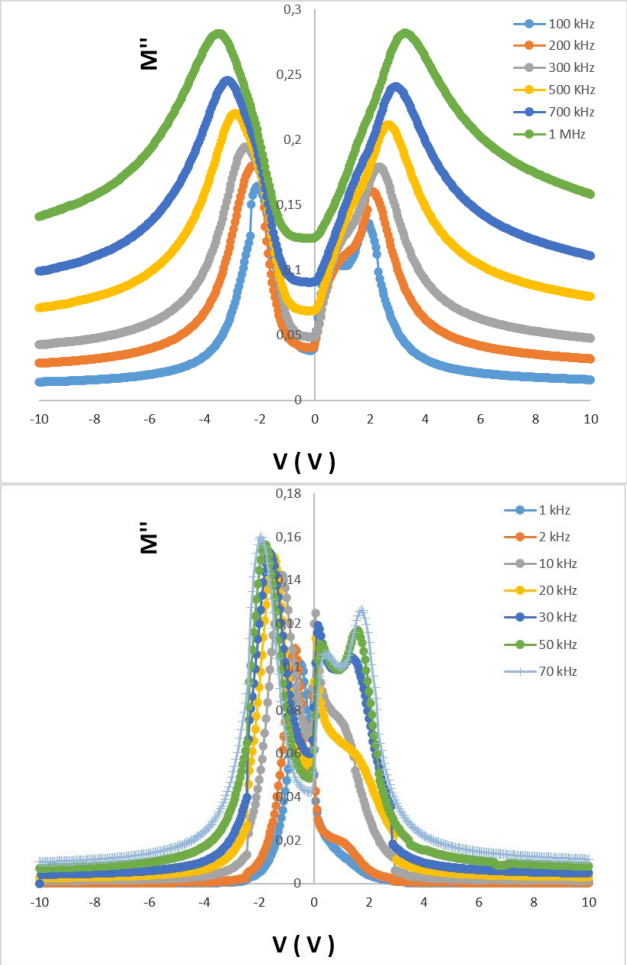


Şekil 5. InGaAs Schottky bariyer heteroyapının farklı frekanslarda alternatif akım iletkenlik eğrileri.





Şekil 6. InGaAs Schottky bariyer heteroyapının farklı frekanslarda elektrik modulus reel kısım eğrileri.



Şekil 7. InGaAs Schottky bariyer heteroyapının farklı frekanslarda elektrik modulus imajinar kısım eğrileri.

SONUÇ VE TARTIŞMA

Bu çalışmada, yeni nesil yüksek hızlı mikroelektronik uygulamalar için kritik öneme sahip Au/InGaAs/GaAs Schottky bariyer heteroyapısı başarıyla fabrikasyon sürecinden geçirilmiş ve geniş bir frekans-voltaj pencerelerinde elektriksel yanıtı incelenmiştir. Elde edilen deneysel verilerin analizi sonucunda, heteroyapının tüm dielektrik profillerinin ve elektriksel modül spektrumlarının hem çalışma frekansına hem de uygulanan uygulanan voltaja karşı aşırı duyarlı olduğu kanıtlanmıştır. Düşük frekanslarda kapasitans ve dielektrik sabitinde gözlenen anomaliler ve pik oluşumları, Au metalizasyonu ile InGaAs tabakası arasında kaçınılmaz olarak bulunan arayüzey durumlarının (N_{ss}) ve uzaysal yük polarizasyonunun doğrudan bir sonucudur. Frekansın 1 MHz seviyesine çıkarılmasıyla bu tuzak merkezlerinin AC sinyalini takip edemediği ve aygıtın daha ideal bir dielektrik yanıta yaklaştığı görülmüştür.

Elektriksel modül (M' ve M'') spektrumlarında gözlenen piklerin frekansla kayması, yük taşıyıcı dinamiklerinin voltaj ve frekans bağımlı bir relaksasyon sürecine tabi olduğunu ortaya koymuştur. Ayrıca alternatif akım iletkenliğinin (σ_{ac}) davranış biçimi, InGaAs Schottky eklemlerindeki ana iletim mekanizmasının arayüzey durumlarının tuzaklama-salma (trapping-detrapping) kinetiğiyle kontrol edildiğini kesinleştirmiştir.

Sonuç olarak; Au/InGaAs/GaAs heteroyapısının sergilediği yüksek frekans kararlılığı ve dinamik dielektrik özellikleri, malzemenin gelecekteki yüksek hızlı mikroelektronik, optoelektronik ve fotovoltaik aygıt tasarımlarında güvenle kullanılabilecek potansiyel bir aday olduğunu doğrulamaktadır.

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COMPREHENSIVE ANALYSIS OF LOW-FREQUENCY DIELECTRIC PROPERTIES AND CHARGE-CARRIER DYNAMICS IN SCHOTTKY BARRIER HETEROSTRUCTURES

SCHOTTKY BARİYER HETEROYAPILARINDA DÜŞÜK FREKANSLI DİELEKTRİK ÖZELLİKLERİN VE YÜK TAŞIYICI DİNAMİKLERİNİN KAPSAMLI ANALİZİ

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ÖZET

Bu çalışmada, p-tipi tek kristal silisyum alttaş kullanılarak Al/doğal oksit/p-Si Schottky diyot fabrikasyonu gerçekleştirilmiştir. Kararlı, homojen ve yüksek yoğunluklu bir doğal SiO2 arayüzey tabakasının büyümesi için Si alttaş, steril bir kabin içerisinde 295 K sabit sıcaklıkta 18 ay boyunca uzun süreli kontrollü doğal oksitlenmeye bırakılmıştır. Üretilen hetero yapının alçak frekanslardaki dielektrik özellikleri ve kompleks elektriksel modül profilleri, 700 Hz - 700 kHz frekans aralığında sistematik olarak incelenmiştir. Deneysel kapasitans-voltaj (C-V) ve iletkenlik-voltaj (G/w-V) ölçümlerinden yararlanılarak; kompleks dielektrik sabitinin gerçek (□□) ve sanal (□□□) kısımları, kayıp tanjantı (tan q), kompleks elektriksel modülün gerçek (M') ve sanal (M") bileşenleri ile alternatif akım elektriksel iletkenliği (□ac) elde edilmiştir. Deneysel sonuçlar, hesaplanan tüm dielektrik modül ve iletim parametrelerinin hem çalışma frekansına hem de uygulanan bias voltajına karşı güçlü bir bağımlılık sergilediğini göstermiştir. Bu belirgin bağımlılık, temel olarak arayüzey tuzaklarının (Nss) relaksasyon kinetiği ve uzaysal yük polarizasyon mekanizmaları tarafından kontrol edilmekte olup, Schottky tipi hetero yapılardaki alçak frekans yük taşıyıcı dinamiklerine dair kapsamlı bir bakış açısı sunmaktadır.
Anahtar Kelimeler: Schottky engel heteroyapıları; Doğal oksit arayüzey katmanı, Dielektrik gevşeme; Elektriksel modül spektrumları, Arayüzey durumları.

ABSTRACT

In this study, an Al/native oxide/p-Si Schottky barrier heterostructure was fabricated utilizing a p-type single-crystal silicon substrate. To ensure the formation of a stable, uniform, and high-density native SiO2 interfacial layer, the Si substrate was subjected to a controlled ambient oxidation process inside a sterile environment at a constant temperature of 295 K for a prolonged duration of 18 months. The low-frequency dielectric properties and complex electric modulus profiles of the fabricated heterostructure were systematically investigated across a frequency spectrum spanning from 700 Hz to 700 kHz. From the experimental capacitance-voltage (C-V) and conductance-voltage (G/w-V) measurements, the real (□□) and imaginary (□□□) parts of the complex dielectric constant, the loss tangent (tan q), the real (M') and imaginary (M") components of the complex electric modulus, and the alternating current electrical conductivity (□ac) were extracted. The experimental results demonstrate that all extracted dielectric, modulus, and transport parameters exhibit a profound dependence on both the operational frequency and the applied bias voltage. This distinct dependency is primarily governed by the relaxation kinetics of interface states (Nss) and spatial charge polarization mechanisms, thereby providing comprehensive insights into the low-frequency charge carrier dynamics within Schottky-type heterostructures.
Keywords: Schottky barrier heterostructures; Native oxide interfacial layer; Dielectric relaxation; Electric modulus spectra; Interface states.

GİRİŞ

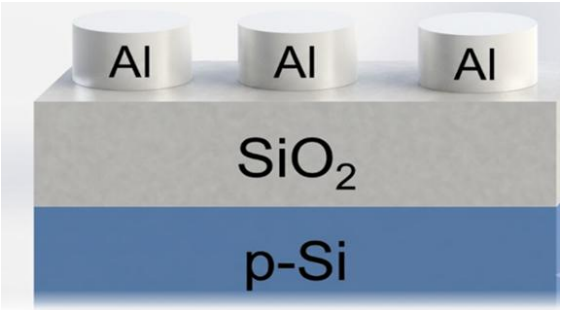
Yarıiletken yüzey özelliklerinin, arayüzey tuzaklarının ve yük taşıma mekanizmalarının mikroskobik düzeyde anlaşılmasında metal-yarıiletken (MS) ve metal-yalıtkan-yarıiletken (MIS) Schottky diyotları

oldukça güçlü birer karakterizasyon aracı olarak hizmet etmektedir [1-4]. MIS tipi yapılarda, metal ile yarıiletken aktif bölge arasında yer alan ince bir yalıtkan katman (örneğin SiO2), arayüzey durumlarının (Nss) sürekli bir dağılım göstermesine neden olur. Bu tür hetero-eklemli yapılar literatürde onlarca yıldır yoğun bir şekilde inceleniyor olsa da arayüzey homojensizliklerinin ve yapısal kusurların şarj dinamikleri üzerindeki etkileri tüm detaylarıyla henüz tam olarak aydınlatılabilmiş değildir [5].
Yalıtkan arayüzey tabakasının kalınlığı kritik bir sınır olan 50 Å değerinin altına indiğinde, taşıyıcıların doğrudan kuantum mekaniksel tünelleme (direct tunnelling) yapması mümkün hale gelmekte ve bu durum cihazın elektriksel parametrelerini kökten değiştirmektedir [1,5]. Literatürde, arayüzey durum yoğunluğunun Nss ve seri direncin Rs karakterizasyonu için akım-voltaj I-V ve kapasitans-voltaj C-V gibi geleneksel kararlı durum (steady-state) yöntemleri yaygın olarak kullanılmaktadır [3]. Genellikle, yüksek ileri beslemeli gerilimlerde I-V grafiklerinin doğrusallıktan sapması bu Rs ve Nss parametrelerinin baskın etkisine atfedilir [6]. Benzer şekilde, arayüzey durumları C-V karakteristiklerinde sapmalara, idealite faktörünün (n) artmasına ve 1/C2-V grafiklerinde bükülmelere yol açar. Son yıllarda yapılan çalışmalarda, ileri besleme altında gözlenen anormal kapasitans pikleri, arayüzey tuzaklarının ve seri direncin voltaj altındaki dinamik tepkisinin bir sonucu olarak rapor edilmiştir [2]. Schottky bariyer hetero yapılarındaki yük taşıyıcı dinamiklerinin ve tuzaklama mekanizmalarının doğasını tam olarak anlamak, sadece kararlı durum analizleri ile mümkün değildir. Özellikle alçak frekans rejiminde, arayüzey durumları uygulanan alternatif akım AC sinyalini takip edecek yeterli zamana sahip olur; bu da yüklerin yeniden yapılanma, tünelleme ve dielektrik gevşeme (relaxation) süreçlerini doğrudan görünür kılar. Genişletilmiş dielektrik spektroskopisi ve kompleks elektriksel modül formalizmi; malzemenin dielektrik sabiti (ε'), kayıp faktörü (ε''), kayıp tanjantı ($\tan\Theta$), kompleks elektriksel modül bileşenleri (M' ve M'') ve alternatif akım elektriksel iletkenliği (σ_{ac}) gibi parametrelerin frekans ve voltaj bağımlılığını inceleyerek arayüzeydeki uzaysal yük polarizasyon mekanizmalarını analiz etmede benzersiz bir hassasiyet sunar [1,3].
Bu çalışmada, p-tipi tek kristal silisyum alttaş kullanılarak Al/doğal oksit/p-Si Schottky bariyer heteroyapısının fabrikasyonu gerçekleştirilmiştir. Kararlı, homojen ve yüksek yoğunluklu bir doğal SiO_2 arayüzey tabakasının elde edilmesi amacıyla Si alttaş, steril bir kabin içerisinde 295 K sabit sıcaklıkta 18 ay boyunca uzun süreli kontrollü doğal oksitlenmeye bırakılmıştır. Üretilen hetero yapının alçak frekanslardaki dielektrik özellikleri ve kompleks elektriksel modül profilleri, 700 Hz - 700 kHz frekans aralığında sistematik olarak incelenmiştir. Deneysel kapasitans-voltaj ve iletkenlik-voltaj G/w-V ölçümlerinden yararlanılarak hesaplanan tüm dielektrik modül ve iletim parametrelerinin hem çalışma frekansına hem de uygulanan bias voltajına karşı güçlü bir bağımlılık sergilediği saptanmıştır. Bu belirgin bağımlılık, temel olarak arayüzey tuzaklarının relaksasyon kinetiği ve uzaysal yük polarizasyonu çerçevesinde tartışılarak, Schottky tipi hetero yapılardaki alçak frekans yük taşıyıcı dinamiklerine dair kapsamlı bir bakış açısı sunmaktadır.

DENEYSEL YÖNTEM

Bu çalışmada incelenen Al/doğal oksit/p-Si Schottky bariyer heteroyapılarının fabrikasyonunda; $<100>$ yüzey yönelimli, 2 inç çaplı ve 8 Ωcm özdirence sahip p-tipi (bor katkılı) tek kristal silisyum (Si) alttaşlar kullanılmıştır. Fabrikasyon işleminin ilk adımında, Si alttaş üzerindeki organik kirlilikleri uzaklaştırmak amacıyla yüzey sırasıyla trikloroetilen, aseton ve metanol organik çözücüleri içerisinde temizlenmiştir. Ardından alttaşlar saf su içerisinde uzun süreli durulanmıştır. Temizlenen Si alttaşın tüm arka yüzeyine ohmik kontak oluşturmak amacıyla, 200 nm kalınlığında yüksek saflıkta (%99.999) alüminyum (Al) termal olarak buharlaştırılmıştır. Ohmik kontak oluşumunun ardından, Si alttaşın ön yüzeyinde kararlı, homojen ve yüksek yoğunluklu bir doğal arayüzey tabakasının büyümesi sağlanmıştır. Bu amaçla numune, steril bir cam kabin içerisinde, oda sıcaklığında 18 ay boyunca uzun süreli ve kontrollü doğal oksitlenmeye bırakılmıştır.
Doğal oksit tabakası büyütüldükten sonra, ön doğrultucu (Schottky) kontakları oluşturmak üzere SiO_2 tabakası üzerine ~ 1 mm çapında metal maskeler kullanılarak 200 nm kalınlığında Al noktalar termal olarak evapore edilmiştir. Metal tabaka kalınlığı ve biriktirme hızları bir kuvars kristal kalınlık monitörü vasıtasıyla anlık olarak kontrol edilmiştir. Arayüzey yalıtkan tabaka kalınlığı, güçlü birikim (accumulation) bölgesinde yapılan yüksek frekanslı (1 MHz) oksit kapasitansı (C_{ox}) ölçümlerinden yararlanılarak yaklaşık 3,2 nm olarak hesaplanmıştır. Üretilen hetero yapının (Şekil 1) kapasitans-voltaj ve iletkenlik-voltaj ölçümleri empedans analizörü kullanılarak oda sıcaklığında alınmıştır. Sistematik

dielektrik analizleri için $C-V$ ve $G/\omega-V$ ölçümleri 700 Hz − 700 kHz alçak frekans aralığında gerçekleştirilmiştir.



