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THE EMERGENCE OF ARTIFICIAL INTELLIGENCE IN TECHNOLOGY: EVALUATION OF OUTCOMES, CHALLENGES, AND ECONOMIC IMPACTS

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Abstract: Agricultural productivity growth is constrained by several interrelated factors, including the limited availability of arable land, labor shortages, the impacts of climate change, environmental challenges, and the continuous decline in soil fertility. These challenges compel the agricultural sector to continuously adapt and seek innovative solutions. Throughout history, each technological era has introduced new approaches aimed at improving efficiency and optimizing production processes, while in recent years the application of artificial intelligence (AI) has gained increasing significance. Artificial intelligence has emerged as a transformative technology with the potential to revolutionize agricultural practices. AI encompasses a range of technologies, including machine learning, deep learning, computer vision, and robotics, which can be utilized to analyze large–scale datasets, identify patterns, predict outcomes, and automate complex processes. AI–driven models can provide precise, data–driven insights that support optimal decision–making, thereby enabling farmers to maximize yields while minimizing input requirements and reducing environmental impacts. However, proponents of advanced technological approaches argue that neither individual farmers nor large–scale agricultural enterprises currently exploit the full potential offered by artificial intelligence in agricultural practice. Although numerous scientific studies and professional publications address the application of AI in agriculture, most focus only on specific subfields of AI and frequently present generalized conclusions. The aim of the present study is therefore to collect and systematically organize the knowledge derived from the practical application of artificial intelligence in agriculture, with particular emphasis on experiences and solutions that have already been implemented in everyday agricultural practice.

Keywords: artificial intelligence in agriculture, benefits and challenges of AI, role of AI in agricultural technology

1. INTRODUCTION

Economic Impacts of Artificial Intelligence in Agriculture

The economic benefits of artificial intelligence in agriculture are multifaceted, encompassing cost reduction, increased crop yields, and enhanced market competitiveness. AI-driven solutions can significantly reduce operational costs by optimizing the use of inputs such as water, fertilizers, and pesticides. Precision agriculture technologies enable farmers to apply these inputs more efficiently, resulting in substantial cost savings. By optimizing irrigation scheduling through artificial intelligence, farmers can reduce water consumption by up to 40%, leading to considerable savings in water-related expenditures [1].

Artificial intelligence algorithms can also recommend the optimal quantities of fertilizers and pesticides to be applied, thereby reducing input costs while maintaining or improving crop health. The increased efficiency and precision provided by AI technologies also contribute to higher agricultural yields [5].

By providing real-time data on soil conditions, weather forecasts, and crop health, artificial intelligence enables farmers to make informed decisions that enhance productivity. For example, AI models can predict optimal planting and harvesting periods based on meteorological data, ensuring that crops are cultivated and harvested under the most favorable conditions. This may result in yield increases of up to 30%, as demonstrated by several precision farming initiatives [3].

In addition to reducing costs and increasing yields, artificial intelligence can improve market competitiveness by enhancing supply chain efficiency and reducing post-harvest losses. AI algorithms are capable of analyzing market trends and consumer demand in order to optimize the distribution of agricultural products, ensuring timely delivery to consumers. This reduces the risk of spoilage and waste, particularly in the case of perishable products such as fruits and vegetables [8].

Challenges of Implementing Artificial Intelligence in Agriculture

Despite the promising opportunities offered by artificial intelligence for transforming agriculture, several challenges and barriers must be addressed to ensure its widespread adoption. Technical

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challenges include the need for high-quality data, the complexity of agricultural environments, and the integration of AI technologies into existing agricultural systems. High-quality datasets are essential for training accurate artificial intelligence models; however, acquiring such data can be difficult due to the variability of soil types, weather conditions, and crop varieties [2].

Socioeconomic barriers include the high initial investment costs associated with artificial intelligence technologies, limited access to technological infrastructure, and the lack of technical expertise among farmers. The substantial cost of AI-driven equipment and infrastructure may be prohibitive for small-scale farmers, who often operate under constrained financial conditions. Furthermore, the limited level of technical expertise among agricultural producers hinders AI adoption, as many farmers may lack the necessary skills and knowledge required to implement and maintain these technologies effectively [4].

Ethical considerations also play a critical role in the agricultural implementation of artificial intelligence. Issues such as data privacy, algorithmic bias, and the potential impact on employment require careful evaluation. Concerns regarding data privacy arise from the collection and utilization of large volumes of agricultural operational data, which may contain sensitive information [6].

