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Artificial Intelligence in Forestry: A Comprehensive Analysis of Current Applications and Future Perspectives

Ormancılıkta Yapay Zeka: Mevcut Uygulamalar ve Gelecek Perspektifi Üzerine Kapsamlı Bir Analiz

Ourania ARETA HIZIROĞLU[1], Tarık SEMIZ[2]

Abstract

This study systematically analyzes artificial intelligence (AI) applications in forestry management, exploring current implementations, challenges, and future perspectives. A review of 580 articles from Web of Science (211) and Scopus (369) databases (2021-2025) identifies key themes where AI is transforming forestry practices. Forest Monitoring and Management Systems (30.4%) and Digital Transformation (23.6%) dominate current research, followed by Resource Optimization (17.1%) and Biodiversity Conservation (14.6%). Significant opportunities are noted in productivity enhancement, risk analysis, biodiversity conservation, and carbon management through AI. However, challenges such as data quality, resource constraints, operational complexities, and regulatory requirements remain. Emerging trends like human-centered AI, digital twins, and integrated sensor networks show promise. This analysis offers valuable insights for forestry professionals, researchers, and policymakers, providing a framework to understand AI's potential and limitations while emphasizing balanced integration for environmental sustainability and operational efficiency.

Keywords: Artificial Intelligence, Forest Management, Digital Transformation, Sustainability, Forest Technology

Özet

Bu çalışma, yapay zekâ (YZ) uygulamalarının ormancılık yönetimindeki rolünü sistematik bir şekilde analiz ederek mevcut uygulamaları, zorlukları ve gelecekteki perspektifleri incelemektedir. Web of Science (211) ve Scopus (369) veri tabanlarından (2021-2025) seçilen 580 makalenin incelenmesiyle YZ'nin ormancılık uygulamalarını dönüştürdüğü temel temalar belirlenmiştir. Araştırmaların büyük bir kısmı Orman İzleme ve Yönetim Sistemleri (%30,4) ve Dijital Dönüşüm (%23,6) üzerine yoğunlaşırken, Kaynak Optimizasyonu (%17,1) ve Biyoçeşitliliğin Korunması (%14,6) da önemli alanlar olarak öne çıkmaktadır. YZ kullanımıyla verimliliğin artırılması, risk analizi, biyoçeşitliliğin korunması ve karbon yönetimi gibi alanlarda önemli fırsatlar bulunmaktadır. Ancak, veri kalitesindeki teknik sınırlamalar, kaynak kısıtları, operasyonel karmaşıklıklar ve düzenleyici gereklilikler gibi zorluklar devam etmektedir. İnsan odaklı YZ, dijital ikizler ve entegre sensör ağları gibi yeni trendler umut vaat etmektedir. Bu analiz, ormancılık profesyonelleri, araştırmacılar ve politika yapıcılar için değerli içgörüler sunarak YZ'nin potansiyelini ve sınırlamalarını anlamak için bir çerçeve sağlamakta ve çevresel sürdürülebilirlik ile operasyonel verimliliği dengeli bir şekilde bir arada ele almanın önemini vurgulamaktadır.

Anahtar Kelimeler: Yapay Zeka, Orman Yönetimi, Dijital Dönüşüm, Sürdürülebilirlik, Orman Teknolojisi

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Address: [1]Izmir Bakircay University, Faculty of Economics and Administrative Sciences, Department of MIS
E-mail: ourania.areta@bakircay.edu.tr
Address: [2]Izmir Bakircay University, Faculty of Economics and Administrative Sciences, Department of Business Administration
E-mail: tarik.semiz@bakircay.edu.tr

1. Introduction

Artificial intelligence (AI) in forestry can provide important benefits within the framework of the management and conservation of forests. Indeed, with forests worldwide facing ever-increasing challenges due to climate change, population growth, and resource demands at an unprecedented level, it has never been more necessary than now to have advanced tools capable of monitoring and managing these ecosystems (Jha & Saxena, 2020). AI offers pioneering solutions for these problems in terms of much better, more accurate, and wholesaling approaches towards forestry management.

The advancement of AI technologies, especially machine learning, remote sensing, and robotics, has enabled a reassessment of traditional forestry practices. Shivaprakash et al. (2022) note that improvements in data availability, decreased computational costs, and the increased availability of data sources like satellite imagery, drones, and sensor networks have promoted AI applications in the forestry sector. Nevertheless, AI technology adoption in forestry is still very uneven across regions and applications.

The applications of AI in forestry stretch from basic inventory management to the most advanced ecosystem analysis. Borz et al. (2022) demonstrate how the integration of electronics, proximity sensors, and AI is transforming forest management with big data analytics and novel algorithms. These have increased accuracy and productivity in forest operations; however, the wide dissemination of these technologies still faces significant challenges such as data quality, resource constraints, operational complexities, and regulatory requirements.