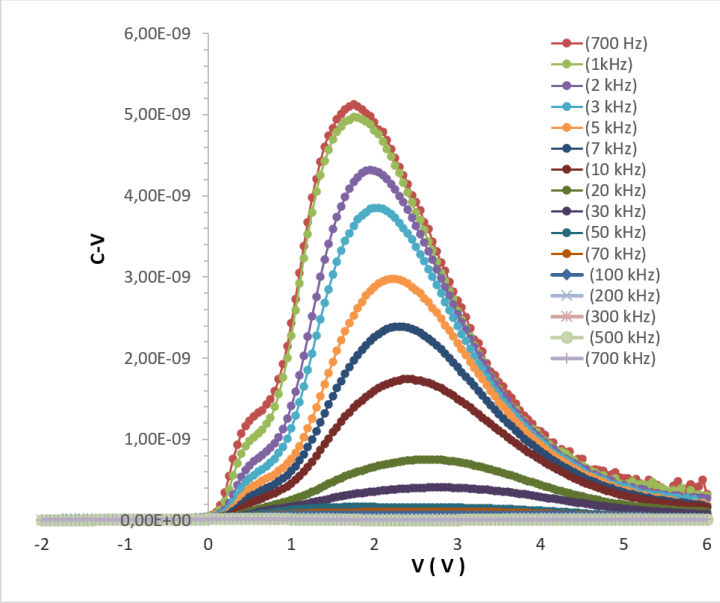
Şekil 1. Al/doğal oksit/p-Si Schottky bariyer hetero yapı.

BULGULAR

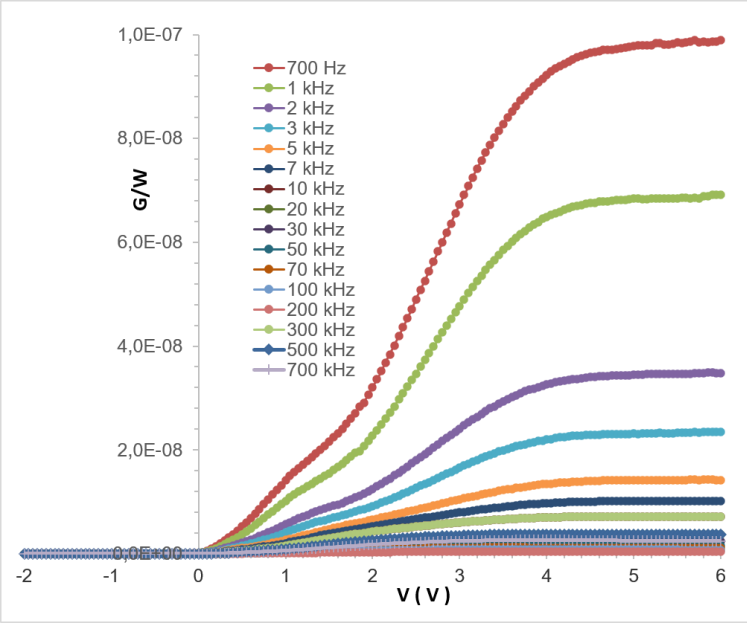
Schottky diyotların $C-V$ analizi ile arayüzey durumlarının neden olduğu enerji kayıpları ve seri direnç değerleri analiz edilebilmektedir. Bu analiz, üretilen hetero yapının bir diyot veya sensör olarak ne kadar kararlı çalışacağını belirleyen en temel adımdır. İletkenlik-voltaj ölçümleri de yapılarak, arayüzey durumlarının neden olduğu enerji kayıpları ve yapısal parametreler incelenmiştir.

Şekil 2 ve Şekil 3'te sırasıyla Al/doğal oksit/p-Si Schottky bariyer hetero yapısının farklı frekanslardaki $C-V$ ve $G/\omega-V$ eğrileri görülmektedir. Her iki grafikte de artan frekansla kapasitans ve iletkenliğin azaldığı saptanmıştır. Bunun nedeni, özellikle düşük frekanslarda (<1 MHz) arayüzey durumlarının (N_{ss}) uygulanan sinyale dinamik olarak yanıt verebilmesi ve yapıya ilave kapasitans ile iletkenlik katkısı getirmesidir. Yeterince yüksek frekanslarda ise bu etkiler ortadan kalkmaktadır; çünkü arayüzey durumlarının relaksasyon (yaşam) süreleri yüksek frekanslı sinyalleri takip edemeyecek kadar yavaştır. İletkenlik ve kapasitans değerlerinden faydalanılarak hesaplanan seri direncin (R_s) voltaja ve frekansa bağlı değişimleri Şekil 4'de sunulmuştur. Grafikler incelendiğinde, özellikle alçak frekanslarda (700 Hz ve 1 kHz) direnç değerlerinin megaohm (MΩ) seviyelerine ulaşarak oldukça yüksek değerler aldığı görülmektedir. Bu durum, arayüzey durumlarının ve arayüzeydeki yük birikimlerinin seri dirence doğrudan ve baskın bir ilave katkı sağladığını doğrulamaktadır.

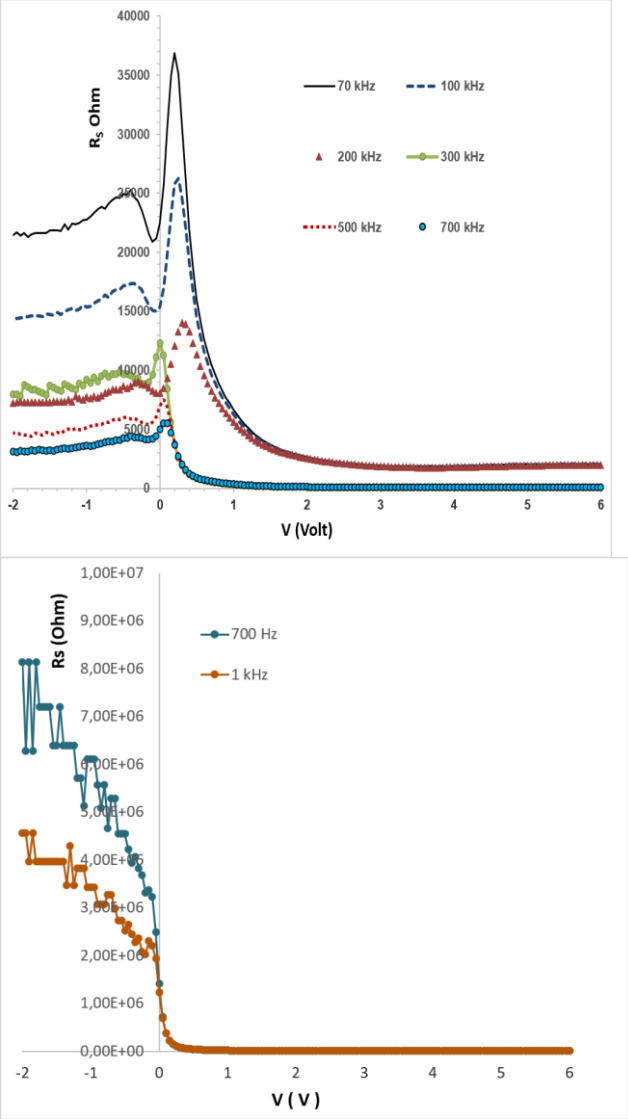
Dielektrik sabiti, bir malzemenin elektrik alan altında elektriksel enerjiyi ne kadar depolayabildiğini ve kutuplanma (polarizasyon) yeteneğini gösteren temel bir ölçüttür. Bu çalışmada, kompleks dielektrik sabitinin gerçek (ε') ve imajiner (ε'') kısımlarının frekansa bağlı değişimi sırasıyla Şekil 5 ve Şekil 6'da verilmiştir. Dielektrik sabitleri de frekansın artmasıyla azalan bir eğilim göstererek arayüzey kutuplanma mekanizmalarıyla uyumlu bir davranış sergilemektedir. Ayrıca yapıya ait kayıp tanjantı ($\tan\theta$) ve alternatif akım iletkenlik (σ_{AC}) eğrileri sırasıyla Şekil 7 ve Şekil 8'de sunulmuştur. Şekil 8'de açıkça görüldüğü üzere, alçak frekans rejiminde arayüzey durumlarının etkisiyle seri direnç arttığından, alternatif akım iletkenliği düsen frekanslarda azalma eğilimi göstermektedir



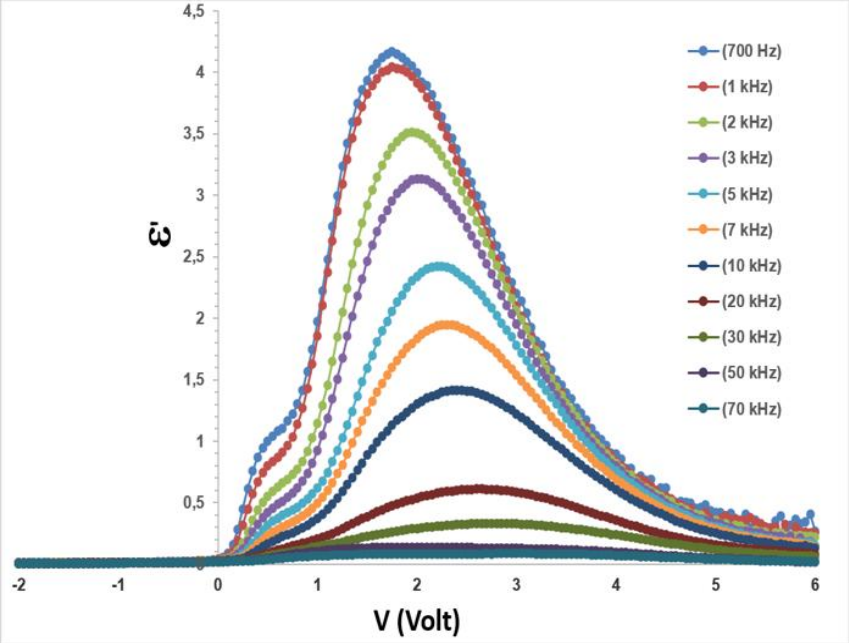
Şekil 2. Al/doğal oksit/p-Si Schottky bariyer heteroyapının farklı frekanslarda C-V eğrileri.



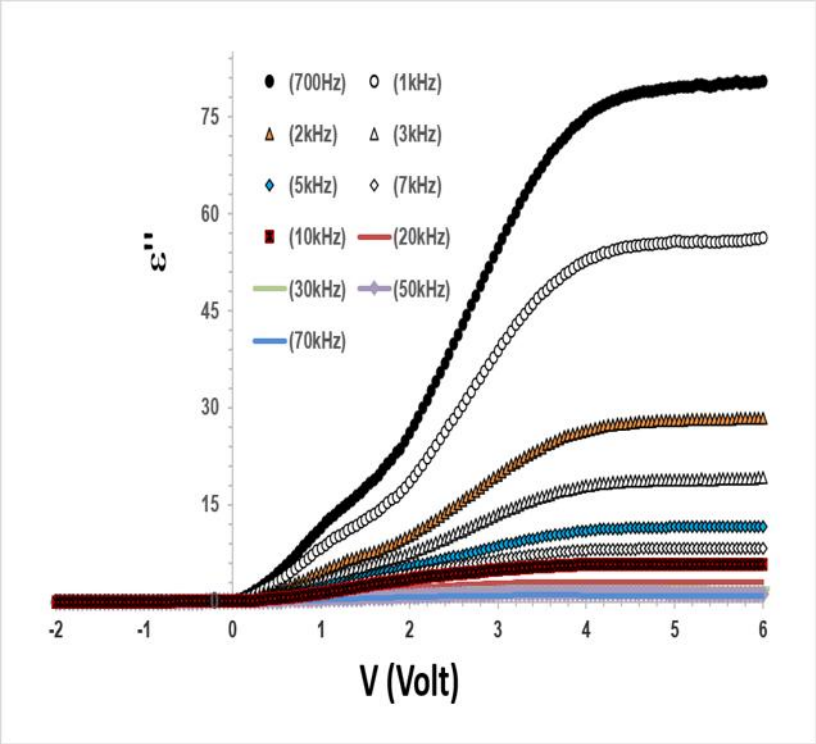
Şekil 3. Al/doğal oksit/p-Si Schottky bariyer heteroyapının farklı frekanslarda G/w-V eğrileri.



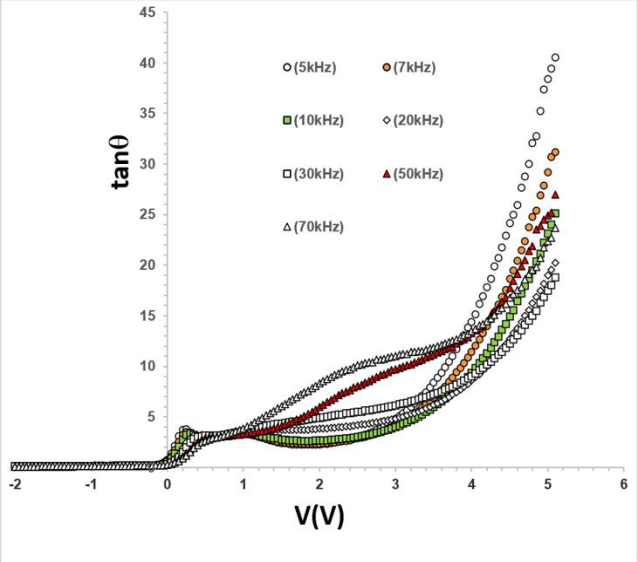
Şekil 4. Al/doğal oksit/p-Si Schottky bariyer heteroyapının farklı frekanslarda Rs-V eğrileri.

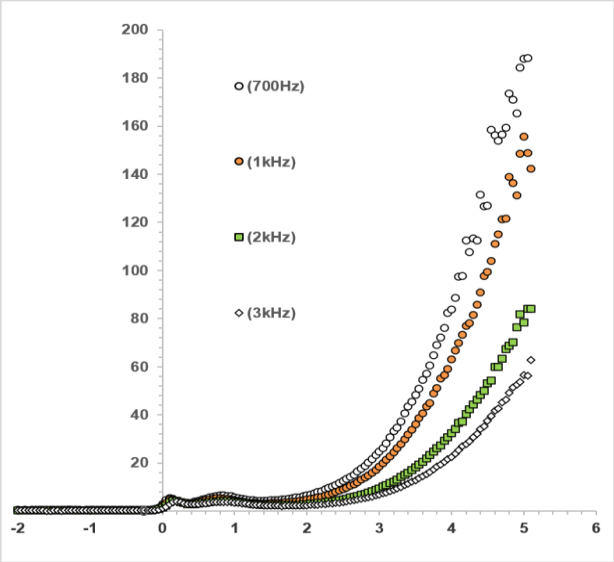


Şekil 5. Al/doğal oksit/p-Si Schottky bariyer heteroyapının farklı frekanslarda dielektrik sabiti eğrileri.

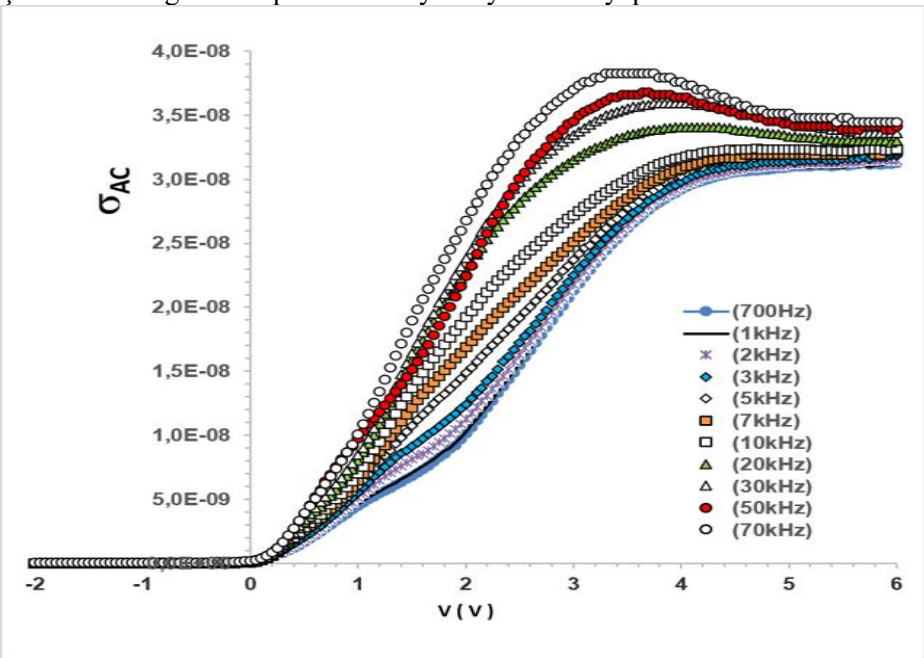


Şekil 6. Al/doğal oksit/p-Si Schottky bariyer heteroyapının farklı frekanslarda dielektrik sabiti imajiner kısım eğrileri.





Şekil 7. Al/doğal oksit/p-Si Schottky bariyer heteroyapının farklı frekanslarda tanq eğrileri.



Şekil 8. Al/doğal oksit/p-Si Schottky bariyer heteroyapının farklı frekanslarda alternatif akım iletkenlik eğrileri.

