Overview of Artificial Intelligence (AI) in Agricultural Farming Systems: Opportunities and Challenges

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https://doi.org/10.62345/jads.2025.14.4.1

Abstract

Artificial intelligence (AI) is revolutionizing the agriculture sector by tackling key challenges such as climate change, resource scarcity, and the necessity for sustainable food production. The incorporation of AI technologies, like machine learning, IoT, and AIoT, offers transformative opportunities to enhance agricultural productivity, efficiency, and sustainability. Precision farming, predictive analytics, and agricultural robotics are examples of AI applications in agriculture that optimize resource utilization, enhance decision-making, and reduce reliance on labor. However, implementing artificial intelligence in agriculture poses several challenges. Issues such as data quality, connectivity, cost, privacy, and user acceptance need to be addressed before AI can fully unlock its potential. Additionally, ethical considerations and trust-building among farmers are crucial for the successful integration of AI technologies. Future research should focus on building advanced AI algorithms, increasing interoperability, and exploring AI's role in climate resilience and resource management. By tackling these challenges, AI can significantly contribute to the resilience and food security of agriculture.

Keywords: Agriculture; Artificial Intelligence; Challenges; Management; Opportunities.

Introduction

Artificial intelligence (AI) is increasingly recognized as a transformative force in agriculture, offering innovative solutions to address the sector's pressing challenges. These challenges include climate change, resource limitations, and the need to ensure food security for a growing global population (Elbasi et al., 2023; Leong et al., 2023; Vocaturo et al., 2023). AI technologies, particularly when integrated with the Internet of Things (IoT), known as AIoT, have the potential to revolutionize agricultural practices by optimizing resource utilization, enhancing production management, and reducing labor dependency (Leong et al., 2023; Adli et al., 2023).

The opportunities presented by AI in agriculture are vast. They include precision farming, predictive analytics, autonomous farming, and improved supply chain efficiency (Leong et al., 2023; Linaza et al., 2021; Misra et al., 2020). AI-driven systems can enhance decision-making by analyzing real-time data, thereby increasing efficiency and productivity (Leong et al., 2023; Elbasi et al., 2023). Moreover, AI applications in agriculture, such as machine learning, expert systems, and image processing, are being used to improve crop, water, and soil management, ultimately boosting yields and reducing environmental impacts (Elbasi et al., 2023; Benos et al., 2021).

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Compliance with ethical standards: There are no conflicts of interest (financial or non-financial). This study did not receive any funding.

However, implementing AI in agriculture is not without its challenges. Issues such as data quality, connectivity, cost, privacy, and user adoption need to be addressed to fully harness AI's potential (Leong et al., 2023; Vocaturo et al., 2023; Gardezi et al., 2023). Additionally, the ethical and practical implications of AI technologies must be considered to build trust among farmers and stakeholders (Gardezi et al., 2023). Future research should focus on developing advanced AI algorithms, promoting interoperability, and exploring AI's role in climate resilience and resource management (Leong et al., 2023; Adli et al, 2023).

AI offers significant opportunities to enhance agricultural productivity and sustainability. Overcoming the associated challenges is crucial for its successful integration into the agricultural sector. By addressing these challenges, AI can play a pivotal role in achieving a resilient and food-secure future.

Artificial Intelligence (AI) Overview

Artificial Intelligence (AI) has emerged as a transformative force in science and engineering, reshaping the relationships among people and organizations and providing a foundation for understanding intelligent behavior in both living and engineered systems (Garg, 2021). At its core, AI is defined as the ability of a system to interpret external data, learn from it, and use those learning's to achieve specific goals through flexible adaptation (Haenlein and Kaplan, 2019). This concept extends to the creation of machines that mimic cognitive functions of the human mind, such as learning and problem-solving (Gursoy and Cai, 2025; Garg, 2021).

The field of AI encompasses a wide range of techniques and approaches, including expert systems, neural networks, fuzzy logic, and more, each contributing to the development of intelligent systems (Garg, 2021; Huang et al., 2022). These technologies have already demonstrated significant impact across industries such as technology, banking, marketing, agriculture, and entertainment, enhancing efficiency and enabling new capabilities (Huang et al., 2022; Oliveira, 2019).

Despite the progress, AI continues to pose challenges, particularly in areas such as data privacy, fairness, and the need for more explainable systems (Jaboob et al., 2024). Ongoing research and development in AI suggest a future in which human and machine capabilities may merge, leading to the concept of transhumanism, in which cybernetic organisms could surpass the capabilities of either humans or machines alone (Garg, 2021).