Hokans' 1984 research on scheduling timber harvests serves as an example of early AI implementations in forestry, which led to today's deep learning and autonomous technologies. This trajectory describes a rise in technological capability, an increasing understanding of the complexities of forest ecosystems, and an escalating demand for sophisticated management approaches. Recent research by Buchelt et al. (2024) demonstrates how AI-integrated drones have already changed the game regarding mapping, monitoring, and cataloging forests. Given the rapid development in related technologies, such as in drone applications (Buchelt et al., 2024) and digital twin systems (Nita, 2021), there is an ongoing need for reviews of new tools to guide further developments and their successful use.

The integration of AI in forestry also introduces severe problems concerning accessibility, reliability, and ethical consequences. Galaz et al. (2021) introduce some systemic risks of applying AI to this sector: algorithmic bias and technology access inequity. Overcoming these challenges is necessary for the responsible advancement of AI tools in forestry.

This review presents a comprehensive assessment of the status of AI applications in forestry, as well as future opportunities and challenges. It examines how AI technologies are applied to different aspects of forest management and conservation based on recent studies and findings. Besides, it identifies crucial barriers and opportunities and provides a deeper understanding of the future development of the field.

The organization of the paper follows a structured approach for an in-depth analysis of applications of AI to forestry management. Section 2 provides a literature review about the basics of AI, and its application in forestry management, based on seminal works and recent contributions to the field. Section 3 outlines the methodology, which includes a dual database search strategy, as well as the systematization of data collection and analysis. Section 4 delivers the quantitative results of the review, deeply analyzing important domains of application and current trends within AI forestry technologies. Section 5 critically discusses opportunities and challenges for the implementation of AI, balancing potential benefits with implementation barriers. Section 6 covers emerging technologies and future perspectives, especially focusing on transformative developments, all while providing insights into future research directions and technological evolution in the field. The conclusion synthesizes these findings by providing strategic recommendations for practitioners and researchers on the importance of sustainable integration strategies that balance technological advancement with ecological preservation. Our comprehensive review thus seeks to provide actionable insights into the status and future directions of AI in forestry, while emphasizing the critical need for balanced approaches that are sensitive to both technological innovation and environmental stewardship.

2. Literature Review

2.1. Concept of artificial intelligence

The basic idea of AI is described as "the capability of a system to understand data, learn from data, and utilize this gained understanding for specific tasks" (Başcillar et al., 2022). This description encompasses the basic functions and objectives involved in AI and depicts the diversity of its current application domains.

AI can additionally be characterized as systems that replicate human cognitive processes and possess the ability to enhance their functionality based on the data they acquire (Şener and Şen, 2022). In the year 1956, McCarthy *et al.* (2006) articulated the notion of AI as "the science and engineering of making intelligent machines," a definition that remains applicable in contemporary discourse (Çelik et al., 2021). AI represents the sphere of technology where computers gain the ability to imitate thinking, learning, and solving problems-like processes of a human brain. An idea first introduced by John McCarthy in the Dartmouth Conference of 1956 became the very cornerstone for achievements that transformed health, education, industry, and logistics up to this date. AI is the result of a merger of different disciplines, such as mathematics, computer science, psychology, and linguistics. Its development has been significantly influenced by the recent emergence of data science, machine learning, and big data technologies (Russell and Norvig, 2021). There are many different definitions and areas of application for AI in the literature. For example, in the health sector, AI is used in various areas such as early diagnosis of diseases, determination of health risks, and epidemiological research (Alıcılar and Çöl, 2021). In addition, studies investigating the effects of AI on health services demonstrate how this technology is changing the healthcare sector (Güzel et al., 2022).

On the other hand, possible negative effects of AI must be considered, too. All these lead to quite critical discussions, especially considering ethical and privacy matters, as mentioned by Alıcılar and Çöl, (2021) and Dost (2023). Specialized areas supporting this development include machine learning and deep learning. AI can take part in more complex works thanks to these methodologies and enable the increase of speed for processes of data analysis with more speed (Çivilibal et al., 2023; Erkutlu, 2023). For instance, applications of AI enhance the processes related to patient treatment and support healthcare professionals in making decisions (Yılmaz et al., 2021; Akalın and Veranyurt, 2021). Furthermore, it has been noted that AI is utilized effectively in various domains, including education and agriculture (Çoşkun and Gülleroğlu, 2021; Çiçekdemir et al., 2021).

Thus, AI has become one of those fields that have several definitions and various application areas. Its advantages in several aspects of human life widen the potential scope of this technology and make it an important driver for changing various industries.

2.2. AI in forestry

Forests play a crucial role in maintaining the global ecosystem. However, many factors such as climate change, anthropogenic degradation, and natural disasters threaten forest ecosystems. In the present scenario, AI has been offering innovative solutions in critical areas of environmental sustainability, economic efficiency, and risk management associated with forest governance. AI, in forestry, enables more innovative and effective decision-making based on the processing of vast amounts of data from satellites, sensors, and drones (Kumar et al., 2022).