The impact of artificial intelligence on agricultural employment must also be considered. Although AI technologies can increase productivity and reduce labor costs, they may simultaneously displace certain categories of jobs, particularly those involving manual labor. Therefore, the successful implementation of artificial intelligence in agriculture requires ensuring that displaced workers are provided with opportunities for retraining and integration into new forms of employment [7].

2. METHODOLOGY

This study employs a mixed-methods research approach that combines qualitative and quantitative data analysis to assess the impact of artificial intelligence on sustainable agriculture. The research provides a comprehensive review of existing literature, case studies, and empirical data derived from AI-driven agricultural projects. Scientific publications were collected from major academic databases, including Google Scholar and ResearchGate, as well as from relevant industry reports and conference proceedings.

In addition, the study incorporates the perspectives of professionals and researchers working in this field and applies analytical models to evaluate the collected data and derive meaningful conclusions regarding the environmental and economic benefits of artificial intelligence in agriculture.

3. RESULTS

Automated Agriculture

Automated agriculture is based on the application of artificial intelligence and various sensor technologies in order to improve the efficiency of crop production and livestock farming while reducing the need for human intervention in agricultural processes. In contrast to traditional farming methods, these systems rely on intelligent technologies capable of autonomous operation based on real-time data provided by sensors, cameras, and environmental monitoring devices.

Figure 1. Greenhouse Robot During Operation

Automated agriculture plays a significant role in increasing both production efficiency and sustainability. Its implementation enables farmers to address labor shortages more effectively, reduce operational costs, and enhance productivity. Furthermore, the targeted and optimized use of resources such as water, fertilizers, and pesticides contributes to the reduction of environmental impacts. The application of intelligent technologies also supports stable crop yields and the production of higher-quality agricultural products, thereby strengthening global food security and improving resilience to climate change over the long term.

Data-Driven Decision-Making

In the modern world, virtually all processes are driven by data. With the support of artificial intelligence, farmers can collect and process substantially larger volumes of data in significantly less time. Organizations operating within the agricultural sector utilize these data to obtain detailed insights into every aspect of agricultural operations, ranging from comprehensive product traceability throughout the supply chain to in-depth analyses of crop yield and production processes. Artificial intelligence has emerged as a transformative technology with the potential to revolutionize agricultural practices. AI encompasses a wide range of technologies, including machine learning, deep learning, computer vision, and robotics, which can be applied to analyze massive datasets, identify hidden patterns, predict outcomes, and automate complex processes.

Figure 2. Data Collection Using Artificial Intelligence

The Role of Artificial Intelligence in Crop Production Technology

Traditional agriculture involves numerous manual processes. The introduction of AI models in this context can provide a wide range of advantages. When integrated with existing technologies, intelligent agricultural systems are capable of significantly facilitating various operational tasks.

- *Soil condition sensing:* Artificial intelligence in agriculture can support the assessment of soil health, the monitoring of weather conditions, and the recommendation of appropriate fertilizer and pesticide applications. IoT sensor networks, including ground-based robots equipped with soil probes, moisture sensors, and cameras, generate detailed field-level data models. Based on these models, irrigation, fertilization, and pesticide application can be adapted to the micro-level conditions of different field zones.

AI-powered soil monitoring systems provide real-time information on soil moisture, nutrient levels, pH values, and other critical parameters, enabling immediate insights for more efficient soil management. In contrast to traditional monitoring methods, which are often time-consuming and less accurate, AI-based solutions deliver faster and more precise results, reduce operational costs, and promote sustainable agricultural practices.

Figure 3. Ultimate Guide to AI–Powered Soil Monitoring

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— *Tillage:* The tractor is capable of generating high torque at low speeds, enabling efficient execution of tillage operations. It is programmed to independently monitor its position, determine appropriate operating speed, and avoid obstacles, including humans and animals. Compared to conventional technologies, this system can increase field productivity by approximately 30% while reducing fuel consumption by nearly 10%. The figure 4 shows the Case IH Magnum Self-Driving Tractor with a seed drill in the field, figure 5 shows the artificial intelligence-controlled agricultural robot developed for crop care tasks.