AI is a rapidly evolving field with the potential to revolutionize numerous aspects of society. Its development is driven by advancements in machine learning, deep learning, and other AI technologies, which promise to enhance human capabilities and transform industries. However, there are challenges that need to be addressed to ensure ethical and fair use.

Applications of Artificial Intelligence (AI) in Agriculture

The integration of Artificial Intelligence (AI) in agriculture represents a transformative shift in how farming practices are conducted, addressing numerous challenges faced by the sector. AI technologies offer flexibility, high performance, accuracy, and cost-effectiveness, which are crucial for tackling issues such as improper soil treatment, disease and pest infestations, and the knowledge gap between farmers and technology (Eli-Chukwu, 2019). The application of AI in agriculture spans various domains, including soil, crop, weed, and disease management, enhancing productivity and sustainability (Eli-Chukwu, 2019; Elbasi et al., 2023).

AI's role in agriculture is not limited to traditional farming practices but extends to precision agriculture, where data-driven approaches optimize inputs for each crop, thereby boosting yields and reducing resource use (Linaza et al., 2021; Berrahal, 2024). The use of AI in the agri-food sector has revolutionized processes by improving efficiency, reducing waste, and enhancing food safety and quality (Taneja et al., 2023). Moreover, AI technologies are pivotal in smart farming, aiding in crop monitoring, predictive analytics, and the development of autonomous agricultural robots (Elbasi et al., 2023; Holzinger et al., 2024).

Despite promising advancements, implementing AI in agriculture faces challenges, including limited replicability and difficulties in systematic data collection due to the unique nature of each field (Linaza et al., 2021). However, the potential benefits, including improved decision support, optimized production, and reduced environmental impact, underscore the importance of continued research and development in this area (Linaza et al., 2021; Khanna et al., 2024). As AI continues to evolve, its integration with other technologies like the Internet of Things (IoT) further enhances its capabilities, paving the way for a more sustainable and efficient agricultural future (Adli et al, 2023).

Crop and Soil Management

The integration of artificial intelligence (AI) in crop and soil management represents a transformative shift in agricultural practices, addressing the pressing challenges of food security, resource optimization, and environmental sustainability. As the global population continues to rise, traditional farming methods are increasingly inadequate to meet the growing demand for food and employment. AI technologies, including machine learning, expert systems, and robotics, offer innovative solutions to enhance agricultural productivity and efficiency (Talaviya et al., 2020; Elbasi et al., 2023; Eli-Chukwu, 2019). These technologies enable precise irrigation, fertilization, and pest control, thereby optimizing resource use and minimizing environmental impact (Linaza et al., 2021; Fuentes-Peñailillo et al., 2024; Liakos et al., 2018).

AI applications in agriculture are diverse, encompassing soil and crop monitoring, predictive analytics, and agricultural robotics. These applications facilitate real-time data collection and analysis, allowing farmers to make informed decisions that improve crop yields and soil health (Benos et al., 2021; Elbasi et al., 2023; Chen et al., 2021). For instance, AI-driven systems can predict crop diseases and optimize water usage, significantly reducing waste and enhancing sustainability (Talaviya et al., 2020; Mishra et al., 2022; Araújo et al., 2023). Moreover, the use of AI in agriculture is not limited to crop management; it extends to soil management, where AI models such as Support Vector Machines and Neural Networks are used for tasks such as classification and forecasting (Chen et al., 2021; Eli-Chukwu, 2019).

The adoption of AI in agriculture is not without challenges, including data variability and the need for systematic data gathering across different fields and conditions. However, ongoing research and technological advancements continue to address these issues, paving the way for more robust and scalable AI solutions in agriculture (Linaza et al., 2021; Fuentes-Peñailillo et al., 2024). As AI technologies evolve, they hold the promise of revolutionizing agricultural practices, ensuring food security, and promoting sustainable farming for future generations.

Disease and Pest Control

The application of artificial intelligence (AI) in disease and pest control is revolutionizing the agricultural sector by enhancing precision, efficiency, and sustainability. AI technologies, such as deep learning and machine learning, are being integrated with Internet of Things (IoT) devices and environmental sensors to create smart agricultural systems capable of real-time pest detection and management. For instance, AIoT-based systems use image recognition and environmental data to accurately identify pests such as Tessaratoma papillosa, achieving identification rates of up to 90% (Chen et al., 2020). This precision enables targeted pesticide application, reducing both environmental impact and labor required for pest control.