The following table is designed to explain how AI can be applied to the forestry industry, using current examples taken from the literature.

Table 1. Areas of use of AI in the forestry.

Area of Use	AI Applications	Benefits	Sources
Forest Management	Creation and analysis of forest maps using data from satellites	More accurate planning and resource management	Kumar et al., 2022; FAO Report, 2020
Detection of Tree Diseases	Detection of sick trees with image processing technologies	Preventing the spread of diseases with early intervention	Smith and Zhang, 2021; NASA Earth Science, 2021
Fire Risk Analysis	Analysis of data such as weather, humidity and vegetation with machine learning	Predicting forest fires	Jones et al., 2020; Copernicus EU, 2023
Sustainable Harvest Planning	Determining the amount and time of tree cutting with optimization algorithms	Sustainable use of resources	Fernandez et al., 2019; WRI Report, 2022
Wildlife Conservation	Monitoring animal movements using sensor data and image processing	Ecosystem protection	Global Forest Watch, 2021; Brown et al., 2023
Rehabilitation and Renewal	Determining tree species according to suitable soil type and climate conditions	More efficient afforestation with the right species selection	Gomez et al., 2020; UNEP Report, 2023
Carbon Footprint Monitoring	AI-powered carbon accounting and reporting tools	Assessing the potential of forests to reduce carbon emissions	IPCC Report, 2022; Miller et al., 2021
Climate Change Analysis	Examining the effects of climate change on forests with big data analysis	Improving forest policies	Liu and Wang, 2022; Nature Climate Change, 2023
Productivity Analysis	Analysis of drone and sensor data with AI algorithms	Speeding up operations and reducing costs	Johnson et al., 2021; Drone Applications in Forestry, 2020
Loss/Leakage Control	Detection of unauthorized tree felling or forest damage with AI-supported surveillance systems	Protection of forest assets	Chen et al., 2022; Forest Watch EU, 2023

The table above aims to detail the areas of use of AI in the forestry sector with current examples in the literature. As seen here, AI has been used in forestry in many areas.

3. Methodology

In this study, firstly, through an initial literature review, the impact of AI in different forestry areas was categorized, and specific themes were determined. Furthermore, a systematic dual database search strategy was employed to ensure comprehensive coverage of the literature examining applications of AI in forestry. The methodology utilised both the Web of Science Core Collection and Scopus databases, recognising their complementary strengths in indexing academic literature and acknowledging their complementary strengths in academic literature indexing.

Table 2. Database search parameters and results.

Parameter	Web of Science	Scopus
Search Fields	"Artificial Intelligence" (Author Keywords) AND "Forestry" (All Fields)	"Artificial AND intelligence" AND "Forestry" (Keywords)
Document Type	Articles	Articles
Time Period	2021-2025	2021-2025
Access Type	All	Open Access
Results	211	369

The search strategy was deliberately constructed to maintain methodological rigor while ensuring comprehensive coverage. The temporal boundary of 2021-2025 was established to capture contemporary developments in artificial intelligence applications within forestry, reflecting the rapid evolution of this technological domain. The exclusive focus on peer-reviewed articles ensures scholarly rigor and standardization of the analyzed content.

The complementary nature of the selected databases merits particular attention. The Web of Science Core Collection is renowned for its rigorous inclusion criteria and comprehensive coverage of high-impact journals, while Scopus offers broader coverage and enhanced accessibility through its open access filter. This dual-database approach facilitates:

Table 3. Methodological benefits of dual-database strategy.

Benefit Category	Description
Coverage Enhancement	Broader capture of relevant literature across different journals and geographic regions (Qin, 2022)
Quality Assurance	Cross-validation of findings through multiple indexing systems (Grazhdani et al., 2018)
Bias Mitigation	Reduction of database-specific indexing biases (Grazhdani et al., 2018)
Accessibility	Integration of open access considerations for broader research impactg (Venter & Eck, 2020)

The resulting corpus of articles establishes a robust foundation for subsequent analytical procedures. The methodological framework adheres to established protocols for systematic literature reviews in scientific research, ensuring reproducibility and reliability of findings. This approach enables a comprehensive examination of artificial intelligence applications in forestry while maintaining scholarly rigor and methodological transparency.

3.1. Analytical framework

The analysis applied a thematic approach. Thus, papers were categorized into five major themes, including:

- Digital transformation and technological integration
- Forest monitoring and management systems
- Fire prevention and management
- Biodiversity conservation
- Resource optimization

The data analysis followed the following steps:

a) Content Analysis

Each paper was systematically analyzed for:

- Key findings and contributions
- Technical specifications
- Implementation challenges
- Future recommendations

b) Cross-reference

Moreover, papers were cross-referenced to identify:

- Common themes and patterns
- Technological convergences
- Research gaps
- Future research directions

c) Synthesis and Integration

The findings were synthesized through:

- Time analysis: Observation based on each year's research directions
- Thematic Synthesis: Consolidating findings within identified themes to develop a comprehensive understanding of the current state and future directions.
- Opportunities and Challenges Analysis: Identifying opportunities that forestry can benefit from AI applications, and the challenges that it can face at the same time.

d) Quality Assurance

To ensure the reliability and validity of the analysis:

- Multiple reviews of each paper were conducted
- Findings were cross validated across multiple sources

This methodology provided a structured approach to analyzing the current state of AI in forestry while ensuring comprehensive coverage of technical, practical, and future-oriented aspects of the field.