Figure 4. Driverless tractor

Figure 5. AI–controlled soil cultivation robot

In precision tillage operations, AI-assisted machinery performs shallow or deep tillage only where it is necessary. Convolutional neural networks (CNNs) can analyze camera-captured imagery and sensor data to determine the optimal tillage intensity, thereby reducing excessive soil disturbance and mitigating soil erosion. When combined with satellite data, sensors, and robotics, AI optimizes tractor guidance, improves seedbed quality, and reduces fuel consumption.

— *Nutrient management*: AI-driven precision fertilizer applicators are capable of evaluating variable-rate application efficiency and uniformity. They incorporate soil conditions, machine speed, and real-time data from GPS and sensor systems to control fertilizer distribution systems, resulting in more accurate nutrient management. AI-based software solutions, such as Borealis NutriGuide, in cooperation with agronomic expertise, support the precise planning of crop nutrient requirements. In addition, researchers increasingly use artificial intelligence to analyze satellite imagery of agricultural fields, and the derived data are applied to optimize nutrient management strategies. A representative system is the Amazone AutoSpread, a radar- and artificial intelligence-based, self-regulating fertilizer spreading system (Figure 6). The ZA-TS 01 AutoSpread is a self-adjusting twin-disc centrifugal spreader that first measures the actual spreading pattern, including both spreading direction and distribution range, and then automatically calibrates the spreader settings accordingly.

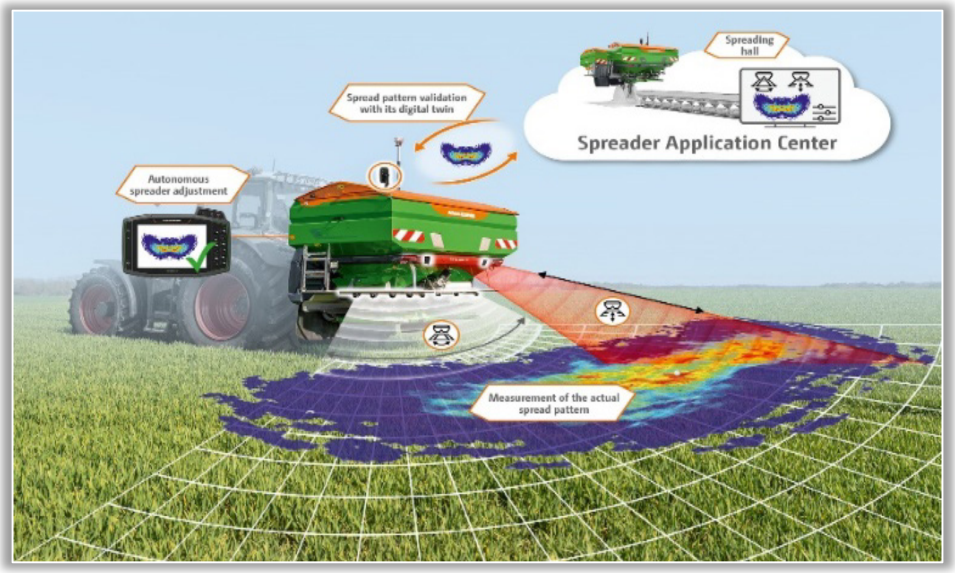

Figure 6. AI–controlled fertilizer spreading system

— *AI-assisted sowing:* During sowing operations, AI analyzes soil nutrient and moisture levels in order to automatically adjust seeding rates across different field zones, maximizing productive potential in each soil area. Autonomous robots and AI-driven seeding machines use computer vision to place seeds at precisely calculated depths and spacing. This approach can reduce sowing costs by up to 85%, and some systems are capable of injecting seeds together with nutrient-containing capsules directly into the soil. The figure 7 presents the FarmDroid FD20 large-scale seeding machine. This is the world's first fully autonomous, solar-powered agricultural robot, capable of performing both seeding and mechanical weed control simultaneously. The figure 8 shows the RoamIO-HCT small-scale tracked agricultural robot.

Figure 7. Large–scale AI seeding machine

Figure 8. Small–scale tracked AI seeding machine

— *Role in plant protection.* Advances in technology have enabled the development of autonomous agricultural robots capable of mechanically removing weeds or performing targeted spraying. Computer vision-enabled robots can accurately identify and target weeds, reducing herbicide use by up to 90% compared to conventional broadcast spraying methods, while improving germination rates.