SONUÇ VE TARTIŞMA

Bu çalışmada, p-tipi Si alttaş üzerinde 18 ay gibi uzun süreli ve kontrollü bir doğal oksidasyon süreciyle yaklaşık 3.2 nm kalınlığında , homojen ve yüksek yoğunluklu bir SiO_2 arayüzey yalıtkan tabakası başarıyla büyütülmüş ve Al/doğal oksit/p-Si Schottky bariyer heteroyapısı imal edilmiştir. Üretilen cihazın 700 Hz - 700 kHz alçak frekans aralığındaki frekans ve voltaj bağımlı dielektrik, elektriksel modül ve yük iletim karakteristikleri sistematik olarak incelenmiştir.

Deneysel kapasitans-voltaj ($C-V$) ve iletkenlik-voltaj ($G/\omega-V$) karakteristiklerinde alçak frekans rejiminde gözlenen belirgin pik oluşumları , arayüzey tuzaklarının (N_{ss}) uygulanan AC test sinyalini yakından takip edebildiğini ve sisteme ek kapasitans/iletkenlik katkısı sağladığını doğrulamıştır. Frekansın artmasıyla birlikte kapasitans, dielektrik sabiti (ϵ') ve dielektrik kayıp faktörünün (ϵ'') azalması , arayüzey durumlarının relaksasyon (gevşeme) sürelerinin yüksek frekanslı sinyallere yanıt verememesinden (yaşam sürelerinin yetersiz kalmasından) kaynaklanmaktadır. Ayrıca, alçak frekanslarda seri direncin (R_s) yüksek değerlere ulaşması, N_{ss} dağılımının yapısal direnç üzerindeki doğrudan ve baskın rolünü ortaya koymuştur. Alternatif akım iletkenliğinin (σ_{AC}) ise özellikle düşük frekanslarda azalan bir eğilim göstermesi, arayüzey tuzaklarının neden olduğu potansiyel bariyer bükülmeleri ve artan seri direnç mekanizmalarıyla açıklanmıştır. Sonuç olarak, kontrollü ve uzun süreli doğal oksit katmanıyla üretilen Al/doğal oksit/p-Si yapısının, alçak frekans mikroelektronik uygulamalarında ve hassas kapasitif sensör teknolojilerinde kararlı bir yalıtkan arayüzey mimarisi olarak potansiyel bir aday olduğu saptanmıştır.

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THE EFFECT OF HEAT-TREATMENT DURATION ON VICKERS HARDNESS AND SELECTED MAGNETIC PROPERTIES OF $FE_{39}NI_{39}MO_4SI_6B_{12}$ METALLIC GLASS ALLOY

FE39Nİ39MO4Sİ6B12 METALİK CAM ALAŞIMINDA ISIL İŞLEM SÜRESİNİN VİCKERS SERTLİĞİ VE BAZI MANYETO ÖZELLİKLER ÜZERİNE ETKİSİ

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ÖZET

Bu çalışmada yüzeye püskürtme metoduyla (Planar Flow Casting Method) üretilen demir nikel esaslı metalik cam alaşımın (Fe39Ni39Mo4Si6B12) fiziksel özellikleri farklı Isıl İşlemlerde incelenmiştir. Başlangıçtaki amorf numuneler, Curie sıcaklığının üstünde bir sıcaklık olan 500 °C sıcaklıkta sırasıyla 60, 300 ve 1800 saniye sürelerle ısıl işleme tabi tutulmuştur. Metalik cam alaşımın mekanik kararlılık ve manyetik performansı üzerindeki ısıl işlemin doğrudan etkileri incelenmiştir. Koersivite- ısıl işlem süresi, (Hc –t(sn)) ve manyetik duygunluk –ısıl işlem süresi (χo – t (sn)) değerleri elde edilmiş ve değişimler grafiklerle verilmiştir. Sertlik değerlerindeki değişime parallel olarak manyetik özelliklerdeki değişimlerde mekanik karakteristiklerin belirlenmesi amacıyla gerçekleştirilen Vickers sertlik testleri, ısıl işlem süresinin artmasıyla birlikte sertlik değerlerinde belirgin bir artış yaşandığını ortaya koymuştur. Bu değerler SEM görüntüleme tekniği ile de desteklenmiştir. Elde edilen bulgular, optimize edilen sertlik ve yüksek manyetik performans göstermesi sayesinde metalik cam alaşımının, özellikle ileri teknolojik malzeme olarak alıcı verici sensör uygulamalarında, kristal yapılı malzemelere göre kullanımının daha avantajlı olduğunu göstermektedir.
Anahtar Kelimeler: Metalik cam; Vickers; Isıl işlem; Koersivite; Duygunluk

ABSTRACT

In this study, the physical properties of an iron–nickel-based metallic glass alloy (Fe39Ni39Mo4Si6B12) produced by the Planar Flow Casting Method were investigated under different heat-treatment conditions. The initially amorphous samples were subjected to heat treatment at 500 °C, a temperature above the Curie temperature, for 60, 300, and 1800 seconds, respectively. The direct effects of heat treatment on the mechanical stability and magnetic performance of the metallic glass alloy were examined. Coercivity–heat treatment time (Hc–t(s)) and magnetic susceptibility–heat treatment time (χo–t(s)) values were obtained, and their variations were presented graphically. In parallel with the changes in hardness values, variations in magnetic properties were also observed. Vickers hardness tests, conducted to determine the mechanical characteristics, revealed a significant increase in hardness with increasing heat-treatment time. These results were further supported by SEM imaging techniques. The findings indicate that, due to its optimized hardness and high magnetic performance, the metallic glass alloy offers advantages over crystalline materials, particularly for transmitter–receiver sensor applications as an advanced technological material.
Keywords: Metallic glass; Vickers; Heat treatment; Coercivity; Susceptibility.

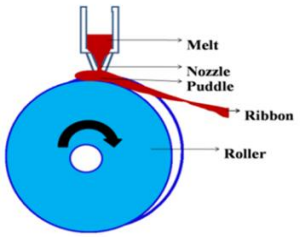
GİRİŞ

Teknolojik gelişmelerle birlikte fiziksel, mekanik ve manyetik özellikleri iyileştirilmiş yeni mühendislik malzemelerine olan ihtiyaç artmaktadır. Bu bağlamda, tane sınırı içermeyen izotropik yapıları sayesinde yüksek sertlik, mükemmel mukavemet ve üstün korozyon direnci sunan amorf alaşımlar (metalik camlar) yoğun araştırmalara konu olmuştur. Araştırmalardaki temel problem, amorf yapıların teknik özelliklerinin kontrol edilebilirliği ile kullanım alanlarının genişletilmesidir. Literatürde, amorf yapıdan

kristale geçiş aşamalarında kristal boyutunun küçülmesiyle manyetik kayıpların önemli ölçüde azaltılabildiği saptanmıştır (Şahingöz vd., 2004).
Tarihsel süreçte eriyikten su verme yöntemiyle üretilen ilk amorf alaşım 1960 yılında rapor edilmiş (Duwez, 1967), sürekli üretim yöntemlerinin geliştirilmesiyle bu malzemelerin yüksek mukavemet (yumuşak manyetik davranış (Egami vd., 1974) ve korozyon direnci özellikleri keşfedilmiştir. 1976'da şerit döküm yönteminin geliştirilmesiyle ticarileşen amorf metaller (Liebermann ve Graham, 1976), yüksek elektrik dirençleri sayesinde alternatif alanlarda girdap akımı kayıplarını minimize ettikleri için özellikle düşük kayıplı transformatör çekirdeklerinde geniş kullanım alanı bulmuştur (Guntherodt, 1985; Inoue, et al.,2008). Katılaşma sırasındaki artık gerilmeler veya uygulanan ısıl işlemler, amorf metallerin alan yapısını ve manyetik davranışlarını doğrudan belirlemektedir (Graham ve Egami, 1978). Bu çalışmada, düzlem akışlı döküm (melt spinning) yöntemiyle 40 µm kalınlığında şerit formunda üretilmiş Fe39Ni39Mo4Si6B12 metalik cam alaşımı kullanılmıştır. Bu özel bileşimin tercih edilme nedeni; yüksek manyetik geçirgenlik (μ), yüksek doyum mıknatıslanması (M_s), düşük koersivite (H_c) ve düşük manyetik kayıp katsayısı gibi üstün yumuşak manyetik özelliklere sahip olmasıdır. Çalışma kapsamında, ısıl işlem süresinin Fe39Ni39Mo4Si6B12 alaşımının Vickers sertliği ve temel manyeto-statik parametreleri üzerindeki etkisi sistematik olarak incelenmiştir.

DENEYSEL YÖNTEM

Çalışmada, kullanılan düzlem Akışlı Döküm Metodunda (Planar Flow Casting) erimiş metal alaşım ince yarıktan, soğuk yüzey üzerine (Şekil 1.) de görüldüğü gibi uygun açılarla püskürtülür. Üretim esnasında şeritlerin yüzey kalitesini optimize etmek amacıyla pota tasarımı, yarık genişliği, eriyik akış hızı, disk dönme hızı ve pota-disk mesafesi gibi işlem parametreleri kontrol altında tutulmuştur. Hızlı katılaşma ile üretilen amorf şeritlerin manyetik domain yapıları ve mekanik özellikleri üzerindeki ısıl işlem süresi etkisini belirlemek amacıyla numuneler eşit boyutlarda 4 parçaya ayrılmıştır. Numuneler ısıl işlem öncesinde alkol ve aseton ile ultrasonik olarak temizlenmiş ve oda koşullarında kurutulmuştur. Bir adet numune karşılaştırma amacıyla as-cast (ısıl işlemsiz) olarak bırakılırken; diğer 3 numune 500 °C sıcaklıkta sırasıyla 1 dk, 5 dk ve 30 dk sürelerle izotermal ısıl işleme tabi tutulmuştur. Tüm numuneler, ısıl işlem sonrasındaki her bir karakterizasyon aşamasından önce alkol ve aseton ile yeniden temizlenmiştir.
Numunelerin yapısal, morfolojik ve kimyasal özelliklerini belirlemek amacıyla X-Işınları Kırınımı (XRD), Taramalı Elektron Mikroskobu (SEM) analizleri gerçekleştirilmiştir. Malzemenin plastik deformasyona karşı direncini tayin etmek amacıyla statik sertlik ölçüm yöntemlerinden Vickers mikrosertlik testi tercih edilmiştir. Ölçümler, EmcoTest DuraScan 20 mikro-sertlik cihazında, 136°'lik elmas piramit ucun malzeme yüzeyinde bıraktığı izin optik olarak değerlendirilmesi esasına dayanarak gerçekleştirilmiştir. Sertlik değerlerinin güvenilirliği için her numuneden çoklu ölçüm alınarak ortalamaları hesaplanmıştır.

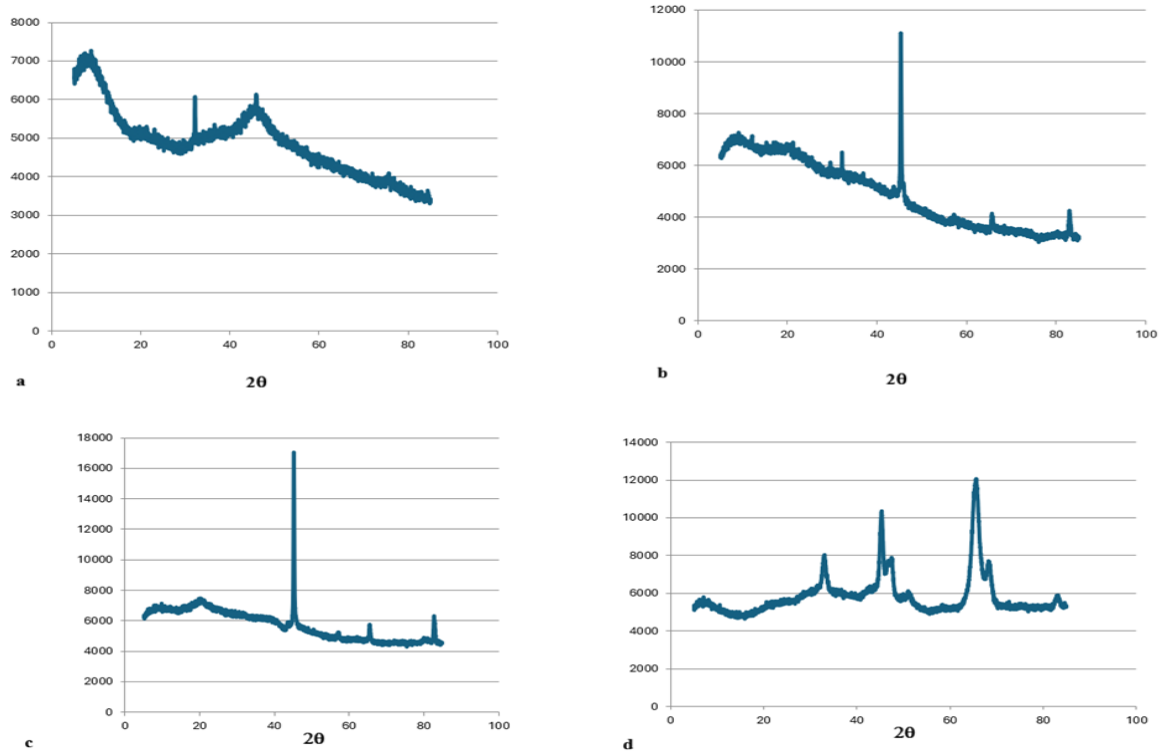


Şekil 1. Melt Spinning tekniğinin şematik diyagramı.

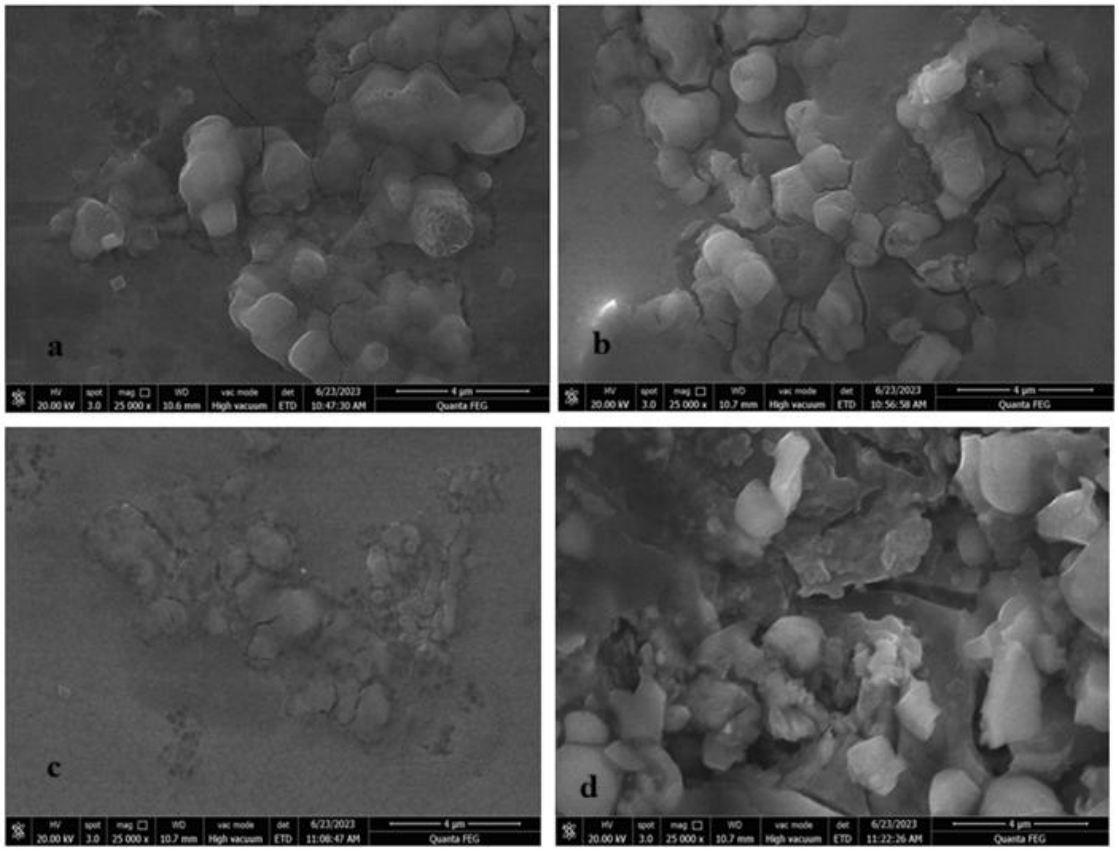
DENEYSEL BULGULAR

Isıl işlemin atomik yapı üzerindeki etkilerini incelemek amacıyla numuneler, 500 °C'ye ayarlanmış fırında sırasıyla 1, 5 ve 30 dakika sürelerle ısıl işleme tabi tutulmuştur. Isıl işlem görmemiş (as-cast) ve farklı sürelerde ısıtılmış numunelerin XRD analizleri gerçekleştirilmiş ve elde edilen difraktogramlar Şekil 2'de sunulmuştur. Şekil 2 incelendiğinde; ısıl işlem görmemiş numunenin amorf yapısı gereği keskin kırınım pikleri yerine geniş bir amorf tepe (halo piki) sergilediği, ancak termal işlemle birlikte kristal piklerin belirginleşmeye başladığı görülmüştür. Isıl işlem süresinin artmasına paralel olarak, pikin şiddetindeki artış ve genişliğindeki azalma, yapıda kristallenme derecesinin arttığını açıkça ortaya koymaktadır. Son grafikteki ($2\theta \approx 32° - 35°$ arsı pikler amorf matristen ayrışan Borür fazlarının