4. Findings

a. The development of the topic throughout the period of 2021-2024 is described in the following figure:

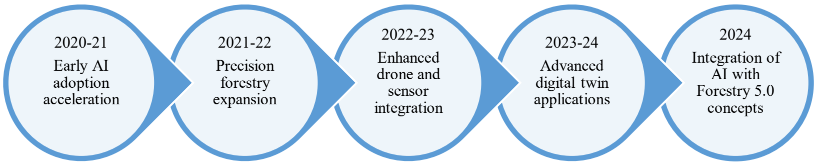

Figure 1. Evolution of topic based on time analysis.

b. Based on the thematic analysis, the following topics were discussed in the articles:

Table 4. Topics on ai in forestry based on thematic analysis.

Research Category	Sub-category	Representative Studies	Key Findings/Applications
I. Monitoring and Detection	Forest Fire Prediction	Wu et al. (2022) "Simulation of forest fire spread based on artificial intelligence"	Development of predictive models utilizing machine learning algorithms for fire behavior analysis
		Thangavel et al. (2023) "Autonomous Satellite Wildfire Detection Using Hyperspectral Imagery"	Integration of satellite data for early warning systems
	Disease/Pest Monitoring	Almadhor et al. (2021) "AI-driven framework for plant disease recognition"	Automated detection systems for early disease identification
		Liu et al. (2021) "Acoustic Denoising Using AI for Wood-Boring Pests"	Novel acoustic monitoring methods for pest detection
	Deforestation Tracking	Xiang et al. (2024) "Rapid Forest Change Detection Using UAVs"	Real-time monitoring of forest cover changes
		Sloan et al. (2024) "Mapping Remote Roads Using AI and Satellite Imagery"	Infrastructure monitoring for deforestation prevention
	Biodiversity Conservation	Warner et al. (2024) "CentralBark Image Dataset	Machine learning applications in species identification

		and Tree Species Classification"	
		Velasquez-Camacho et al. (2024) "Assessing urban forest biodiversity"	Urban forest monitoring systems
II. Resource Management	Tree Inventory	Illarionova et al. (2022) "Estimation of Canopy Height from Multispectral Satellite Imagery"	Remote sensing applications for forest inventory
		Carcereri et al. (2023) "Deep Learning Framework for Forest Height Estimation"	Advanced measurement techniques
	Biomass Estimation	Martins-Neto et al. (2021) "Identification of significative lidar metrics"	LiDAR-based biomass assessment
		Strandgard et al. (2022) "Optimizing Forest Biomass Logistics"	Efficient resource allocation systems
	Growth Modeling	da Rocha et al. (2021) "Configuration of artificial neural networks for height-diameter relationship"	Neural network applications in growth prediction
		Aldea et al. (2023) "Evaluation of growth models for mixed forests"	Advanced modeling techniques
III. Technology Integration	Drone-based Monitoring	Genest et al. (2024) "Automated detection of planting mounds"	UAV applications in forestry operations
		Perez et al. (2022) "Precision silviculture using UAVs"	Integration of drone technology
	IoT Sensor Networks	Singh and Walingo (2024) "Smart Water Quality Monitoring with IoT"	Environmental monitoring systems
		Cardinale-Villalobos et al. (2023) "IoT System Based on AI for Hot Spot Detection"	Advanced sensor networks
	Digital Twin Modeling	Niță (2021) "Testing forestry digital twinning workflow"	Virtual forest management systems
		Holzinger et al. (2024) "From Industry 5.0 to Forestry 5.0"	Digital transformation frameworks
IV. Emerging Trends	Human-centered AI	de Pellegrin Llorente et al. (2023) "Perceptions of uncertainty in forest planning"	Stakeholder integration in AI systems
		Holzinger et al. (2022) "Digital transformation in Smart Farm and Forest Operations"	Human-AI collaboration frameworks
	Precision Forestry	Bont et al. (2022) "Improving forest management by implementing best suitable harvesting methods"	Optimization of forestry operations
		Partel et al. (2021) "Smart tree crop sprayer utilizing sensor fusion"	Precision agriculture applications
	Decision Support Systems	Terribile et al. (2024) "The LANDSUPPORT geospatial decision support system"	Integration of spatial decision support

		Yadav et al. (2024) "A Prototype Decision Support System for Tree Selection"	AI-driven decision-making tools

The analysis of the results from the Scopus database is shown in table 5:

Table 5. Top five thematic classification of research articles from scopus (n=369).