Figure 9. AI–equipped spraying robot

Figure 10. AI–assisted drone spraying system

Spraying drones are lightweight, rapidly deployable aerial systems with relatively low investment costs. Their key advantage is that their operation is not constrained by soil conditions, crop height, or terrain characteristics, making them suitable for a wide range of agricultural environments. These drones use computer vision to determine the required amount of pesticide to be applied to specific areas. Figure 9 shows a laser spraying robot equipped with artificial intelligence, and Figure 10 shows drone-based spraying controlled by artificial intelligence in practice.

— *Optimization of automated irrigation systems:* Sensors installed in the soil, near plants, or within irrigation systems continuously measure soil moisture, temperature, air humidity, and crop water demand. The collected data are processed by AI algorithms and combined with weather forecasts, soil characteristics, and crop-specific requirements. Based on this analysis, AI systems can automatically determine when, how much, and where water should be applied. This helps prevent both over-irrigation and under-irrigation, resulting in significantly more efficient water usage. Figure 11 shows an intelligent irrigation system in

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operation, equipped with a digital monitoring interface, displaying water consumption data in a modern crop production environment.

Figure 11. AI–powered irrigation system

— *Role in the harvest:* Hyperspectral imaging is capable of detecting sweetness levels in fruits. This enables the selective harvesting of only premium-quality produce while minimizing premature harvesting and associated losses. Artificial intelligence-driven autonomous or drone-based robotic systems can identify, locate, and pick ripe fruits.

These systems commonly employ “eye-in-hand” camera configurations to estimate the 6D pose of fruits, enabling precise, damage-free, and fully autonomous harvesting operations (Figure 12). In the case of field crops, artificial intelligence is transforming combine harvesting by converting traditional harvesting processes into precision-based, self-optimizing, partially or fully autonomous systems. AI applications in combine harvesters primarily focus on improving efficiency and minimizing grain loss. AI-based optimization enables modern combines to analyze crop conditions in real time—such as moisture content, density, and contamination—as well as harvesting data, and automatically adjust drum speed, sieve openings, and fan speed to achieve optimal output quality. To minimize grain loss, camera-based AI systems continuously monitor the area behind the combine and detect excessive grain loss; if such conditions occur, the system immediately adjusts machine speed or operational parameters. Figure 13 shows a John Deere combine equipped with on-board robotics and artificial intelligence.

Figure 12. Fruit harvesting robot

Figure 13. AI–controlled combine harvester

4. CONCLUSIONS

The application of artificial intelligence in agriculture has clearly become one of the most important development directions in modern crop production technology. Based on the results of this study, it can be concluded that AI-based systems significantly contribute to increasing production efficiency, optimizing the use of input materials, and reducing environmental impacts. Automated agricultural technologies are capable of real-time data processing and decision support, enabling more precise and faster interventions throughout cultivation processes.

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Artificial intelligence plays a particularly important role in the advancement of precision agriculture, as it enables site-specific operations. The analysis indicates that the application of AI can lead to substantial cost reductions through the optimization of water, fertilizer, pesticide, and labor usage. Intelligent irrigation systems, variable-rate nutrient application, and automated crop protection solutions all contribute to more sustainable resource utilization. In addition, AI-based systems improve crop yields and product quality while reducing production losses.

The study also shows that artificial intelligence provides not only technological but also significant economic advantages for agricultural enterprises. Although initial investment costs may be considerable, long-term operational savings and increasing profitability can offset these expenditures. AI-based systems are particularly effective in addressing labor shortages, as many repetitive and labor-intensive tasks can be automated. The continuous operation of robotic and autonomous agricultural machinery further enhances productivity.

At the same time, the application of artificial intelligence raises several challenges. One of the most important issues is the high cost of technological investment, which may represent a barrier, particularly for small-scale farms. In addition, the availability of sufficiently high-quality and large-scale data is a fundamental requirement for the effective operation of AI systems. The study also highlights that farmers' technological preparedness and digital competencies play a key role in the successful adoption of AI. Therefore, the implementation of these technologies also requires educational and training programs. Ethical and social issues are also critical factors in the widespread adoption of artificial intelligence in agriculture. Data security, the transparency of algorithmic decision-making, and labor market impacts will remain important long-term challenges. As a consequence of automation, certain traditional agricultural occupations may decline, making it essential to provide adequate retraining and reskilling opportunities.

It is clear that artificial intelligence has significant potential in improving the sustainability and competitiveness of agriculture. In the future agricultural sector, autonomous systems, machine learning, and data-driven decision-making are expected to play an increasingly important role. However, a successful transition can only be achieved if technological development is accompanied by appropriate professional expertise, infrastructure, and economic support.

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