Moreover, AI plays a crucial role in combating infectious diseases by accelerating drug discovery and improving diagnostic capabilities. By leveraging systems and synthetic biology, AI enhances our understanding of infection biology and helps control disease outbreaks (Wong et al., 2023). In precision agriculture, AI-driven technologies such as UAV-based remote sensing and optical sensors are being used to monitor and manage plant diseases more effectively. These technologies enable site-specific treatments, contrasting with traditional methods that uniformly treat large areas, thereby optimizing resource use and minimizing environmental damage (Zhu et al., 2024; Mahlein et al., 2024).

AI's integration into integrated pest management (IPM) strategies is also noteworthy. IPM relies on ecological principles and expert decision-making to manage pest populations sustainably. AI can automate routine processes, such as monitoring environmental conditions and pest populations, thereby supporting expert systems in making informed decisions (Demirel and Kumral, 2021). AI offers flexibility, high performance, and cost-effectiveness (Eli-Chukwu, 2019; Anbarasan, 2022).

Weed Management

The application of artificial intelligence (AI) in weed management represents a transformative approach to addressing the challenges posed by traditional agricultural practices. Conventional methods often involve the uniform application of agrochemicals, which can lead to wastage, increased costs, and environmental harm due to the patchy distribution of weeds (Partel et al., 2019). AI technologies, such as machine vision and machine learning, offer precision in identifying and targeting weeds, thereby reducing unnecessary herbicide use and minimizing environmental impact (Partel et al., 2019; Talaviya et al., 2020; Ghatrehsamani et al., 2023).

AI-based systems, including smart sprayers and robotic weed-control systems, have been developed to enhance weed management efficiency. These systems utilize advanced sensors and image processing techniques to distinguish between crops and weeds, enabling targeted treatment applications (Partel et al., 2019; Yu et al., 2024; Rajur and Shivakumar, 2021). The integration of AI in agriculture not only optimizes resource use but also addresses issues such as herbicide resistance by providing alternative, non-chemical weed-control methods (Ghatrehsamani et al., 2023; Yu et al., 2024).

Moreover, AI tools, such as drones and robots equipped with image processing capabilities, are revolutionizing the early detection and management of weeds, thereby improving crop yields and quality (Talaviya et al., 2020; Gupta et al., 2022). These technologies are part of a broader trend towards automation in agriculture, which aims to increase productivity while reducing labor costs and environmental impact (Talaviya et al., 2020; Eli-Chukwu, 2019).

Predictive Analytics

The application of artificial intelligence (AI) in predictive analytics represents a transformative advancement in data-driven decision-making across various sectors. AI technologies, such as natural language processing and deep learning, have significantly enhanced the capabilities of predictive analytics by automating complex data analysis processes and generating accurate predictions with minimal human intervention (Dehankar et al., 2023). This integration allows decision-makers to gain deeper insights into business problems, optimize strategies, and respond swiftly to market dynamics (Dehankar et al., 2023; Okeleke et al., 2024).

In the realm of financial management, AI-driven predictive analytics is revolutionizing forecasting and decision-making by managing vast data volumes, identifying patterns, and producing high-accuracy forecasts (Goel et al., 2023). Similarly, in healthcare, AI enhances market strategy by predicting trends and assessing regulatory impacts, thereby optimizing product positioning and mitigating risks associated with market volatility (Ibikunle et al., 2024). The use of AI in epidemic forecasting, particularly in rural areas, demonstrates its potential to predict outbreaks and optimize resource allocation, offering crucial advantages in underserved regions (Igwama et al., 2024).

Moreover, AI's role in predictive analytics extends to engineering, where it combines machine learning and software engineering processes to improve model development and prediction accuracy (Issaro et al., 2023). In data engineering, AI methodologies have shifted traditional predictive analytics paradigms by enabling systems to autonomously learn and adapt, thus enhancing predictive accuracy and automating feature extraction (Sasmal, 2024).

Overall, integrating AI into predictive analytics not only improves the accuracy and speed of predictions but also addresses challenges such as data quality, privacy concerns, and the need for specialized skills (Okeleke et al., 2024). As AI technologies continue to evolve, their application in predictive analytics will further empower industries to make informed decisions, optimize operations, and drive innovation.