Theme	Count (%)	Representative Citations
Digital Transformation and Technological Integration	87 (23.6%)	Holzinger et al. (2024) "From Industry 5.0 to Forestry 5.0" DOI: 10.1007/s40725-024-00231-7 Niță (2021) "Testing forestry digital twinning workflow" DOI: 10.3390/f12111576 -Partel et al. (2021) "Smart tree crop sprayer utilizing sensor fusion" DOI: 10.1016/j.compag.2021.106556
Forest Monitoring and Management Systems	112 (30.4%)	- Velasquez-Camacho et al. (2024) "Automated taxonomic identification" DOI: 10.1016/j.jag.2024.103735 - Xiang et al. (2024) "Rapid Forest Change Detection" DOI: 10.3390/f15091676 - Guo et al. (2021) "Deep fusion unet for mapping forests" DOI: 10.3390/rs13183613
Fire Prevention and Management	28 (7.6%)	- Wu et al. (2022) "Simulation of forest fire spread" DOI: 10.1016/j.ecolind.2022.108653 - Thangavel et al. (2023) "Autonomous Satellite Wildfire Detection" DOI: 10.3390/rs15030720 - Li et al. (2024) "Spatial prediction of shallow landslide" DOI: 10.1080/19475705.2021.1914753
Biodiversity Conservation	54 (14.6%)	- Warner et al. (2024) "CentralBark Image Dataset" DOI: 10.3390/a17050179 - Yadav et al. (2024) "Tree Selection and Plantation" DOI: 10.3390/f15071219 - Velasquez-Camacho et al. (2024) "Urban forest biodiversity" DOI: 10.1016/j.jag.2024.103735
Resource Optimization	63 (17.1%)	Strandgard et al. (2022) "Optimizing Forest Biomass Logistics" DOI: 10.3390/f13020138 - Nobre et al. (2021) "Compromise programming application" DOI: 10.3390/f12111481 - Bont et al. (2022) "Improving forest management" DOI: 10.1016/j.jenvman.2021.114099

The classification reveals several significant patterns in recent forestry research and technological applications:

- The largest category is Forest Monitoring and Management Systems (30.4%), reflecting the significant emphasis on developing and implementing advanced monitoring technologies in forestry.
- Digital Transformation and Technological Integration represent the second-largest category (23.6%), indicating the rapid technological evolution in forestry practices.
- Resource Optimization (17.1%) and Biodiversity Conservation (14.6%) demonstrate the dual focus on efficiency and environmental protection.

- Fire Prevention and Management (7.6%), while representing smaller proportions, highlight specialized but crucial aspects of modern forestry management.

The analysis of the results from the Web of Science database is shown in table 6:

Table 6. Top five thematic classifications of research articles from wos (n=211).

Theme	Count (%)	Representative Citations
Digital Transformation and Technological Integration	52 (24.6%)	• Tang et al. (2024) "Bolstering Performance Evaluation of Image Segmentation Models" • Xu et al. (2024) "Digital Twin for Aquaponics Factory" • Lopes et al. (2021) "Creating High-Resolution Microscopic Cross-Section Images" • Li et al. (2024) "Improving Artificial Neural Networks for Forest Data"
Forest Monitoring and Management Systems	49 (23.2%)	• Toming et al. (2024) "Estimation of Biogeochemical Properties" • Martins-Neto et al. (2021) "LiDAR Metrics for Estimating Stand Variables" • Slagter et al. (2024) "Monitoring Road Development in Congo Basin Forests" • Marvasti-Zadeh et al. (2023) "Crown-CAM: Tree Crown Detection"
Fire Prevention and Management	28 (13.3%)	• Boroujeni et al. (2024) "AI-enabled UAV Systems in Wildfire Management" • de Domingo et al. (2021) "Cluster-Based Relocation for Fire Management" • Zhou et al. (2022) "Forest Fire Identification System" • Janizadeh et al. (2023) "Machine Learning for Fire Susceptibility"
Biodiversity Conservation	35 (16.6%)	• Dey et al. (2023) "Automated plant species identification from the stomata images using deep neural network: A study of selected mangrove and freshwater swamp forest tree species of Bangladesh • Niţă, M.D. (2021). "Testing Forestry Digital Twinning Workflow Based on Mobile LiDAR Scanner and AI Platform"
Resource Optimization	31 (14.7%)	• Li et al. (2023) "AI Technology Innovation Impact" • Shan et al. (2023) "CPI Prediction Model" • Wang et al. (2024) "HGSNet for Lesion Segmentation" • Ponnan et al. (2021) "AI-Based Quorum System for Sensor Networks"

Accordingly, the key observations can be summarised as follows:

- Digital Transformation and Forest Monitoring collectively represent 47.8% of the research focus, indicating a strong emphasis on technological advancement in forestry management.
- Fire Prevention and Biodiversity Conservation account for approximately 30% of the articles, highlighting the growing importance of environmental protection and species preservation.