(Fe_2B, Ni_2B veya karmaşık $(Fe,Ni)_3B$ / Mo_2B) oluştuğunu gösterir. Kristallenmenin ilk ve en karakteristik göstergelerinden biridir. Ortadaki İkiz/Omuzlu Pik Grubu ($2\theta \approx 43° - 47°$ civarı) çok net ve şiddetli bir ana pik ile onun hemen sağında bir omuz/ikincil pik yapısı (ikili tepe) görülüyor. Burası α-(Fe,Ni) katı çözeltisinin oluştuğu ana bölgedir. Saf Fe ana piki $\sim 44.6°$ civarındayken, nikelin yapıya girmesi ve ısıl işlem gerilmeleriyle bu pikler birleşir veya omuz oluşturur. En sağdaki baskın pik ve yanındaki küçük tepe ($2\theta \approx 65° - 68°$ civarı) bu bölge, α-Fe/Ni kristal yapısının yüksek açılı düzlemlerine (örneğin (200) düzlemi) ve eşlik eden borür/silisid fazlarının ardışık yansımalarına aittir.
Numunelere ait 25.000x büyütmedeki SEM mikrografları Şekil 3'te sunulmuştur. Isıl işlem görmemiş (as-cast) numunenin SEM görüntüsü incelendiğinde, mikroyapının tamamen homojen amorf bir karakter sergilediği anlaşılmaktadır. 500 °C'de 1 dakika süreyle ısıl işleme tabi tutulan Fe39Ni39Mo4Si6B12 metalik cam numunesinde ise yapının kristallenmeye başladığı gözlenmiştir. Isıl işlem süresinin 5 dakikaya çıkarılmasıyla birlikte, alaşımın matrisindeki kristallenme eğiliminin belirginleştiği ve faz dönüşümünün ilerlediği tespit edilmiştir. Şekil incelendiğinde 30 dakika ısıtılmış Fe39Ni39Mo4Si6B12 metalik cam numune için başlangıçtaki ısıl işlemlerde çekirdeklenme ve bölgesel kristallenme (hatta nano yapı) gözlenmiştir (Şahingöz vd, 2009, Şahingöz vd, 2010).



Şekil 2. a) Isıtılmamış Fe39Ni39Mo4Si6B12 metalik camın XRD grafiği b) 500 °C'de 1 dakika ısıtılmış c) 500 °C'de 5 dakika ısıtılmış d) 500 °C'de 30 dakika ısıtılmış Fe39Ni39Mo4Si6B12Metalik Camın XRD grafiği.



Şekil 3. a) Isıtılmamış Fe39Ni39Mo4Si6B12 metalik camın SEM görüntüleri b) 500 °C'de 1 dakika ısıtılmış c) 500°C'de 5 dakika ısıtılmış d) 500°C'de 30 dakika ısıtılmış Fe39Ni39Mo4Si6B12 metalik camın SEM görüntüleri.

Fe39Ni39Mo4Si6B12bileşimindeki metalik cam numuneleri, karakterizasyon çalışmaları öncesinde alkol ile temizlenerek analize hazır hale getirilmiştir. Numunelere ait mikrosertlik ölçüm sonuçları Tablo 1'de sunulmuştur. Isıl işlem süresinin sertlik üzerindeki etkisi ise Şekil 4'te gösterilmiştir. Şekil 4 detaylı incelendiğinde; sertlik değerinin ısıl işlem görmemiş (as-cast) numunede en düşük seviyede olduğu, ısıl işlem süresinin artışıyla birlikte ise sertlikte %25 oranında oldukça belirgin bir artış meydana geldiği anlaşılmaktadır.

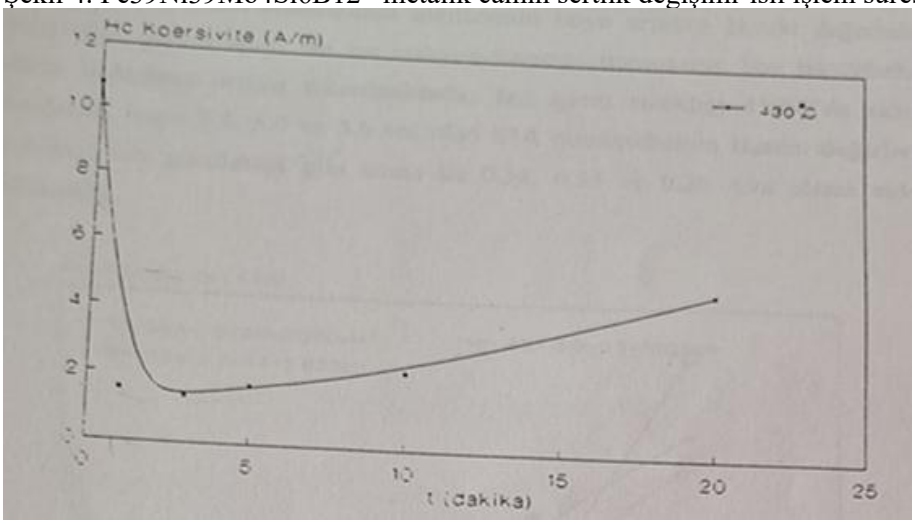
Tamamen amorf olan metalik camlar zaten serttir; ancak yapı içerisinde bu grafikte gördüğümüz gibi sert borür (Fe_2B) ve silisid (Fe_3Si) nanokristalleri çökelmeye başladığında, bu partiküller dislokasyon hareketlerini engelleyerek malzemede çökelme sertleşmesine (precipitation hardening) yol açar ve Vickers sertliğini tepe noktasına ulaştırır.

Manyeto Özellikler a-(Fe,Ni) gibi yumuşak manyetik fazların nanokristal boyutta çökelmesi, başlangıçta koersiviteyi düşürüp manyetik doygunluğu (M_s) artırarak manyetik özellikleri iyileştirebilir. Ancak ısıl işlem süresi çok uzatılıp borür fazları çok fazla büyürse, bu kristaller manyetik alan duvarlarının hareketini zorlaştırır (pinning center görevi görür) ve manyetik kayıpları artırabilir.

Tablo 1. Fe39Ni39Mo4Si6B12 metalik camın Vickers sertlik ölçüm değerleri.

Zaman	a	b	Ortalama
Tavlanmamış	793	759	776
500°C' 1 dakika tavlanmış	841	881	861
500°C' de 5 dakika tavlanmış	902	959	930,5
500°C' de 30 dakika tavlanmı	1048		

Şekil 4. Fe39Ni39Mo4Si6B12 metalik camın sertlik değişimi-ısıl işlem süresi.



Şekil 5. Fe39Ni39Mo4Si6B12 metalik camın koersitivite eğrisi (Şahingöz 1996).

SONUÇ VE TARTIŞMA

Bu çalışma, Fe39Ni39Mo4Si6B12 amorf (metalik cam) alaşımlarına uygulanan ısıl işlemlerin ilk aşamalarında, hızlı katılaştırma yönteminden kaynaklanan kalıntı gerilim (stress-strain) etkilerinin minimize edilebildiğini ortaya koymuştur. Isıl işlem sürecinin başlangıcında mikroyapıda kısmi nanokristallenmeler meydana gelirken; ilerleyen safhalarda önce tam kristallenme, ardından ise farklı kompozisyonlara sahip faz dönüşümleri gözlenmiştir. Yapıda meydana gelen bu yapısal ve morfolojik değişimler SEM, XRD ve Vickers sertlik analizleri ile karakterize edilmiştir. Söz konusu metalik cam

malzemenin en önemli avantajı, uygulanan ısıl işlem optimizasyonları sayesinde manyetik, elektriksel ve mekanik özelliklerinin geliştirilmesine olanak tanımasıdır. Vickers sertliğindeki artışa paralel olarak koersivite (coercivity) değerlerinin de yükseldiği belirlenmiş olup, koersivitedeki bu artış mikroyapıda kristallenme fazının başladığının ve ilerlediğinin bir göstergesi olarak değerlendirilmiştir.

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THE EFFECT OF ENTREPRENEURSHIP EDUCATION ON THE ENTREPRENEURIAL TENDENCIES OF TOURISM UNDERGRADUATE STUDENTS: THE CASE OF ÇANKIRI KARATEKİN UNIVERSITY

GİRİŞİMCİLİK EĞİTİMİNİN TURİZM LİSANS ÖĞRENCİLERİNİN GİRİŞİMCİLİK EĞİLİMLERİ ÜZERİNE ETKİSİ: ÇANKIRI KARATEKİN ÜNİVERSİTESİ ÖRNEĞİ

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ÖZET

Araştırmanın amacı, Çankırı Karatekin Üniversitesi turizm lisans öğrencilerinin girişimcilik eğilimlerinin belirlenmesidir. Araştırmanın evrenini, 2025-2026 Eğitim Öğretim yılı bahar döneminde Çankırı Karatekin Üniversitesi Turizm Fakültesinde eğitim alan turizm lisans öğrencileri oluşturmaktadır. Araştırmada nicel araştırma yaklaşımı benimsenmiş ve veri toplama aracı olarak anket tekniğinden yararlanılmıştır. İki bölüm olarak hazırlanan anket formunun ilk bölümünde, araştırma katılımcısı turizm lisans öğrencilerinin kişisel özelliklerini belirlemeye yönelik sorular yer almıştır. Anket formunun ikinci bölümünde ise araştırma katılımcısı turizm lisans öğrencilerin girişimcilik eğilimlerinin düzeylerini ölçmeyi amaçlayan beşli Likert tipi bir ölçek kullanılmıştır. On dört ifadeden oluşan ölçeğin güvenilirlik ve geçerlilik analizleri Girginer ve Uçkun (2004) tarafından yapılmıştır. Araştırmanın evrenini, Çankırı Karatekin Üniversitesi Turizm Fakültesinde öğrenim gören toplam 300 öğrenci oluşturmuştur. Çalışma kapsamında evrende yer alan öğrencilerin tamamına ulaşılması hedeflenmiş ve anket formları bütün öğrencilere dağıtılmaya çalışılmıştır. Veri toplama sürecinin sonunda eksik ya da hatalı biçimde doldurulan formlar ile yanıtlanmadan bırakılan anketler değerlendirme dışı tutulmuştur. Gerekli ayıklama işlemlerinin ardından kullanılabilir durumda olduğu belirlenen 188 anket formu analiz kapsamına alınmıştır. Böylece araştırma evreninin %63'üne ulaşılmıştır. Katılımcılar tarafından doldurulan anketlerden elde edilen verilerin çözümlenmesinde paket programlardan IBM SPSS 25 kullanılmıştır. Araştırma katılımcısı turizm lisans öğrencilerin kişisel özellikleri betimsel istatistikler aracılığıyla ortaya konmuştur. Anlamlı farklılıkların tespiti için bağımsız örneklem T testi ve tek yönlü Anova testlerinden yararlanılmıştır. Araştırma bulgularına göre; erkek öğrencilerin kadın öğrencilere göre, turizm işletmeciliği bölümü öğrencilerini turizm rehberliği bölümü öğrencilerine göre, üçüncü sınıf öğrencilerinin diğer sınıf öğrencilerine göre, 17-19 yaş aralığı grubundaki öğrencilerin diğer yaş gruplarına göre ve girişimcilik dersi alan öğrencilerin girişimcilik dersi almayan öğrencilere göre girişimcilik eğilimlerinin daha yüksek olduğu görülmüştür. Araştırmada bağımsız örneklem T testi ve tek yönlü Anova testlerinin sonucuna göre Çankırı Karatekin Üniversitesi Turizm Fakültesi öğrencilerinin girişimcilik eğilimlerinin girişimcilik dersi alma değişkenine göre istatistiksel olarak anlamlı farklılık bulunmuştur.

Anahtar Kelimeler: Girişimcilik Eğilimi, Girişimcilik Dersi, Turizm Lisans Öğrencileri, Çankırı Karatekin Üniversitesi.

ABSTRACT

The aim of this research is to determine the entrepreneurial tendencies of tourism undergraduate students at Çankırı Karatekin University. The research population consists of tourism undergraduate students studying at the Faculty of Tourism of Çankırı Karatekin University during the spring semester of the 2025-2026 academic year. A quantitative research approach was adopted in the study, and the survey technique was used as a data collection tool. The survey form, prepared in two parts, included questions in the first part aimed at determining the personal characteristics of the tourism undergraduate students participating in the research. In

the second part of the survey form, a five-point Likert scale was used to measure the level of entrepreneurial tendencies of the tourism undergraduate students participating in the research. Reliability and validity analyses of the scale, which consists of fourteen statements, were performed by Girginer and Uçkun (2004). The research population consisted of a total of 300 students studying at the Faculty of Tourism of Çankırı Karatekin University. Within the scope of the study, it was aimed to reach all students in the population, and survey forms were distributed to all students. At the end of the data collection process, forms that were incomplete or incorrectly filled out, as well as surveys left unanswered, were excluded from the evaluation. After the necessary screening processes, 188 survey forms determined to be usable were included in the analysis. Thus, 63% of the research population was reached. IBM SPSS 25 software package was used to analyze the data obtained from the surveys completed by the participants. The personal characteristics of the tourism undergraduate students participating in the research were revealed through descriptive statistics. Independent samples T-test and one-way ANOVA tests were used to determine significant differences. According to the research findings; male students showed higher entrepreneurial tendencies than female students, tourism management students than tourism guiding students, third-year students than other students, students in the 17-19 age group than other age groups, and students who took an entrepreneurship course than those who did not take an entrepreneurship course. According to the results of the independent samples T-test and one-way ANOVA tests in the research, a statistically significant difference was found in the entrepreneurial tendencies of Çankırı Karatekin University Faculty of Tourism students according to the variable of taking an entrepreneurship course.
Keywords: Entrepreneurial Tendency, Entrepreneurship Course, Tourism Undergraduate Students, Çankırı Karatekin University.