Agricultural Robotics

The application of artificial intelligence (AI) in agricultural robotics is revolutionizing the agricultural sector by addressing the challenges posed by a rapidly growing global population and the increasing demand for food. Traditional farming methods are no longer sufficient to meet these demands, prompting the adoption of AI technologies to enhance agricultural productivity and sustainability. AI applications in agriculture include the use of robots and drones for tasks such as irrigation, weeding, and spraying, which optimize resource use and improve crop yields (Talaviya et al., 2020; Jha et al., 2019; Svetskiy, 2022).

AI technologies, such as machine learning, computer vision, and predictive analytics, are being integrated into agricultural practices to improve decision-making and operational efficiency. These technologies enable precise monitoring of soil and crop conditions, allowing farmers to apply the optimal amount of inputs, thereby boosting yields and reducing environmental impacts such as water use and greenhouse gas emissions (Linaza et al., 2021; Elbasi et al., 2023; Ramachandran et al., 2020). Moreover, AI-driven automation in agriculture helps maintain soil fertility and manage crop diseases, ultimately enhancing the quality and quantity of agricultural output (Jha et al., 2019; Smith, 2020).

The implementation of AI in agriculture also extends to livestock management, where AI systems monitor animal behavior and health, enabling effective management and disease prevention (Svetskiy, 2022; Raikov and Abrosimov, 2022). The use of AI in agriculture not only improves farm efficiency but also supports the development of decision-support systems that aid farmers in making informed choices about crop management and resource allocation (Smith, 2020; Singh et al., 2021).

Livestock Management

The application of artificial intelligence (AI) in livestock management is revolutionizing the agricultural sector by enhancing productivity, improving animal welfare, and optimizing resource use. As demand for meat and dairy products continues to rise, the livestock industry faces challenges such as financial constraints, fewer farms, and the need for more efficient management systems (Michelena et al., 2024). AI technologies, including machine learning, computer vision, and the Internet of Things (IoT), are being integrated into livestock farming to address these challenges by enabling precise monitoring and control of animal health and welfare (Fuentes et al., 2022; Neethirajan, 2023).

AI applications in livestock management encompass a wide range of functions, from automated cattle counting using advanced algorithms such as Mask R-CNN, which achieves high accuracy across diverse environments (Xu et al., 2020), to the use of biometric sensors for assessing animal welfare and affective states (Neethirajan, 2022). These technologies facilitate the collection and analysis of large datasets, allowing for real-time decision-making and improved management practices (Benos et al., 2021; Liakos et al., 2018).

Moreover, AI-driven innovations are transforming livestock export processes by enhancing traceability and monitoring during transportation, thus improving animal welfare and operational efficiency (Neethirajan, 2023). Despite the promising advancements, challenges such as data security, economic feasibility, and ethical considerations remain, necessitating ongoing research and development to fully realize the potential of AI in livestock management (Ghavipanje et al., 2024; Melak et al., 2024).

Postharvest Management

The application of artificial intelligence (AI) in postharvest management has emerged as a transformative approach to addressing challenges in agriculture, particularly by reducing postharvest losses and enhancing food quality. Over the past few decades, significant advancements have been made in integrating AI technologies into postharvest processes, driven by extensive scientific research and technological innovations. The growing body of literature highlights the increasing interest and investment in this field, with countries such as China, the USA, and India leading in research output (Fadiji et al., 2023).

AI technologies, including machine learning frameworks and deep learning models, have been successfully applied to various aspects of postharvest management. These technologies facilitate the analysis of big data, enabling precise quality detection and monitoring of fruits, vegetables, and other agricultural products. For instance, deep learning models such as Convolutional Neural Networks (CNNs) have been employed to detect and predict postharvest deterioration in stored produce, offering a sophisticated means to manage and mitigate postharvest losses (Singh et al., 2022).

The integration of AI into postharvest management aims to reduce losses and enhance the nutritional quality of food, thereby contributing to food security. Current studies identify research gaps and hotspots, providing valuable insights and guidance for future research. This ensures continuous improvement and innovation in the industry (Fadiji et al., 2023). As the global population continues to grow, the role of AI in sustainable agriculture becomes increasingly crucial, offering economically viable, socially responsible, and environmentally sustainable solutions (Singh et al., 2022).