- Resource Optimization Approach, while representing a smaller percentage, demonstrates the increasing recognition of efficiency and user engagement in environmental management systems.

Some articles may address multiple themes but have been categorized based on their primary research focus for analytical clarity. This classification system provides a structured framework for understanding the current research landscape in forestry and environmental management.

4.1. Key findings

• AI technologies in smart forestry are increasingly integrated into conventional forestry practices, demonstrating higher accuracy and effectiveness for a wide range of applications.

• Machine learning and deep learning approaches demonstrate exceptionally good performance in the analysis of remote sensing data for enhanced forest monitoring capabilities.

• Human-centered approaches using AI are gaining momentum, as AI capabilities are combined with the abilities of humans.

• Integration of drone technology, sensors, satellite imaging with AI is creating holistic solutions in forestry management.

The following sections will explain in detail the opportunities and challenges that the forestry sector may derive and encounter, respectively, through the application of artificial intelligence.

4.2. Opportunities and challenges in the implementation of AI in forestry

Increasing forest fires, a decline in biodiversity, and problems with carbon emissions management in forestry have created a pressing need for the introduction of new technologies. AI has emerged as a valuable tool for data analysis, decision-making, and process optimization in forestry management (Zhang and Wang, 2023). However, the adoption of AI in forestry management carries with it a continuum of threats, risks, and opportunities, which are presented in the following sections.

4.2.1 Opportunities

i. Productivity Increase and Optimization

AI has the potential to promote efficiency through the optimization of working processes in forestry management. For instance, many machine learning algorithms have been able to perform excellent forest inventories, classification, and prediction of tree species' growth (Nguyen and Tran, 2023).

ii. Risk Analysis and Forecast

AI in forecasting all kinds of natural disasters, including wildfires, plays a particularly important role. AI-driven models can make reliable estimations of the risk of fire by analyzing meteorological information (Xu and Li, 2022). Applications allow for rapid intervention and the best possible use of resources.

iii. Conservation of Biodiversity

AI-based image processing technologies and sound recognition systems monitor and protect the species that live in the forest ecosystems. For instance, the detection of bird species by sound detection systems contributes to their protection, which are usually threatened (Nguyen and Tran, 2023).

iv. Carbon Management and Combating Climate Change

AI algorithms can inform the design of carbon management projects through the analysis of forests' carbon sequestration capacity - a large opportunity to tackle climate change (Smith, 2021).

v. Sustainability and Profitability

AI-based methods can optimize the balance between sustainability and economic gain in forestry management. Malo et al. (2021) study showed that continuous cover management strategies are more sustainable and economically advantageous than single-cutting practices. Especially in natural disaster risk situations, AI models have been successful in producing optimal results (Back et al., 2022b).

Challenges

Açıklamalı [YB1]: 2. derece alt başlıklarda öncesi ve sonrası 6 nk ve 1.5 satır aralığı

Based on the systematic review, the following is an in-depth analysis of implementation challenges in AI forestry applications:

i. Technical Challenges

• Data Quality and Infrastructure

Sensor coverage and data acquisition are significantly challenging issues in forestry applications. According to Borz et al. (2022), there exist key limitations in the land remote sensing framework, where thick vegetation cover dominates particular regions. Damaševiius et al. (2024) emphasize ensuring the quality of data is coherent over different geographical conditions.

The infrastructure of the networks poses a big challenge for efficient deployment. Kumar et al. (2023) explain the issues related to real-time data transmission in isolated forest areas, while Giannakidou et al. (2024) highlight the challenges in maintaining reliable communication networks for IoT-based forest monitoring systems.

• Performance of Algorithms

The accuracy and reliability of models remain a significant challenge. Holzinger et al. (2024) discuss the challenges of developing algorithms that can successfully oversee the dynamic nature of forest ecosystems. Salii et al. (2024) discuss challenges in maintaining prediction accuracy under fluctuating environmental conditions and seasonal changes.

ii. Resource Challenges

• Economic Constraints

Financial considerations significantly impact implementation. Raihan (2023) identifies substantial initial investment requirements as a significant barrier to adoption, particularly in developing regions. Lozinska et al. (2024) emphasize the ongoing costs associated with system maintenance and upgrades.

• Human Resource Development

There is a dire need for more qualified personnel. Chisika et al. (2024) note the shortfall between technical expertise and practical forestry knowledge. Ramos (2024) again mentions the need for ongoing training and knowledge transfer programs.

iii. Operational Challenges

• System Integration

The integration with the existing systems is, however, significantly challenging. Buchelt et al. (2024) discuss the complexities of the incorporation of AI technologies in the traditional forestry management techniques. Zitouni et al. (2024) identify the need to standardize data format and processing methods.