GİRİŞ

Ekonomik bir değer oluşturmak amacıyla sahip olduğu sermayeyi üretim veya pazarlama faaliyetlerine yönelten birey, girişimci olarak nitelendirilmektedir. Girişimcinin yeni bir işletme kurma, bu işletmenin faaliyetlerini planlama, yönetme ve sürdürülebilirliğini sağlama sürecinde gerçekleştirdiği tüm çalışmalar ise girişimcilik kavramı içerisinde ele alınmaktadır (Demirdöğen, 2013:8). Bu bağlamda girişimcilik, yalnızca bir iş fikrinin hayata geçirilmesini değil, aynı zamanda risk alma, fırsatları değerlendirme, kaynakları etkili biçimde kullanma ve işletmeyi devam ettirme süreçlerini de kapsamaktadır. Bireylerin gelecekte kendi işlerini kurmaya yönelik düşünce, istek ve kararlılık geliştirmeleri girişimcilik eğilimi olarak ifade edilmektedir. Söz konusu eğilim, yalnızca kişisel özelliklerin bir sonucu olmayıp bireyin içinde bulunduğu sosyal, ekonomik ve kültürel çevrenin etkisiyle de şekillenmektedir. Dolayısıyla girişimcilik eğilimi, bireysel nitelikler ile çevresel koşulların karşılıklı etkileşimi sonucunda ortaya çıkan çok boyutlu bir yapı olarak değerlendirilmektedir (Şen ve Aslan, 2017: 1849). Girişimci olma potansiyelinin geliştirilmesinde ve bireylerin bu yönde harekete geçirilmesinde eğitimin belirleyici bir role sahip olduğu düşünülmektedir. Eğitim yoluyla bireylerin girişimcilikle ilgili bilgi düzeyleri artırılmakta, iş kurma süreçlerine yönelik farkındalıkları geliştirilmekte ve karşılaşabilecekleri fırsatları daha doğru değerlendirmeleri sağlanmaktadır. Türkiye'de bu alandaki eğitim faaliyetleri, özellikle KOSGEB (Küçük ve Orta Ölçekli İşletmeleri Geliştirme ve Destekleme İdaresi Başkanlığı) tarafından yürütülen Uygulamalı Girişimcilik Eğitimleri ile üniversiteler başta olmak üzere çeşitli eğitim kurumlarında verilen girişimcilik dersleri aracılığıyla gerçekleştirilmektedir (Seçgin, 2020: 804). Girişimcilik eğitimlerinin temel amacı, hâlihazırda girişimci olan ya da gelecekte girişimci olma potansiyeli taşıyan bireylere gerekli bilgi, tutum ve becerileri kazandırmaktır. Bu eğitimler aracılığıyla girişimci düşünme biçiminin geliştirilmesi, girişimcilik bilincinin oluşturulması, yenilikçi bakış açısının güçlendirilmesi ve iş kurma sürecinde ihtiyaç duyulan uygulamalı yeterliliklerin

kazandırılması hedeflenmektedir. Böylece girişimcilik faaliyetlerinin desteklenmesi ve kurulan işletmelerin başarı şansının artırılması amaçlanmaktadır (Balaban ve Özdemir, 2008:137). Üniversite öğrencileri, sahip oldukları mesleki bilgi ve aldıkları eğitim sayesinde gelecekte kendi işini kurabilecek önemli bir potansiyel grubu oluşturmaktadır. Bu kapsamda turizm alanında lisans eğitimi gören öğrencilerin girişimcilik eğilimlerinin belirlenmesi, onların iş kurmaya yönelik düşüncelerinin ve geleceğe ilişkin kariyer yönelimlerinin anlaşılması bakımından önemlidir. Ayrıca öğrencilerin eğitim süreçlerinde aldıkları girişimcilik derslerinin, girişimci olma istekleri ve bu yöndeki davranışsal eğilimleri üzerindeki etkisinin incelenmesi, verilen eğitimin işlevselliğinin değerlendirilmesine katkı sağlayacaktır. Çankırı ili ve Çankırı Karatekin Üniversitesi özelinde turizm lisans öğrencilerinin girişimcilik eğilimlerini ele alan benzer bir çalışmaya daha önce rastlanmamış olması, araştırmanın özgün yönünü oluşturmaktadır. Çalışmadan elde edilecek sonuçların hem bölgesel düzeyde mevcut durumun ortaya konmasına hem de girişimcilik ve turizm eğitimi alanındaki araştırmalara yeni veriler sunarak ilgili literatürün geliştirilmesine katkı sağlaması beklenmektedir. Bu doğrultuda araştırmanın amacı, Çankırı Karatekin Üniversitesi bünyesinde turizm alanında lisans eğitimi alan öğrencilerin girişimcilik eğilimlerini belirlemek ve bu eğilimlerin öğrencilerin demografik özelliklerine göre istatistiksel açıdan anlamlı bir farklılık gösterip göstermediğini incelemektir.

AMAÇ

Bu araştırmanın amacı, Çankırı Karatekin Üniversitesi turizm lisans öğrencilerinin girişimcilik eğilimlerinin demografik özelliklerine göre istatistiksel olarak anlamlı farklılıklar gösterip göstermediğinin belirlenmesidir. Bu amaç doğrultusunda aşağıdaki hipotezler geliştirilmiştir.

Hipotez 1. Çankırı Karatekin Üniversitesi turizm lisans öğrencilerinin girişimcilik eğilimleri demografik özelliklerine göre istatistiksel olarak anlamlı bir farklılık göstermektedir.

Hipotez 1a. Çankırı Karatekin Üniversitesi turizm lisans öğrencilerinin girişimcilik eğilimleri cinsiyetlerine göre istatistiksel olarak anlamlı bir farklılık göstermektedir.

Hipotez 1b. Çankırı Karatekin Üniversitesi turizm lisans öğrencilerinin girişimcilik eğilimleri bölümlerine göre istatistiksel olarak anlamlı bir farklılık göstermektedir.

Hipotez 1c. Çankırı Karatekin Üniversitesi turizm lisans öğrencilerinin girişimcilik eğilimleri yaşlarına göre istatistiksel olarak anlamlı bir farklılık göstermektedir.

Hipotez 1d. Çankırı Karatekin Üniversitesi turizm lisans öğrencilerinin girişimcilik eğilimleri sınıflarına göre istatistiksel olarak anlamlı bir farklılık göstermektedir.

Hipotez 1e. Çankırı Karatekin Üniversitesi turizm lisans öğrencilerinin girişimcilik eğilimleri girişimcilik dersi alıp almadıklarına göre istatistiksel olarak anlamlı bir farklılık göstermektedir.

YÖNTEM

Araştırmanın bu bölümünde araştırmanın evren ve örneklemi, veri toplama araçları ile verilerin analizi alt başlıkları verilmiştir.

Evren ve Örneklem

Yapılan araştırmanın evrenini, 2025-2026 Eğitim Öğretim yılı bahar döneminde Çankırı Karatekin Üniversitesi Turizm Fakültesinde eğitim alan turizm lisans öğrencileri oluşturmaktadır. Araştırma, 2026 yılının bahar döneminde yürütülmüştür. Araştırma kapsamında tam sayım esasına göre 300 turizm lisans öğrencisine anket formları ulaştırılmaya çalışılmış; eksik, hatalı ya da boş bırakılan formlar elendikten sonra, analizlerde kullanılmak üzere 188 geçerli anket formu elde edilmiştir. Araştırma evreninin %63'üne ulaşılmıştır.

Tablo 1. Turizm Lisans Öğrencilerine İlişkin Demografik Özellikler

Demografik Özellikler	Kategori	n	%
Cinsiyet	Erkek	67	35,6
	Kadın	121	64,4
Bölüm	Turizm İşletmeciliği	59	31,4
	Turizm Rehberliği	129	68,6
Girişimcilik Ders Alma Durumu	Evet	34	18,1
	Hayır	154	81,9
Yaş	17-19 Yaş Arası	71	37,8
	20-21 Yaş Arası	64	34,0
	22 Yaş ve Üzeri	53	28,2
Sınıf	Birinci Sınıf	70	37,2
	İkinci Sınıf	60	31,9
	Üçüncü Sınıf	34	18,1
	Dördüncü Sınıf	24	12,8

Turizm lisans öğrencilerine ilişkin demografik özelliklerin verildiği Tablo 1'e göre erkek öğrenci sayısının 67, kadın öğrenci sayısının ise 121 olduğu görülmektedir.. Turizm işletmeciliği bölümünden araştırmaya katılan öğrenci sayısı 59 ve turizm rehberliği bölümünden ise araştırmaya katılan öğrenci sayısı 129'dur. Öğrencilerin girişimcilik dersi alma durumlarına göre dağılımlarına bakıldığında 34 öğrencinin girişimcilik dersi aldığı görülmektedir. Girişimcilik dersi almayan öğrenci sayısı ise 154'tür. Öğrencilerin yaş gruplarına göre dağılımlarına bakıldığında en büyük grup 71 kişi ile 17-19 yaş aralığında olan gruptur. Bu grubu 64 kişi ile 20-21 yaş aralığı grubun ve 53 kişi ile 22 yaş ve üzeri grubun izlediği görülmektedir. Öğrencilerin okudukları sınıflara göre dağılımlarına bakıldığında en büyük grubun 70 kişi ile birinci sınıf öğrencileri olduğu görülmektedir. Bu grubu 60 kişi ile ikinci sınıf öğrencileri, 34 kişi ile üçüncü sınıf öğrencileri ve 24 kişi ile dördüncü sınıf öğrencilerinin izlediği görülmektedir.

Veri Toplama Araçları

Çalışmanın verileri, nicel araştırma yaklaşımına uygun olarak hazırlanan bir anket formu aracılığıyla toplanmıştır. Formun başlangıç kısmında öğrencilerin kişisel özelliklerini belirlemeyi amaçlayan sorular yer alırken, devamındaki bölüm katılımcıların girişimcilik eğilimlerini ölçmeye yönelik olarak oluşturulmuştur. Bu amaçla, güvenilirlik ve geçerlilik incelemeleri Girginer ve Uçkun (2004) tarafından gerçekleştirilen ve söz konusu araştırmacıların çalışmalarında kullandıkları ölçme aracından yararlanılmıştır. Araştırmada kullanılan ölçek, öğrencilerin girişimciliğe ilişkin tutum ve yönelimlerini ortaya koyan toplam on dört maddeden meydana gelmektedir. Katılımcıların her bir maddeye ilişkin görüşleri beş dereceli Likert sistemi üzerinden değerlendirilmiştir. Puanlamada en yüksek katılım düzeyi 5=Kesinlikle Katılıyorum, bunu izleyen düzey 4=Katılıyorum olarak belirlenmiştir. Kararsız görüşler 3=Ne Katılıyorum Ne Katılmıyorum, olumsuz görüşler 2=Katılmıyorum ve en düşük katılım düzeyi ise 1=Kesinlikle Katılmıyorum biçiminde puanlandırılmıştır. Ölçek sonuçlarının yorumlanabilmesi için hesaplanan aritmetik ortalamalar beş ayrı değerlendirme aralığına ayrılmıştır. Buna göre 4.21-5.00 arasında kalan ortalamalar "Kesinlikle Katılıyorum", 3.41-

4.20 arasındaki ortalamalar "Katılıyorum" ve 2.61-3.40 arasındaki değerler "Ne Katılıyorum Ne Katılmıyorum" şeklinde değerlendirilmiştir. Ortalama değerin 1.81-2.60 aralığında bulunması "Katılmıyorum", 1.00-1.80 aralığında yer alması ise "Kesinlikle Katılmıyorum" düzeyini ifade etmektedir.

Verilerin Analizi

Veri toplama süreci tamamlandıktan sonra kullanılabilir nitelikteki anketler sayısal ortama aktarılmış ve istatistiksel çözümlemeler IBM SPSS 25 yazılımı üzerinden gerçekleştirilmiştir. Öncelikle çalışma grubunun yapısını tanıtmak amacıyla katılımcılara ait demografik değişkenler betimleyici istatistikler kullanılarak özetlenmiştir. Ardından demografik grupların araştırma değişkenlerine ilişkin puanlarının birbirinden farklılaşıp farklılaşmadığı incelenmiştir. Bu incelemede iki kategoriden oluşan değişkenler için bağımsız gruplar t testi, üç veya daha fazla kategori içeren değişkenler için ise tek yönlü varyans analizi uygulanmıştır.

BULGULAR

Araştırma katılımcılarının doldurduğu anket form verilerinden elde edilen bulgular bu bölümde tablolar ve tablo yorumları olarak sunulmuştur.

Tablo 2. Araştırmada Kullanılan Ölçekler

Ölçek / Boyut	Madde Sayısı	Ortalama	Standart Sapma	Cronbach Alpha	KMO
Girişimcilik Eğilimi Ölçeği	14	3,3951	,50380	,734	,731

Ölçme aracının güvenirlik düzeyini belirlemek amacıyla hesaplanan Cronbach Alpha katsayısı ,734 olarak bulunmuştur. Elde edilen bu değer, $0,60 \leq \alpha < 0,80$ aralığında yer aldığından girişimcilik eğilimi ölçeğinin yeterli düzeyde iç tutarlılığa sahip olduğu ve güvenilir bir ölçme aracı olarak değerlendirilebileceği sonucuna ulaşılmıştır (Can, 2013; Ural & Kılıç, 2013). Veri setinin faktör analizine uygunluğunu incelemek için hesaplanan KMO (Kaiser-Meyer-Olkin) örneklem yeterlilik katsayısı ise ,731'dir. Söz konusu değerin $0,70 \leq KMO < 0,90$ sınırları içerisinde bulunması, araştırmadaki örneklem büyüklüğünün faktör analizi açısından iyi düzeyde olduğunu göstermektedir (Kalaycı, 2014; Can, 2013; Çokluk vd., 2012). Tablo 2'de sunulan betimsel sonuçlara göre katılımcıların girişimcilik eğilimi ölçeğinden elde ettikleri genel puan ortalaması 3,3951 olarak hesaplanmıştır.

Tablo 3. Girişimcilik Eğilimi Ölçeği Tanımlama Tablosu

Boyut	Ölçek Maddeleri	Ortalama	Standart Sapma
Girişimcilik Eğilimi Ölçeği	Sosyal yaşamı iş yaşamını eğlenceyi dengeli bir şekilde yaşayan bir kişiliğe sahip olmak isterim.	4,3989	,83723
	Kariyerimin gelecek 5 yılında yüksek maaşlı bir iş fırsatı karşıma çıksa kabul ederim.	4,2500	,94572
	Mevcut gerçeklere birebir bağlı kalarak hareket etmeyi tercih ederim.	3,7128	,97698
	Bölümümüz mezunları mutlaka girişimci olmaya odaklanmalıdır.	3,6649	1,08438
	Bölümümüz mezunları kendiişlerini kurmak için fırsat yaratma yeteneğine sahiptirler.	3,5266	1,04156
	Bölümümüz mezunları mutlaka kendi islerini kurmayı hedeflemelidir.	3,4947	1,03674
	Kariyerim için gerekli olsa dahi önceliklerimden vazgeçmem.	3,4574	1,05633

	İnandığım bir konuda negatif bir değerlendirmeye maruz kalma pahasına karar veririm.	3,4468	1,04054
	Bölümümüz mezunları özel sektörde çalışmayı planlamalıdır.	3,2926	,91602
	Gerçekleri zorlayarak sezgiye ve hayallere dayalı hareket etmeyi tercih ederim.	3,2447	1,07660
	İnandığım bir konu dahi olsa kural dışı davranmayı göze alamam.	3,2128	1,15506
	Bir isin fırsatlar sunması emniyetli ve garantili olmasından daha önemlidir.	3,1223	1,30443
	Bölümümüz mezunları asla kamu sektöründe çalışmayı planlamamalıdır.	2,4415	1,06061
	Çok çalışan sürekli hedef büyüten bir kişiliğe sahip olmak istemem.	2,2660	1,27229

Girişimcilik eğilimi ölçeği maddelerinin puan ortalamalarının verildiği Tablo 3'e göre "Sosyal yaşamı iş yaşamını eğlenceyi dengeli bir şekilde yaşayan bir kişiliğe sahip olmak isterim." ifadesinin 4,3989 ile en yüksek puan ortalamasına sahip olduğu görülmektedir. Tablo 3'te yer alan ilk iki maddenin puan ortalamasının 4,21 – 5,00 puan aralığında ve "Kesinlikle Katılıyorum" düzeyinde çok yüksek olduğu görülmektedir. Üç ve sekiz arasında yer alan altı maddenin ise puan ortalamasının 3,41 – 4,20 puan aralığında ve "Katılıyorum" düzeyinde yüksek olduğu görülmektedir. Sonraki üç maddenin puan ortalamasının 2,61 – 3,40 puan aralığında ve "Ne Katılıyorum Ne Katılmıyorum" düzeyinde kararsız olduğu görülmektedir. Son iki maddenin ise puan ortalamasının 1,81 – 2,60 puan aralığında ve "Katılmıyorum" düzeyinde olumsuz olduğu görülmektedir.

Tablo 4. Turizm Lisans Öğrencilerinin Demografik Özellikleri İle Girişimcilik Eğilimi Arasındaki Farklılığa İlişkin T-Testi ve Anova Testi Sonuçları

Ölçek	Değişken	Grup	n	Ortalama	Standart Sapma	F/t	p	Tukey HSD
Girişimcilik Eğilimi Ölçeği	Cinsiyet	Erkek	67	3,4797	,50703	1,713	,089	-
		Kadın	121	3,3483	,49792			
	Bölüm	Turizm İşletmeciliği	59	3,4395	,55706	,770	,443	-
		Turizm Rehberliği	129	3,3749	,47841			
	Girişimcilik Dersi Alma Durumu	Evet	34	3,5756	,45036	2,521	,015	-
		Hayır	154	3,3553	,50758			
	Yaş	17-19 Yaş Arasıa	71	3,4074	,57020	,098	,907	-
		20-21 Yaş Arasıb	64	3,4029	,50562			
		22 Yaş ve Üzeric	53	3,3693	,40545			

	Sınıf	Birinci Sınıfa	70	3,3306	,56769	,733	,533	-
		İkinci Sınıfb	60	3,4250	,42724			
		Üçüncü Sınıfc	34	3,4748	,49795			
		Dördüncü Sınıfd	24	3,3958	,49844			

Turizm lisans öğrencilerinin demografik özellikleri ile girişimcilik eğilimi arasındaki farklılığa ilişkin T-testi ve Anova testi sonuçlarının verildiği Tablo 4'te istatistiksel olarak anlamlı farklılık girişimcilik dersi alma durumu değişkeninde bulunmuştur. Anlamlı farklılığın bulunduğu girişimcilik dersi alma durumu değişkeninde girişimcilik dersi alan öğrencilerin girişimcilik eğilimlerinin girişimcilik dersi almayan öğrencilere göre daha yüksek olduğu görülmektedir. Cinsiyet, bölüm, yaş ve sınıf değişkenlerine göre ise istatistiksel olarak anlamlı bir farklılık bulunamamıştır. Tablo 4'ten elde edilen bulgulara göre cinsiyet, bölüm, yaş ve sınıf değişkenlerine göre istatistiksel olarak anlamlı bir farklılık bulunamamış ve hipotez 1a, hipotez 1b, hipotez 1c ve hipotez 1d reddedilmiştir. Girişimcilik dersi alma durumu değişkenine göre ise istatistiksel olarak anlamlı bir farklılık bulunmuş ve hipotez 1e kabul edilmiştir.