Opportunities of Artificial Intelligence (AI) in Agriculture

The integration of Artificial Intelligence (AI) into agriculture presents a transformative opportunity to address the challenges posed by a rapidly growing global population, climate change, and increasing food demand. AI technologies, including expert systems, machine learning, and computer vision, are revolutionizing traditional farming practices by enhancing productivity, efficiency, and sustainability (Elbasi et al., 2023; Berrahal, 2024). These technologies enable precision agriculture, in which data-driven insights optimize crop management, soil monitoring, and resource use, ultimately boosting yields and reducing environmental impact (Linaza et al., 2021; Liakos et al., 2018).

AI applications in agriculture are diverse, encompassing soil and crop monitoring, predictive analytics, and agricultural robotics. These innovations allow for real-time data collection and analysis, facilitating informed decision-making and efficient farm management (Elbasi et al., 2023; Talaviya et al., 2020). For instance, AI-driven systems can predict crop diseases, manage irrigation, and optimize fertilizer and pesticide use, thereby maintaining soil fertility and improving crop quality (Jha et al., 2019; Talaviya et al., 2020).

Moreover, AI use in agriculture extends to livestock management, where it helps monitor animal welfare and optimize production processes (Liakos et al., 2018; Shaikh et al., 2022). The integration of IoT and big data further enhances these capabilities, providing comprehensive insights into agricultural systems and enabling the development of prescriptive management tools (Misra et al., 2020; Jung et al., 2020).

Challenges of Artificial Intelligence (AI) in Agriculture

The integration of Artificial Intelligence (AI) in agriculture presents a transformative opportunity to enhance productivity, efficiency, and sustainability in farming practices. However, adopting AI in this sector is not without its challenges. One significant hurdle is the low replicability and difficulty in systematic data collection due to the unique characteristics of each agricultural field, which complicate comparisons of pilot experiments across different environments and farming techniques (Linaza et al., 2021). Additionally, the effective implementation of AI requires integrating and visualizing large, multidimensional datasets from diverse sources, a task that remains complex (Williamson et al., 2021).

Moreover, the automation of agricultural practices through AI technologies such as IoT, machine learning, and robotics is essential to address issues like crop diseases, pesticide control, and water management. Yet, these technologies also introduce challenges related to data management and the need for robust systems to handle the vast amounts of data generated (Jha et al., 2019; Elbasi et al., 2023). The convergence of AI with IoT, known as AIoT, further complicates the landscape by introducing new barriers that must be overcome to fully realize the potential of smart agriculture (Adli et al., 2023).

Furthermore, the ethical and social implications of AI in agriculture, such as the potential disruption to traditional farming roles and the need for transparency and accountability in AI decision-making, are critical considerations that must be addressed to build trust among farmers and stakeholders (Gardezi et al., 2023). Despite these challenges, AI continues to offer promising solutions for precision farming, predictive analytics, and agricultural robotics, which are crucial for meeting the growing global food demand amid climate change and resource constraints (Berrahal, 2024; Smith, 2020).

Conclusion

AI is a rapidly evolving field with significant implications for society and various industries. It holds the promise of enhancing human capabilities and transforming how we interact with technology, though it also presents challenges that must be addressed to ensure its responsible and beneficial development. The application of AI in crop and soil management is transforming agriculture by providing innovative solutions to traditional challenges, improving efficiency, and promoting sustainable practices. As AI technologies continue to evolve, they hold the potential to further revolutionize the agricultural sector, ensuring food security and environmental sustainability. AI is transforming disease and pest control in agriculture by providing innovative solutions that enhance precision, reduce environmental impact, and improve overall agricultural productivity. These advancements are crucial for meeting the growing demands of modern agriculture and ensuring food security amid challenges such as climate change and rising pest outbreaks.

The application of AI in weed management offers a promising solution to the limitations of traditional methods, providing precision, efficiency, and sustainability in agricultural practices. This technological advancement is crucial for meeting the growing global food demand while preserving environmental health. The integration of AI in agricultural robotics is transforming the agricultural landscape by improving efficiency, sustainability, and productivity. This technological advancement is crucial for meeting the food security needs of a growing global population while minimizing environmental impacts. AI is playing a crucial role in modernizing livestock management by providing tools that enhance productivity, ensure animal welfare, and support sustainable farming practices. As these technologies continue to evolve, they hold the promise of addressing the complex demands of the livestock industry while contributing to a more sustainable and efficient agricultural sector. AI holds significant promise for revolutionizing agriculture, and overcoming the challenges of data management, system integration, and ethical considerations is essential for its successful implementation and acceptance in the agricultural sector.

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