• Environmental Factors

The ambient conditions contribute to large variance in the system's performance. For example, Somwong et al. (2023) presented changes due to weather conditions to sensor reliability, and Bogomolov (2021) discussed issues caused by seasonality of data collection.

iv. Regulatory and Organizational Challenges

• Compliance Requirements

Regulatory frameworks also pose great challenges in implementation. Causevic et al. (2024) present the challenges of data privacy and environmental protection management, while Holzinger et al. (2024) call for standardized protocols that should also meet technical and regulatory requirements.

• Institutional Adaptation

Institutional issues also impact implementation success. Ramos (2024) highlights resistance to technology adoption, whereas Chisika et al. (2024) put a strong case for stakeholder involvement in successful implementation.

Table 7. Challenges of AI applications in forestry.

Challenge Category	Specific Aspects	Key Findings	Citations
Data Quality and Infrastructure	-Sensor coverage limitations - Network reliability - Power management - Data transmission	Remote areas face significant infrastructure limitations affecting data collection consistency and quality. Network reliability presents substantial barriers to real-time monitoring systems.	Borz et al. (2022) Damaševičius et al. (2024) Kumar et al. (2023)
Algorithm Performance	- Model accuracy - Processing requirements -Environmental complexity - Seasonal variations	Complex forest environments challenge model accuracy. Real-time processing demands exceed available computational resources in remote locations.	Holzinger et al. (2024) Salii et al. (2024) Zitouni et al. (2024)
Economic Constraints	- Implementation costs - Maintenance expenses - Technology upgrades - Return on investment	High initial investment requirements present significant adoption barriers, particularly in developing regions. Ongoing maintenance costs affect long-term sustainability.	Raihan (2023) Lozinska et al. (2024)
Human Resource Development	- Technical expertise - Knowledge transfer - Training requirements - Skill gap management	Significant gap exists between technical AI expertise and practical forestry knowledge. Continuous training programs require substantial resource allocation.	Chisika et al. (2024) Ramos (2024)
System Integration	- Technical compatibility - Workflow integration - Data standardization - Interface development	Integration with existing forestry management systems presents significant technical and operational challenges. Standardization issues affect cross-system compatibility.	Buchelt et al. (2024) Zitouni et al. (2024)
Environmental Factors	- Weather impacts - Terrain accessibility - Canopy interference - Seasonal effects	Environmental conditions significantly affect system performance and reliability. Physical access limitations impact maintenance capabilities.	Somwong et al. (2023) Bogomolov (2021)
Regulatory Requirements	- Data privacy -Environmental protection - Cross-border sharing - Compliance protocols	Complex regulatory frameworks require careful consideration in system design and implementation. Privacy concerns affect data collection and sharing capabilities.	Causevic et al. (2024) Holzinger et al. (2024)
Organizational Adaptation	- Technology adoption - Change management - Traditional integration - Strategic planning	Institutional resistance to technology adoption presents significant implementation barriers. Stakeholder engagement crucial for successful implementation.	Ramos (2024) Chisika et al. (2024)
Future Considerations	- Technology evolution	Emerging technologies require scalable and adaptable implementation strategies. Environmental impact	Damaševičius et al. (2024)

	-Scalability requirements -Sustainability needs - Long-term planning	considerations affect long-term sustainability.	Jing et al. (2023)

This comprehensive analysis of technical challenges demonstrates the complex nature of implementing AI systems in forestry applications. Successful implementation requires careful consideration of multiple factors and continued innovation in both technology and methodology.

Açıklamalı [YB2]: Çizelgelerden sonra 12 nk aralık

The following section presents the emerging technologies and the future perspective of AI applications in the forestry sector, as derived from a review of existing scholarly works.

Emerging Technologies and Future Perspectives

Açıklamalı [YB3]: 2. derece alt başlıkların sadece ilk harfi büyük harf olacak

Drawing on a wide-ranging review of the available research literature, the following section outlines emerging technologies and future trends in the area of AI for forestry applications, focusing on major technological developments and their potential impacts on the sector.

i. Digital Twin Technologies

Recent research shows significant developments in the application of digital twins for forest management. Damaševičius et al. (2024) developed an Adaptive Digital Twin model based on Reinforcement Learning, which marks significant improvements in forest monitoring capabilities. Their study demonstrates how digital twins can perform real-time simulations and predictions about the development of forests, thus allowing more accurate management decisions.

Niţa et al. (2021) further illustrate that integrated digital twin technology with mobile LiDAR scanning develops three-dimensional models of forest ecosystems with high accuracy, thus enabling thorough monitoring of the health and growth status of forests while supporting environmentally friendly operations and conserving biodiversity.

ii. Human-Centered AI

The concept of human-centered AI represents a paradigm shift in forestry technology. In Holzinger et al. (2024), the "Forestry 5.0" concept is discussed, emphasizing that human competencies must be combined with AI. Even though AI can process large datasets and identify patterns, this approach emphasizes the human ability to understand and make decisions for successful forestry management.