TARTIŞMA VE SONUÇ

Araştırmada, erkek öğrencilerin kadın öğrencilere göre, turizm işletmeciliği bölümü öğrencilerini turizm rehberliği bölümü öğrencilerine göre, üçüncü sınıf öğrencilerinin diğer sınıf öğrencilerine göre, 17-19 yaş aralığı grubundaki öğrencilerin diğer yaş gruplarına göre ve girişimcilik dersi alan öğrencilerin girişimcilik dersi almayan öğrencilere göre girişimcilik eğilimlerinin daha yüksek olduğu sonucuna ulaşılmıştır

Araştırmada bağımsız örneklem T testi ve tek yönlü Anova testlerinin sonucuna göre Çankırı Karatekin Üniversitesi Turizm Fakültesi öğrencilerinin girişimcilik eğilimlerinin girişimcilik dersi alma değişkenine göre istatistiksel olarak anlamlı farklılık bulunmuştur. Araştırmadan elde eilen sonuçlar literatürdeki benzer araştırmalardan, Girginer ve Uçkun (2004), Balaban ve Özdemir (2008), Yüksel, Cevher ve Yüksel (2015), Özcan, Çeltek, Sönmez ve Kırım (2018), Seçkin (2020) elde edilen sonuçları destekler niteliktedir.

Bu araştırmadan elde edilen bulgular ve ulaşılan sonuçlar doğrultusunda gelecekte gerçekleştirilecek çalışmalar için çeşitli öneriler geliştirilmiştir.

Araştırmanın evreni, Çankırı Karatekin Üniversitesi'nde turizm alanında lisans eğitimi gören öğrencilerle sınırlandırılmıştır. Bu nedenle, ileride yapılacak araştırmalarda farklı üniversitelerin ve bu üniversitelerde öğrenim gören daha geniş bir öğrenci grubunun örnekleme dâhil edilmesi, elde edilecek sonuçların genellenebilirliğini artıracaktır.

Çalışma yalnızca turizm lisans öğrencileri üzerinde yürütülmüştür. Gelecek araştırmalarda turizm bölümü dışındaki farklı lisans programlarında öğrenim gören öğrencilerin de araştırma kapsamına alınması önerilmektedir. Böylece bölümler arasında karşılaştırmalar yapılarak incelenen değişkenlerdeki farklılıklar ortaya konabilir.

Bu araştırmada nicel araştırma yöntemi tercih edilmiştir. Gelecek araştırmalarda nicel ve nitel yöntemlerin birlikte kullanıldığı karma yöntem araştırmalarıyla bulguların daha kapsamlı biçimde değerlendirilmesi sağlanabilir.

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A RESEARCH ON HEALTH TOURISM AWARENESS OF TOURISM UNDERGRADUATE STUDENTS: THE CASE OF ÇANKIRI KARATEKİN UNIVERSITY

TURİZM LİSANS ÖĞRENCİLERİNİN SAĞLIK TURİZMİ FARKINDALIKLARI ÜZERİNE BİR ARAŞTIRMA: ÇANKIRI KARATEKİN ÜNİVERSİTESİ ÖRNEĞİ

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Çankırı Karatekin Üniversitesi, Turizm Fakültesi, Turizm İşletmeciliği Bölümü, Ilgaz, Çankırı.

ÖZET

Araştırmanın amacı, Çankırı Karatekin Üniversitesi turizm lisans öğrencilerinin sağlık turizmi farkındalıklarının belirlenmesidir. Araştırmanın evrenini, 2025-2026 Eğitim Öğretim yılı bahar döneminde Çankırı Karatekin Üniversitesi Turizm Fakültesinde eğitim alan turizm lisans öğrencileri oluşturmaktadır. Araştırmada nicel araştırma yaklaşımı benimsenmiş ve veri toplama aracı olarak anket tekniğinden yararlanılmıştır. İki bölüm olarak hazırlanan anket formunun ilk bölümünde, araştırma katılımcısı turizm lisans öğrencilerinin kişisel özelliklerini belirlemeye yönelik sorular yer almıştır. Anket formunun ikinci bölümünde ise araştırma katılımcısı turizm lisans öğrencilerin sağlık turizmine yönelik farkındalık düzeylerini ölçmeyi amaçlayan beşli Likert tipi bir ölçek kullanılmıştır. Çankırı İlinin Sağlık Turizmi Potansiyeli, Altyapı ve Destek Hizmetleri, Hizmet Yetkinliği ve Bilinç ve Farkındalık olmak üzere dört boyuttan ve toplam yirmi beş ifadeden oluşan araştırma ölçeğinin güvenilirlik ve geçerlilik analizleri Alkaç ve Büyükşalvarcı (2024) ve Acar ve Turan (2016) tarafından gerçekleştirilmiştir. Araştırmanın evrenini, Çankırı Karatekin Üniversitesi Turizm Fakültesinde öğrenim gören toplam 300 öğrenci oluşturmuştur. Çalışma kapsamında evrende yer alan öğrencilerin tamamına ulaşılması hedeflenmiş ve anket formları bütün öğrencilere dağıtılmaya çalışılmıştır. Veri toplama sürecinin sonunda eksik ya da hatalı biçimde doldurulan formlar ile yanıtlanmadan bırakılan anketler değerlendirme dışı tutulmuştur. Gerekli ayıklama işlemlerinin ardından kullanılabilir durumda olduğu belirlenen 204 anket formu analiz kapsamına alınmıştır. Böylece araştırma evreninin %68'ine ulaşılmıştır. Katılımcılar tarafından doldurulan anketlerden elde edilen verilerin çözümlenmesinde paket programlardan IBM SPSS 25 kullanılmıştır. Araştırma katılımcısı turizm lisans öğrencilerin kişisel özellikleri betimsel istatistikler aracılığıyla ortaya konmuştur. Katılımcı grupları arasında istatistiksel açıdan anlamlı bir farklılık bulunup bulunmadığını belirlemek amacıyla ise bağımsız örneklem T testi ile tek yönlü ANOVA analizleri uygulanmıştır. Araştırma bulgularına göre; bilinç ve farkındalık boyutunda erkek öğrencilerin kadın öğrencilere göre, turizm rehberliği bölümü öğrencilerini turizm işletmeciliği bölümü öğrencilerine göre, dördüncü sınıf öğrencilerinin diğer alt sınıf öğrencilerine göre ve 20-21 yaş aralığı grubundaki öğrencilerin diğer yaş gruplarına göre puan ortalamalarının daha yüksek olduğu görülmüştür. Hizmet yetkinliği boyutunda erkek öğrencilerin kadın öğrencilere göre, turizm işletmeciliği bölümü öğrencilerini turizm rehberliği bölümü öğrencilerine göre, dördüncü sınıf öğrencilerinin diğer alt sınıf öğrencilerine göre ve 22 yaş ve üzeri grubundaki öğrencilerin diğer yaş gruplarına göre puan ortalamalarının daha yüksek olduğu görülmüştür. Altyapı ve destek hizmetleri boyutunda kadın öğrencilerin erkek öğrencilere göre, turizm işletmeciliği bölümü öğrencilerini turizm rehberliği bölümü öğrencilerine göre, dördüncü sınıf öğrencilerinin diğer alt sınıf öğrencilerine göre ve 22 yaş ve üzeri grubundaki öğrencilerin diğer yaş gruplarına göre puan ortalamalarının daha yüksek olduğu görülmüştür. Çankırı ilinin sağlık turizmi potansiyeli boyutunda erkek öğrencilerin kadın öğrencilere göre, turizm işletmeciliği bölümü öğrencilerini turizm rehberliği bölümü öğrencilerine göre, ikinci sınıf öğrencilerinin diğer farklı sınıf öğrencilerine göre ve 17-19 yaş aralığı grubundaki öğrencilerin diğer yaş gruplarına göre puan ortalamalarının dah yüksek olduğu görülmüştür. Araştırmada bağımsız örneklem T testi ve tek yönlü Anova

testlerinin sonucuna göre Çankırı Karatekin Üniversitesi Turizm Fakültesi öğrencilerinin hizmet yetkinliği boyutunda cinsiyet, bölüm ve sınıf değişkenlerinde, altyapı ve destek hizmetleri boyutunda sınıf değişkeninde ve Çankırı ilinin sağlık turizmi potansiyeli boyutunda cinsiyet, bölüm ve sınıf değişkenlerinde istatistiksel olarak anlamlı farklılıklar bulunmuştur.
Anahtar Kelimeler: Sağlık Turizmi, Farkındalık, Turizm Lisans Öğrencileri, Çankırı Karatekin Üniversitesi.

ABSTRACT

The aim of this research is to determine the awareness of tourism undergraduate students at Çankırı Karatekin University regarding health tourism. The research population consists of tourism undergraduate students studying at the Faculty of Tourism of Çankırı Karatekin University during the spring semester of the 2025-2026 academic year. A quantitative research approach was adopted in the study, and the survey technique was used as a data collection tool. The survey form, prepared in two parts, included questions in the first part aimed at determining the personal characteristics of the tourism undergraduate students participating in the research. In the second part of the survey form, a five-point Likert-type scale was used to measure the awareness level of the tourism undergraduate students participating in the research regarding health tourism. The reliability and validity analyses of the research scale, which consists of four dimensions and a total of twenty-five statements: Çankırı Province's Health Tourism Potential, Infrastructure and Support Services, Service Competence, and Awareness, were carried out by Alkaç and Büyükşalvarcı (2024) and Acar and Turan (2016). The study population consisted of a total of 300 students studying at the Faculty of Tourism of Çankırı Karatekin University. The aim of the study was to reach all students in the population, and survey forms were distributed to all students. At the end of the data collection process, incomplete or incorrectly filled forms, as well as unanswered surveys, were excluded from the evaluation. After the necessary selection process, 204 survey forms deemed usable were included in the analysis. Thus, 68% of the research population was reached. IBM SPSS 25 software package was used to analyze the data obtained from the surveys completed by the participants. The personal characteristics of the tourism undergraduate students participating in the research were revealed through descriptive statistics. To determine whether there were statistically significant differences between the participant groups, independent samples T-test and one-way ANOVA analyses were applied. According to the research findings; In the dimension of awareness and consciousness, male students scored higher than female students, tourism guiding students scored higher than tourism management students, fourth-year students scored higher than other lower-year students, and students in the 20-21 age group scored higher than other age groups. In the dimension of service competence, male students scored higher than female students, tourism management students scored higher than tourism guiding students, fourth-year students scored higher than other lower-year students, and students in the 22 years and older age group scored higher than other age groups. In the dimension of infrastructure and support services, female students scored higher than male students, tourism management students scored higher than tourism guiding students, fourth-year students scored higher than other lower-year students, and students in the 22 years and older age group scored higher than other age groups. In the study, regarding the health tourism potential of Çankırı province, it was observed that male students scored higher than female students, tourism management students scored higher than tourism guiding students, second-year students scored higher than students from other classes, and students in the 17-19 age group scored higher than other age groups. According to the results of independent samples T-test and one-way ANOVA tests, statistically significant differences were found in the service competency dimension of Çankırı Karatekin University Faculty of Tourism students based on gender, department, and class variables; in the

infrastructure and support services dimension based on class variable; and in the health tourism potential dimension of Çankırı province based on gender, department, and class variables.
Keywords: Health Tourism, Awareness, Tourism Undergraduate Students, Çankırı Karatekin University.

GİRİŞ

Sağlık turizminin, medikal turizm, ileri yaş ve engelli turizmi ve termal sağlık turizmi ve spa wellness olarak sınıflandırıldığı görülmektedir. Kişilerin tıbbi olarak hizmet almak amacıyla yapmış oldukları seyahatlere medikal turizm adı verilmektedir. Medikal turizmin; diş tedavileri, göz tedavileri, plastik cerrahi ameliyatları, kalp cerrahisi, kısırlık tedavisi, obezite cerrahisi, kanser tedavisi, saç ekimi gibi bir çok seçeneği içerisinde barındıran geniş kapsamlı bir alan olduğu görülmektedir (Aba, Gümüş ve Çakır, 2019). İlerlemiş yaşta bulunan veya çalışamayacak durumda olan kişilerin turizm hizmetlerinden faydalanmak amacıyla farklı bölgelere yaptıkları seyahatlere ileri yaş ve engelli turizmi olarak değerlendirilmektedir. Engelli bireylerin turizm faaliyetleri engelli turizmi olarak isimlendirilmektedir ve ileri yaş turizminde turizme katılan kişiler içerisinde engelli kişi sayısı oldukça fazladır. Termal turizm, yer altından yer yüzüne çıkan zengin mineraller içeren sıcak su kaynaklarından şifa bulmak amacıyla faydalanılan bir sağlık turizmi çeşididir. Sağlık turizminin temel amaçlarından biri, hastaların ve hasta yakınlarının sağlık hizmeti alma süreçlerinde kendilerini güvende ve rahat hissetmelerini sağlamaktır. Bu doğrultuda bireylere farklı hizmet seçenekleri sunulması, hizmetlerin hasta odaklı biçimde yürütülmesi ve memnuniyet düzeyinin mümkün olan en yüksek seviyeye çıkarılması önem taşımaktadır. Küresel ölçekte hızla gelişen sağlık turizmi, ülkeler arasındaki rekabetin giderek yoğunlaştığı stratejik sektörlerden biri hâline gelmiştir. Türkiye; elverişli coğrafi konumu, gelişmiş sağlık hizmetleri altyapısı, maliyet bakımından avantajlı tedavi olanakları, kısa bekleme süreleri ve sahip olduğu zengin tarihî ve kültürel değerler sayesinde sağlık ve medikal turizm pazarındaki payını her geçen gün artırmaktadır (Tamer, 2026: 456-457; Büyük ve Akkuş, 2024: 1113). Uluslararası Sağlık Hizmetleri (USHAŞ) verilerine göre 2025 yılında sağlık hizmetlerinden yararlanmak amacıyla Türkiye'yi ziyaret eden kişi sayısı 1.398.580 olarak gerçekleşmiş, sağlık turizminden elde edilen gelir ise 3.022.452 bin ABD Doları'na ulaşmıştır. Sağlığını korumak veya geliştirmek isteyen bireyler ile mevcut bir hastalığının tedavisi için hizmet talep eden kişileri kabul eden sağlık kuruluşlarının, yeterli ve güncel teknolojik donanıma sahip olması gerekmektedir. Bunun yanı sıra sağlık hizmetlerinin etkili, güvenli ve kaliteli biçimde sunulabilmesi için alanında yetkin ve nitelikli iş gücünün istihdam edilmesi de büyük önem taşımaktadır.Bu açıdan gelecekte sağlık turizmi işletmeleri çalışanları olabilecek turizm lisans öğrencilerinin sağlık turizmi farkındalıklarının belirlenmesi ile mevcut durumun ortaya konması ve Çankırı ili ve Çankırı Karatekin Üniversitesi özelinde benzer bir araştırmanın daha önceden yapılmamış olması ve araştırmanın araştırma literatürüne sağlayacağı katkı araştırmanın önemini ortaya koymaktadır. Araştırmada Çankırı Karatekin Üniversitesi turizm lisans öğrencilerinin sağlık turizmi farkındalıklarının demografik özelliklerine göre istatistiksel olarak anlamlı farklılıklar gösterip göstermediğinin belirlenmesi amaçlanmıştır.

AMAÇ

Bu araştırmanın amacı, Çankırı Karatekin Üniversitesi turizm lisans öğrencilerinin sağlık turizmi farkındalıklarının demografik özelliklerine göre istatistiksel olarak anlamlı farklılıklar gösterip göstermediğinin belirlenmesidir. Bu amaç doğrultusunda aşağıdaki hipotezler geliştirilmiştir.