Building further on this foundation, Chisika et al. (2024) present the role of human-centered AI in enhancing participatory forestry management. Their findings show that if the development of AI systems is made to support, rather than replace, human decision-making, there is significant improvement in community involvement: 90% of stakeholders reported gaining increased confidence in management decisions.

iii. Integrated Sensor Networks

Advances in sensor technology are indicative of bright prospects for future forestry applications. Borz et al. (2022) express that the integration of close-range sensors with AI opens up new avenues for monitoring and managing forests. Their study illustrates the fact that advanced sensor networks can provide a wide range of information on forest health, growth patterns, and potential risks.

Giannakidou et al. (2024) go further to investigate the possibility of integrating IoT technology with AI for higher-order wildfire prevention and detection methods. Their study demonstrates that integrated sensor networks are able to provide early warning systems, besides helping in post-event restoration efforts.

iv. Advanced Imaging and Remote Sensing

The development of AI in forestry depends mainly on the improvement of imaging technology. According to Buchelt et al. (2024), there has been significant progress in the integration of drone-operated imaging systems with AI analysis. Their findings demonstrate how these technologies enable better acquisition of inventory data and timely identification of forest health issues.

Salii et al. (2024) show the potential of genetic algorithms and neural networks in enhancing the analysis of satellite data for the classification of forest conditions. Their work indicates that future developments will lead to even more accurate and automated forest health monitoring systems.

v. Predictive Analytics and Decision Support

Studies show that the role of predictive analytics in forest management is only going to increase. Zitouni et al. (2024) were able to achieve high accuracy in wildfire prediction using spatiotemporal data mining techniques. Their work confirms that future systems will be capable of providing even more accurate predictions about various aspects of forest management.

vi. Sustainable Resource Management

The future trend of AI in forestry indicates much interest in sustainability. Causevic et al. (2024) investigate the capabilities of AI technologies to advance the sustainability of forests through advanced mapping and monitoring capabilities. From their results, it is evident that future AI systems will be crucial in balancing conservation needs with resource use.

vii. Future Considerations

Research points out a set of dynamic challenges that demand attention. Damaševičius et al. (2024) point out scalability issues, since developing technology calls for evolved solutions. Jing et al. (2023) note the importance of developing sustainable implementation strategies with consideration for long-term environmental impact.

Recent work by Holzinger et al. (2024) shows that research in forestry AI is based on human-centered methods aimed at combining technological skills with expert knowledge. In this respect, Ramos (2024) underlines the necessity of formulating standards concerning the gathering and processing of data, especially in territories with restricted technological infrastructure.

Raihan (2023) claims that overcoming such technical challenges requires continued development of hardware and software technologies, along with increased collaboration between forestry experts and developers of AI. As suggested by Chisika et al. (2024), such a collaborative approach would lead to more practical and effective methods of managing forestry.

These developing technologies and future directions demonstrate that forests will be managed and treated very differently than in the past. Indeed, the research trend is toward even more integrated, smart systems with the integration of various technologies by maintaining human supervision and judgment. Successful deployment will demand sustained innovation, collaboration amongst the stakeholder groups, and thoughtful consideration to practical implementation issues.

5. Conclusion

The incorporation of AI in forestry management signifies a revolutionary change in our strategies for forest conservation and the management of resources. Our thorough examination uncovers both the considerable possibilities and intricate difficulties associated with the utilization of AI technologies in forestry operations. As highlighted by recent studies (Holzinger et al., 2024; Causevic et al., 2024), effective implementation necessitates a careful equilibrium between technological potentials and real-world limitations, all while emphasizing sustainable practices.

The development path for AI in the forestry sector will depend on integrated solutions that effectively address several interlinked challenges. Recent studies by Raihan (2023) and Chisika et al. (2024) highlight the need for sound technical infrastructure, improvement in human resource competencies, and comprehensive regulatory frameworks. The integration of AI with other emerging technologies, particularly IoT and big data analytics, might lead to the development of more sophisticated and integrated approaches toward forest management.

Our analysis shows that AI applications efficiently enhance human-machine collaboration, optimize resource allocation, and increase operational efficiency. However, as Zhang and Wang (2023) note, successful integration requires addressing key challenges, including cost considerations, data privacy concerns, and technical infrastructure constraints. The application of AI-based optimization techniques must carefully balance factors such as data quality, model accuracy, and computational requirements. Looking forward, the development of AI in forestry should be prioritised:

- Enhanced integration with complementary technologies for comprehensive forest monitoring and management
- Development of ethical frameworks and regulatory standards for responsible AI deployment
- Investment in human capital development to bridge the technical expertise gap
- Creation of scalable solutions that can adapt to diverse forestry environments

The successful evolution of AI in forestry will depend on fostering more equitable access to these technologies while ensuring their deployment contributes meaningfully to economic sustainability and ecological conservation. This balanced approach will be crucial for realizing AI's full potential in advancing sustainable forest management practices.

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This study declares that AI tools have been used for grammar and translation purposes.

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