Hipotez 1. Çankırı Karatekin Üniversitesi turizm lisans öğrencilerinin sağlık turizmi farkındalıkları demografik özelliklerine göre (cinsiyet, yaş, bölüm ve sınıf) istatistiksel olarak anlamlı bir farklılık göstermektedir.

Hipotez 1a. Çankırı Karatekin Üniversitesi turizm lisans öğrencilerinin bilinç ve farkındalıklara yönelik farkındalıkları demografik özelliklerine göre (cinsiyet, yaş, bölüm ve sınıf) istatistiksel olarak anlamlı bir farklılık göstermektedir.
Hipotez 1b. Çankırı Karatekin Üniversitesi turizm lisans öğrencilerinin hizmet yetkinliğine yönelik farkındalıkları demografik özelliklerine göre (cinsiyet, yaş, bölüm ve sınıf) istatistiksel olarak anlamlı bir farklılık göstermektedir.
Hipotez 1c. Çankırı Karatekin Üniversitesi turizm lisans öğrencilerinin altyapı ve destek hizmetlerine yönelik farkındalıkları demografik özelliklerine göre (cinsiyet, yaş, bölüm ve sınıf) istatistiksel olarak anlamlı bir farklılık göstermektedir.
Hipotez 1d. Çankırı Karatekin Üniversitesi turizm lisans öğrencilerinin Çankırı ilinin sağlık turizmi potansiyeline yönelik farkındalıkları demografik özelliklerine göre (cinsiyet, yaş, bölüm ve sınıf) istatistiksel olarak anlamlı bir farklılık göstermektedir.

YÖNTEM

Araştırmanın bu bölümünde evren ve örneklem, veri toplama araçları, verilerin analizi alt başlıklarına yer verilmiştir.

Evren ve Örneklem

Yapılan araştırmanın evrenini, 2025-2026 Eğitim Öğretim yılı bahar döneminde Çankırı Karatekin Üniversitesi Turizm Fakültesinde eğitim alan turizm lisans öğrencileri oluşturmaktadır. Araştırma, 2026 yılının bahar döneminde yürütülmüştür. Araştırmada tam sayım yaklaşımı benimsenmiş ve çalışma evreninde yer alan 300 turizm lisans öğrencisinin tamamına anket formu ulaştırılması hedeflenmiştir. Veri toplama sürecinin ardından eksik, hatalı veya yanıtlanmadan bırakılmış formlar değerlendirme dışı tutulmuş; gerekli kontroller sonucunda analizlerde kullanılmaya uygun 204 geçerli anket formu elde edilmiştir. Bu doğrultuda araştırma evreninin %68'ine ulaşılmıştır.

Tablo 1. Turizm Lisans Öğrencilerine İlişkin Demografik Özellikler

Demografik Özellikler	Kategori	n	%
Cinsiyet	Erkek	56	27,5
	Kadın	148	72,5
Bölüm	Turizm İşletmeciliği	64	31,4
	Turizm Rehberliği	140	68,6
Yaş	17-19 Yaş Arası	72	35,3
	20-21 Yaş Arası	67	32,8
	22 Yaş ve Üzeri	65	31,9
Sınıf	Birinci Sınıf	69	33,8
	İkinci Sınıf	67	32,8
	Üçüncü Sınıf	44	21,6
	Dördüncü Sınıf	24	11,8

Turizm lisans öğrencilerine ilişkin demografik özelliklerin verildiği Tablo 1'e göre 56 öğrencinin erkek, 148 öğrencinin ise kadın olduğu görülmektedir. Turizm işletmeciliği bölümünden araştırmaya katılan öğrenci sayısı 64 ve turizm rehberliği bölümünden ise

araştırmaya katılan öğrenci sayısı 140'tır. Öğrencilerin yaş gruplarına göre dağılımlarına bakıldığında en büyük grup 72 kişi ile 17-19 yaş aralığında olan gruptur. Bu grubun ardından 67 kişi ile 20-21 yaş aralığı grubunun ve 65 kişi ile 22 yaş ve üzeri grubunun geldiği görülmektedir. Araştırma katılımcısı turizm lisans öğrencilerinin okudukları sınıflara göre dağılımlarına bakıldığında en büyük grubun 69 kişi ile birinci sınıf öğrencileri olduğu görülmektedir. Bu grubu 67 kişi ile ikinci sınıf öğrencileri, 44 kişi ile üçüncü sınıf öğrencileri ve 24 kişi ile dördüncü sınıf öğrencilerinin izlediği görülmektedir.

Veri Toplama Araçları

Araştırmada nicel araştırma yaklaşımı benimsenmiş ve veri toplama aracı olarak anket tekniğinden yararlanılmıştır. İki bölüm olarak hazırlanan anket formunun ilk bölümünde, araştırma katılımcısı turizm lisans öğrencilerinin kişisel özelliklerini belirlemeye yönelik sorular yer almaktadır. Anket formunun ikinci bölümünde ise araştırma katılımcısı turizm lisans öğrencilerin sağlık turizmine yönelik farkındalık düzeylerini ölçmeyi amaçlayan beşli Likert tipi bir ölçek kullanılmıştır. Ölçek; Bilinç ve Farkındalık, Hizmet Yetkinliği, Altyapı ve Destek Hizmetleri ile Çankırı İlinin Sağlık Turizmi Potansiyeli olmak üzere dört boyuttan ve toplam yirmi beş ifadeden oluşmaktadır. Araştırmada, güvenilirlik ve geçerlilik analizleri Alkaç ve Büyükşalvarcı (2024) ve Acar ve Turan (2016) tarafından gerçekleştirilen ve söz konusu araştırmalarda kullanılan ölçeklerden yararlanılmıştır. Ölçekteki ifadeler, beşli Likert tipi derecelendirme kullanılarak değerlendirilmiştir. Buna göre yanıt seçenekleri 5=Kesinlikle Katılıyorum, 4=Katılıyorum, 3=Ne Katılıyorum Ne Katılmıyorum, 2=Katılmıyorum ve 1=Kesinlikle Katılmıyorum biçiminde düzenlenmiştir. Ölçekten elde edilen aritmetik ortalamaların yorumlanmasında ise 4.21-5.00 puan aralığının "Kesinlikle Katılıyorum", 3.41-4.20 puan aralığının "Katılıyorum", 2.61-3.40 puan aralığının "Ne Katılıyorum Ne Katılmıyorum", 1.81-2.60 puan aralığının "Katılmıyorum" ve 1.00-1.80 puan aralığının "Kesinlikle Katılmıyorum" şeklinde puan derecelendirilmesi yapılmıştır.

Verilerin Analizi

Katılımcılar tarafından doldurulan anket formlarından elde edilen veriler, IBM SPSS 25 paket programı kullanılarak analiz edilmiştir. Araştırma grubunun demografik özellikleri betimsel istatistikler aracılığıyla ortaya konmuştur. Gruplar arasında istatistiksel açıdan anlamlı farklılık bulunup bulunmadığını belirlemek amacıyla tek yönlü ANOVA ve bağımsız örneklem t testi analizlerinden yararlanılmıştır.

BULGULAR

Bu bölümde, araştırmaya katılan bireylerin doldurduğu anket formlarından elde edilen bulgulara yer verilmiştir. Elde edilen veriler tablolar aracılığıyla sunulmuş ve her tabloya ilişkin açıklamalar ile değerlendirmeler ayrıntılı biçimde ele alınmıştır.

Tablo 2. Araştırmada Kullanılan Ölçekler

Ölçek / Boyut	Madde Sayısı	Ortalama	Standart Sapma	Cronbach Alpha	KMO
Sağlık Turizmi Farkındalık Ölçeği	20	3,5102	,60163	,881	,855
Bilinç ve Farkındalık Boyutu	9	3,8279	,64111	,848	
Hizmet Yetkinliği Boyutu	6	3,2557	,83790	,834	
Altyapı ve Destek Hizmetleri Boyutu	5	3,4471	,85047	,845	

Çankırı İlinin Sağlık Turizmi Potansiyeli Boyutu	5	3,2176	1,06705	,917	

Güvenirlik analizinden elde edilen sonuçlar, araştırmada kullanılan ölçme aracının tutarlı sonuçlar ürettiğine işaret etmektedir. Sağlık turizmi farkındalık ölçeğinin tamamına ilişkin iç tutarlılık katsayısı ,881'dir. Alt boyutlar düzeyinde ise bu değerler; Çankırı ilinin sağlık turizmi potansiyeli için ,917, bilinç ve farkındalık için ,848, altyapı ve destek hizmetleri için ,845 ve hizmet yetkinliği için ,834 olarak belirlenmiştir. Hesaplanan katsayıların tamamının $0,80 \leq \alpha < 1,00$ sınırları içinde kalması, gerek genel ölçeğin gerekse ölçeği oluşturan boyutların yüksek güvenirlik düzeyine sahip olduğunu göstermektedir (Can, 2013; Ural & Kılıç, 2013). Analiz öncesinde örneklemin yeterliliğini değerlendirmek üzere KMO (Kaiser-Meyer-Olkin) değeri de hesaplanmıştır. Elde edilen ,855 düzeyindeki sonuç, $0,70 \leq KMO < 0,90$ değerlendirme aralığında yer almaktadır. Buna göre araştırmanın örneklem yapısının analiz için iyi düzeyde yeterlilik gösterdiği söylenebilir (Kalaycı, 2014; Can, 2013; Çokluk vd., 2012). Katılımcıların verdikleri yanıtların ortalamaları karşılaştırıldığında, en olumlu değerlendirmenin bilinç ve farkındalık boyutunda toplandığı görülmektedir. Bu boyutun ortalaması 3,8279 olarak hesaplanmıştır. Ölçeğin bütününe ait ortalama değer 3,5102 iken altyapı ve destek hizmetleri boyutunda 3,4471, hizmet yetkinliği boyutunda 3,2557 ve Çankırı ilinin sağlık turizmi potansiyeli boyutunda 3,2176 ortalama elde edilmiştir. Bu dağılım, öğrencilerin sağlık turizmine ilişkin genel bilinç düzeylerinin diğer boyutlara kıyasla daha yüksek olduğunu; en düşük değerlendirmenin ise Çankırı ilinin sağlık turizmi potansiyeline yönelik ifadelerde ortaya çıktığını göstermektedir.

Tablo 3. Bilinç ve Farkındalık Boyutu Tanımlama Tablosu

Boyut	Ölçek Maddeleri	Ortalama	Standart Sapma
Bilinç ve Farkındalık Boyutu	Sağlık turizmi sektörü uzun yıllar çalışmak için uygun bir sektördür.	3,9412	,85181
	Sağlık Turizminde ülkemizin fırsatlarının farkındayım.	3,9314	,90167
	Sağlık turizmi için teşvik paketleri oluşturulmalıdır.	3,8971	,86200
	Sağlık turizmi sayesinde ülkemize gelen turist sayısında artışlar olmaktadır.	3,8922	1,01619
	Sağlık turizminin ülkemize sunduğu fırsat ve avantajların farkındayım.	3,8873	,88336
	Sağlık turizminin ülke ekonomisine olan katkısının bilincindeyim.	3,8186	,89961
	Yabancıların sağlık turizmi kapsamında ülkemizi tercih etme nedenleri hakkında bilgi sahibiyim.	3,7794	,98529
	Sağlık turizmi konusunda uluslararası rakiplerimiz sayıca çok fazladır.	3,7059	1,02758
	Sağlık Turizm ve Etik ilkeler konusunda yeteri kadar bilgiye sahip olduğumu düşünüyorum	3,5980	1,12526

Bilinç ve farkındalık boyutu maddelerinin puan ortalamalarının verildiği Tablo 3'e göre "Sağlık turizmi sektörü uzun yıllar çalışmak için uygun bir sektördür." ifadesinin 3,9412 ile en yüksek puan ortalamasına sahip olduğu görülmektedir. Tablo 3'te yer alan maddelerin tamamında puan ortalamasının 3,41 – 4,20 puan aralığında ve "Katılıyorum" düzeyinde yüksek olduğu görülmektedir.

Tablo 4. Hizmet Yetkinliği Boyutu Tanımlama Tablosu

Boyut	Ölçek Maddeleri	Ortalama	Standart Sapma
Hizmet Yetkinliği Boyutu	Uluslararası sağlık turizmi standartları hakkında yeterli bilgiye sahibim.	3,3922	1,14605
	Sağlık turizmi ve sağlık turizmi türleri konusunda bilgi sahibiyim.	3,3873	1,04199
	Aldığım eğitimle bu alanda yeterli bilgi ve donanıma sahibim.	3,2157	1,12847
	Sağlık turizminde ülkemizin zayıf ve eksik olduğu alanlar konusunda yeterli bilgiye sahibim.	3,1814	1,04643
	Ülkemizde sağlık turizmini geliştirmek adına atılan adımlardan (kurum ve kuruluşlara verilen teşvikler, vergi indirimleri, sağlık turizminin 10. Kalkınma Planı içinde yer alması, sağlık turizmi için hazırlanan protokol vb.) haberdarım.	3,1814	1,27169
	Hastanelerdeki sağlık turizmi ofislerinin işlevleri hakkında bilgi sahibiyim.	3,1765	1,15252

Hizmet yetkinliği boyutu maddelerinin puan ortalamalarının verildiği Tablo 4'e göre "Uluslararası sağlık turizmi standartları hakkında yeterli bilgiye sahibim." ifadesinin 3,3922 ile en yüksek puan ortalamasına sahip olduğu görülmektedir. Tablo 4'te yer alan maddelerin tamamında puan ortalamasının 2,61 – 3,40 puan aralığında ve "Ne Katılıyorum Ne Katılmıyorum" düzeyinde kararsız olduğu görülmektedir.

Tablo 5. Altyapı ve Destek Hizmetleri Boyutu Tanımlama Tablosu

Boyut	Ölçek Maddeleri	Ortalama	Standart Sapma
Altyapı ve Destek Hizmetleri Boyutu	Ülkemizdeki otellerin misafirler için yeterli kapasiteye ve altyapıya sahip olduğunu düşünüyorum.	3,6176	1,07405
	Ülkemizin sağlık turizmi alanında uzmanlaşmış personel konusunda yeterli seviyede olduğunu düşünüyorum.	3,4804	1,10735
	Ülkemizdeki sağlık turizmi hizmetlerinin kalitesini memnuniyet verici buluyorum.	3,4559	1,07960
	Sağlık turizminin gelişiminde, ülkemizin altyapısal ve teknolojik seviyesini yeterli görüyorum.	3,4118	1,06769
	Sağlık turizmi için Sağlık Bakanlığı ve Kültür ve Turizm Bakanlığı çalışmaları yeterli düzeydedir.	3,2696	1,08317

Altyapı ve destek hizmetleri boyutu maddelerinin puan ortalamalarının verildiği Tablo 5'e göre "Ülkemizdeki otellerin misafirler için yeterli kapasiteye ve altyapıya sahip olduğunu düşünüyorum." ifadesinin 3,6176 ile en yüksek puan ortalamasına sahip olduğu görülmektedir. Tablo 5'te yer alan ilk dört maddenin puan ortalamasının puan ortalamasının 3,41 – 4,20 puan aralığında ve "Katılıyorum" düzeyinde yüksek olduğu görülmektedir. Boyutun son maddesinin ise 3,2696 puan ortalaması ile 2,61 – 3,40 puan aralığında ve "Ne Katılıyorum Ne Katılmıyorum" düzeyinde kararsız olduğu görülmektedir.

Tablo 6. Çankırı İlinin Sağlık Turizmi Potansiyeli Boyutu Tanımlama Tablosu

Boyut	Ölçek Maddeleri	Ortalama	Standart Sapma

Çankırı İlinin Sağlık Turizmi Potansiyeli Boyutu	Çankırı, termal su kaynakları açısından yeterli rezerve sahiptir.	3,3186	1,13669
	Çankırı, yabancı hastaların konaklaması açısından yeterli niteliktedir.	3,2843	1,25457
	Çankırı, 12 ay turizme olanak sağlayacak potansiyele sahiptir.	3,1912	1,27798
	Çankırı, yabancı hastalar için yeterli hizmet sektörü potansiyeline sahiptir.	3,1471	1,23892
	Çankırı, yabancı hastaların kolay ulaşabileceği bir konumdadır.	3,1471	1,24684

Çankırı ilinin sağlık turizmi potansiyeli boyutu maddelerinin puan ortalamalarının verildiği Tablo 6'ya göre "Çankırı, termal su kaynakları açısından yeterli rezerve sahiptir." ifadesinin 3,3186 ile en yüksek puan ortalamasına sahip olduğu görülmektedir. Tablo 6'da yer alan yer alan maddelerin tamamında puan ortalamasının 2,61 – 3,40 puan aralığında ve "Ne Katılıyorum Ne Katılmıyorum" düzeyinde kararsız olduğu görülmektedir.

Turizm lisans öğrencilerinin demografik özellikleri ile sağlık turizmi farkındalığı arasındaki farklılığa ilişkin Anova testi ve T testi sonuçlarının açıklandığı Tablo 7'de istatistiksel olarak anlamlı farklılık sınıf değişkeninde bulunmuştur. Anlamlı farklılığın bulunduğu sınıf değişkeninde farklılığın ikinci sınıf ve dördüncü sınıf öğrencileri ile birinci sınıf öğrencileri arasında olduğu görülmektedir. Sınıf değişkenine göre puan ortalamaları karşılaştırıldığında dördüncü sınıf öğrencilerinin en yüksek puan ortalamasına sahip olduğu, birinci sınıf öğrencilerin ise en düşük puan ortalamasına sahip olduğu görülmektedir. Cinsiyet, bölüm ve yaş değişkenlerine göre ise istatistiksel olarak anlamlı bir farklılık bulunamamıştır. Tablo 7'den elde edilen bulgulara göre hipotez 1, sınıf değişkenine göre kabul edilmiştir. Cinsiyet, bölüm ve yaş değişkenleri açısından ise hipotez 1 reddedilmiştir.

Tablo 7. Turizm Lisans Öğrencilerinin Demografik Özellikleri İle Sağlık Turizmi Farkındalığı Arasındaki Farklılıklara İlişkin Anova Testi ve T-Testi Sonuçları

Ölçek	Değişken	Grup	n	Ortalama	Standart Sapma	F/t	p	Tukey HSD
Sağlık Turizmi Farkındalık Ölçeği	Cinsiyet	Erkek	56	3,6159	,61170	1,529	,130	-
		Kadın	148	3,4702	,59497			
	Bölüm	Turizm İşletmeciliği	64	3,6068	,71507	1,402	,164	-
		Turizm Rehberliği	140	3,4661	,53908			
	Yaş	17-19 Yaş Arasıa	72	3,4727	,54435	,377	,686	-
		20-21 Yaş Arasıb	67	3,5012	,65509			
		22 Yaş ve Üzeric	65	3,5611	,61035			
	Sınıf	Birinci Sınıfa	69	3,3261	,60489	4,555	,004	b ile a d ile a
		İkinci Sınıfb	67	3,5969	,60013			
		Üçüncü Sınıfc	44	3,5153	,60639			
		Dördüncü Sınıfd	24	3,7883	,43319			

Tablo 8. Turizm Lisans Öğrencilerinin Demografik Özellikleri İle Bilinç ve Farkındalık Boyutu Arasındaki Farklılıklara İlişkin Anova Testi ve T-Testi Sonuçları

Boyut	Değişken	Grup	n	Ortalama	Standart Sapma	F/t	p	Tukey HSD
Bilinç ve Farkındalık Boyutu	Cinsiyet	Erkek	56	3,9583	,62803	1,814	,073	-
		Kadın	148	3,7785	,64117			
	Bölüm	Turizm İşletmeciliği	64	3,7969	,76663	-,420	,675	-
		Turizm Rehberliği	140	3,8421	,57728			
	Yaş	17-19 Yaş Arasıa	72	3,8256	,63208	,008	,992	-
		20-21 Yaş Arasıb	67	3,8358	,70760			
		22 Yaş ve Üzeric	65	3,8222	,58657			
	Sınıf	Birinci Sınıfa	69	3,7150	,60273	1,374	,252	-
		İkinci Sınıfb	67	3,8574	,73367			
		Üçüncü Sınıfc	44	3,8687	,63863			
		Dördüncü Sınıfd	24	3,9954	,41636			

Turizm lisans öğrencilerinin demografik özellikleri ile bilinç ve farkındalık boyutu arasındaki farklılığa ilişkin Anova testi ve T testi sonuçlarının açıklandığı Tablo 8'de cinsiyet, bölüm, yaş ve sınıf değişkenlerine göre istatistiksel olarak anlamlı bir farklılık bulunamamıştır. Tablo 8'den elde edilen bulgulara göre hipotez 1a, cinsiyet, bölüm, yaş ve sınıf değişkenlerine göre reddedilmiştir.

Tablo 9. Turizm Lisans Öğrencilerinin Demografik Özellikleri İle Hizmet Yetkinliği Boyutu Arasındaki Farklılıklara İlişkin Anova Testi ve T-Testi Sonuçları

Boyut	Değişken	Grup	n	Ortalama	Standart Sapma	F/t	p	Tukey HSD
Hizmet Yetkinliği Boyutu	Cinsiyet	Erkek	56	3,4643	,86557	2,150	,034	-
		Kadın	148	3,1768	,81632			
	Bölüm	Turizm İşletmeciliği	64	3,4766	,89426	2,468	,015	-
		Turizm Rehberliği	140	3,1548	,79382			
	Yaş	17-19 Yaş Arasıa	72	3,2315	,48550	,107	,899	-
		20-21 Yaş Arasıb	67	3,2438	,74118			
		22 Yaş ve Üzeric	65	3,2949	,71739			
	Sınıf	Birinci Sınıfa	69	3,0314	,84321	3,588	,015	d ile a
		İkinci Sınıfb	67	3,3632	,85474			

		Üçüncü Sınıfc	44	3,2500	,84028			
		Dördüncü Sınıfd	24	3,6111	,60126			

Turizm lisans öğrencilerinin demografik özellikleri ile hizmet yetkinliği boyutu arasındaki farklılığa ilişkin Anova testi ve T testi sonuçlarının açıklandığı Tablo 9'da cinsiyet, bölüm ve sınıf değişkenlerine göre istatistiksel olarak anlamlı bir farklılık bulunmuştur. Anlamlı farklılığın bulunduğu cinsiyet değişkeninde erkek öğrencilerin hizmet yetkinliği farkındalıkların daha yüksek olduğu görülmektedir. Bölüm değişkenine göre ise turizm işletmeciliği bölümü öğrencilerinin hizmet yetkinliği farkındalıkları turizm rehberliği bölümü öğrencilerine göre daha yüksek olduğu görülmektedir. Sınıf değişkeninde ise anlamlı farklılığın dördüncü sınıf öğrencileri ile birinci sınıf öğrencileri arasında olduğu görülmektedir. Puan ortalamasına göre dördüncü sınıf öğrencilerinin hizmet yetkinliği farkındalıkların en yüksek, birinci sınıf öğrencilerinin ise hizmet yetkinliği farkındalıkların en düşük olduğu görülmektedir. Yaş değişkenine göre ise istatistiksel olarak anlamlı bir farklılık bulunamamıştır. Tablo 9'dan elde edilen bulgulara göre hipotez 1b, cinsiyet, bölüm ve sınıf değişkenine göre kabul edilmiştir. Yaş değişkeni açısından ise hipotez 1b reddedilmiştir.

Tablo 10. Turizm Lisans Öğrencilerinin Demografik Özellikleri İle Altyapı ve Destek Hizmetleri Boyutu Arasındaki Farklılıklara İlişkin Anova Testi ve T-Testi Sonuçları

Boyut	Değişken	Grup	n	Ortalama	Standart Sapma	F/t	p	Tukey HSD
Altyapı ve Destek Hizmetleri Boyutu	Cinsiyet	Erkek	56	3,4250	,86219	-,226	,822	-
		Kadın	148	3,4554	,84879			
	Bölüm	Turizm İşletmeciliği	64	3,5469	,90728	1,093	,277	-
		Turizm Rehberliği	140	3,4014	,82252			
	Yaş	17-19 Yaş Arasıa	72	3,3611	,83084	1,030	,359	-
		20-21 Yaş Arasıb	67	3,4239	,84961			
		22 Yaş ve Üzeric	65	3,5662	,87219			
	Sınıf	Birinci Sınıfa	69	3,2319	,92076	3,114	,027	d ile a
		İkinci Sınıfb	67	3,5701	,78567			
		Üçüncü Sınıfc	44	3,4273	,88983			
		Dördüncü Sınıfd	24	3,7583	,58378			

Turizm lisans öğrencilerinin demografik özellikleri ile altyapı ve destek hizmetleri boyutu arasındaki farklılığa ilişkin Anova testi ve T testi sonuçlarının açıklandığı Tablo 10'da istatistiksel olarak anlamlı farklılık sınıf değişkeninde bulunmuştur. Anlamlı farklılığın bulunduğu sınıf değişkeninde farklılığın dördüncü sınıf öğrencileri ile birinci sınıf öğrencileri arasında olduğu görülmektedir. Sınıf değişkenine göre puan ortalamaları karşılaştırıldığında dördüncü sınıf öğrencilerinin en yüksek puan ortalamasına sahip olduğu ve altyapı ve destek hizmetleri farkındalıklarının en yüksek olduğu görülmektedir. Birinci sınıf öğrencilerin ise en

düşük puan ortalaması ile en düşük altyapı ve destek hizmetleri farkındalığına sahip oldukları görülmektedir. Cinsiyet, bölüm ve yaş değişkenlerine göre ise istatistiksel olarak anlamlı bir farklılık bulunamamıştır. Tablo 10'dan elde edilen bulgulara göre hipotez 1c, sınıf değişkenine göre kabul edilmiştir. Cinsiyet, bölüm ve yaş değişkenleri açısından ise hipotez 1c reddedilmiştir.

Turizm lisans öğrencilerinin demografik özellikleri ile Çankırı ilinin sağlık turizmi potansiyeli boyutu arasındaki farklılığa ilişkin Anova testi ve T testi sonuçlarının açıklandığı tablo 11'de cinsiyet, bölüm ve sınıf değişkenlerine göre istatistiksel olarak anlamlı bir farklılık bulunmuştur. Anlamlı farklılığın bulunduğu cinsiyet değişkeninde erkek öğrencilerin Çankırı ilinin sağlık turizmi potansiyeli farkındalıkların daha yüksek olduğu görülmektedir. Bölüm değişkenine göre ise turizm işletmeciliği bölümü öğrencilerinin Çankırı ilinin sağlık turizmi potansiyeli farkındalıkları turizm rehberliği bölümü öğrencilerine göre daha yüksek olduğu görülmektedir. Sınıf değişkeninde ise anlamlı farklılığın ikinci sınıf öğrencileri ile üçüncü sınıf öğrencileri arasında olduğu görülmektedir. Puan ortalamasına göre ikinci sınıf öğrencilerinin Çankırı ilinin sağlık turizmi potansiyeli farkındalıkların en yüksek, üçüncü sınıf öğrencilerinin ise Çankırı ilinin sağlık turizmi potansiyeli farkındalıkların en düşük olduğu görülmektedir. Yaş değişkenine göre ise istatistiksel olarak anlamlı bir farklılık bulunamamıştır. Tablo 11'den elde edilen bulgulara göre hipotez 1d, cinsiyet, bölüm ve sınıf değişkenine göre kabul edilmiştir. Yaş değişkeni açısından ise hipotez 1d reddedilmiştir.

Tablo 11. Turizm Lisans Öğrencilerinin Demografik Özellikleri İle Çankırı İlinin Sağlık Turizmi Potansiyeli Boyutu Arasındaki Farklılıklara İlişkin Anova Testi ve T-Testi Sonuçları

Boyut	Değişken	Grup	n	Ortalama	Standart Sapma	F/t	p	Tukey HSD
Çankırı İlinin Sağlık Turizmi Potansiyeli Boyutu	Cinsiyet	Erkek	56	3,6000	,97980	3,345	,001	-
		Kadın	148	3,0730	1,06602			
	Bölüm	Turizm İşletmeciliği	64	3,4594	1,13679	2,120	,036	-
		Turizm Rehberliği	140	3,1071	1,01879			
	Yaş	17-19 Yaş Arasıa	72	3,4056	1,10465	2,212	,112	-
		20-21 Yaş Arasıb	67	3,2030	1,09903			
		22 Yaş ve Üzeric	65	3,0246	,96664			
	Sınıf	Birinci Sınıfa	69	3,2174	1,15440	2,732	,045	b ile c
		İkinci Sınıfb	67	3,4746	1,00111			
		Üçüncü Sınıfc	44	2,9136	,95323			
		Dördüncü Sınıfd	24	3,0583	1,06727			

TARTIŞMA VE SONUÇ

Araştırmada, bilinç ve farkındalık boyutunda erkek öğrencilerin kadın öğrencilere göre, turizm rehberliği bölümü öğrencilerini turizm işletmeciliği bölümü öğrencilerine göre, dördüncü sınıf öğrencilerinin diğer alt sınıf öğrencilerine göre ve 20-21 yaş aralığı grubundaki öğrencilerin diğer yaş gruplarına göre puan ortalamalarının daha yüksek olduğu görülmüştür.

Hizmet yetkinliği boyutunda erkek öğrencilerin kadın öğrencilere göre, turizm işletmeciliği bölümü öğrencilerini turizm rehberliği bölümü öğrencilerine göre, dördüncü sınıf öğrencilerinin diğer alt sınıf öğrencilerine göre ve 22 yaş ve üzeri grubundaki öğrencilerin diğer yaş gruplarına göre puan ortalamalarının daha yüksek olduğu görülmüştür.
Altyapı ve destek hizmetleri boyutunda kadın öğrencilerin erkek öğrencilere göre, turizm işletmeciliği bölümü öğrencilerini turizm rehberliği bölümü öğrencilerine göre, dördüncü sınıf öğrencilerinin diğer alt sınıf öğrencilerine göre ve 22 yaş ve üzeri grubundaki öğrencilerin diğer yaş gruplarına göre puan ortalamalarının daha yüksek olduğu görülmüştür.
Çankırı ilinin sağlık turizmi potansiyeli boyutunda erkek öğrencilerin kadın öğrencilere göre, turizm işletmeciliği bölümü öğrencilerini turizm rehberliği bölümü öğrencilerine göre, ikinci sınıf öğrencilerinin diğer farklı sınıf öğrencilerine göre ve 17-19 yaş aralığı grubundaki öğrencilerin diğer yaş gruplarına göre puan ortalamalarının dah yüksek olduğu görülmüştür.
Araştırmada bağımsız örneklem T testi ve tek yönlü Anova testlerinin sonucuna göre Çankırı Karatekin Üniversitesi Turizm Fakültesi öğrencilerinin hizmet yetkinliği boyutunda cinsiyet, bölüm ve sınıf değişkenlerinde, altyapı ve destek hizmetleri boyutunda sınıf değişkeninde ve Çankırı ilinin sağlık turizmi potansiyeli boyutunda cinsiyet, bölüm ve sınıf değişkenlerinde istatistiksel olarak anlamlı farklılıklar bulunmuştur. Araştırmadan elde eilen sonuçlar literatürdeki benzer araştırmalardan, Acar ve Turan (2016), Şahin, Yılmaz ve Karamustafa (2023), Alkaç ve Büyükşalvarcı (2024) ve Altıparmak ve Soysal (2024) elde edilen sonuçları destekler niteliktedir.
Bu araştırmadan elde edilen bulgular ve ulaşılan sonuçlar doğrultusunda gelecekte gerçekleştirilecek çalışmalar için çeşitli öneriler geliştirilmiştir.
Araştırmanın evreni, Çankırı Karatekin Üniversitesi'nde turizm alanında lisans eğitimi gören öğrencilerle sınırlandırılmıştır. Bu nedenle, ileride yapılacak araştırmalarda farklı üniversitelerde öğrenim gören daha geniş bir öğrenci grubunun örnekleme dâhil edilmesi, elde edilecek sonuçların genellenebilirliğini artıracaktır.
Çalışma yalnızca turizm lisans öğrencileri üzerinde yürütülmüştür. Gelecek araştırmalarda turizm bölümü dışındaki farklı lisans programlarında öğrenim gören öğrencilerin de araştırma kapsamına alınması önerilmektedir. Böylece bölümler arasında karşılaştırmalar yapılabilir ve incelenen değişkenlerin farklı öğrenci gruplarında nasıl bir görünüm sergilediği ortaya konabilir.
Bu araştırmada nicel araştırma yöntemi tercih edilmiştir. Konunun daha ayrıntılı ve çok yönlü biçimde ele alınabilmesi için sonraki çalışmalarda görüşme, odak grup veya gözlem gibi nitel veri toplama tekniklerinden yararlanılabilir. Ayrıca nicel ve nitel yöntemlerin birlikte kullanıldığı karma yöntem araştırmalarıyla bulguların daha kapsamlı biçimde değerlendirilmesi sağlanabilir.

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