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Artificial intelligence in agriculture: Advancing crop productivity and sustainability

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ABSTRACT

The challenges posed by both climate change and population expansion are unlike anything agriculture has ever seen, and in order to sustain and boost agricultural output, new and creative technology must be used. Artificial intelligence (AI) is one such exponent of change that offers possible solutions in a number of agricultural production fields. Emphasis will be placed on robotic automation, machine learning applications, and the concept of precision farming. This research explores how integration in agriculture has made AI an excellent support for decision processes in crop management, providing real-time monitoring and predictive analytics. Higher agricultural yields and resilience are made possible by genetic advancements and AI in resource optimization. However, due to technological, societal, and legal obstacles, the promise for AI in agriculture has not yet materialized. Against this background, this study requires holistic policy frameworks, education, and stakeholder engagement as countermeasures to such challenges. The future potential applications of AI in agriculture continue to change the sector on behalf of improving global food security and sustainability; this concludes the study. This paper tries to bring to light the critical role that AI is most likely to play in shaping future agricultural practices based on an in-depth analysis of the current state of technology and upcoming opportunities.

1. Introduction

The rapid growth of the global population, expected to reach 10 billion by 2050, presents unprecedented pressure on agriculture to sustainably increase production [1]. With the added challenges of dwindling water resources, shifting climate patterns, and the loss of agricultural land, there is an urgent need for innovative solutions to boost farm productivity and efficiency. Among the most promising of these solutions is Artificial Intelligence (AI), which has the potential to revolutionize agricultural practices worldwide [2]. AI gives new meaning to modern agriculture and, in particular, precision farming, in developing integrated farm management. Drones, robots, and automated monitoring systems are significant components of agricultural innovation Fig. 1. For instance, drones can be used in locations for real-time monitoring by capturing aerial data to assess crop health and detect diseases, enabling the optimization of field management [3]. Precision farming, therefore, is supported by these technologies by providing accurate data based on which informed decisions can be made regarding irrigation, fertilization, and pest control. Robots help in efficient labor by automating large tasks such as sowing, weeding, and harvesting, thus reducing reliance on manual labor [4] (see Table 1).

AI further supports the analysis and maintenance of key environmental variables such as soil pH [5,6], ambient temperature [7,8], and rainfall [9,10]. Predictive models using AI highlight trends in weather patterns that enable farmers to take necessary actions and reduce the negative consequences of extreme weather conditions. Continuous monitoring of soil health and environmental parameters creates an ideal environment for crop growth and enhances productivity towards sustainability. Large datasets are then analyzed further using machine learning models, which also enable real-time decision-making, thereby

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fostering a shift toward more efficient and sustainable farming practices [11]. The integration of AI into agriculture offers enormous opportunities for better resource use, waste reduction, and environmental sustainability. Beyond mere automation of agriculture, it involves several technologies to make farming intelligent, accurate, and productive [12–14].

These technologies will help fully control the production settings and results because they go beyond the optimization of existing techniques. For example, AI-driven precision agriculture determines the best possible conditions for planting, watering, and harvesting schedules based on information received from satellite imagery and IoT sensors [15,16]. Machine-learning algorithms identify plant diseases before they turn up in plain human vision and estimate crop yields with an astounding degree of precision [17,18]. However, there are many societal, technological, and financial barriers to full-scale application of AI in agriculture. AI is a key factor in future agricultural practices because of its potential to increase production, sustainability, and profitability despite existing obstacles [19,20].

Our proposed work makes the following important contributions:

- Provide a comprehensive review of the current state of AI technologies in agriculture, covering their key applications in precision farming, crop management, and sustainability.
- Analyze the benefits of AI in enhancing productivity, resource efficiency, and environmental sustainability, while also addressing the technological, societal, and financial challenges hindering its widespread adoption.
- Highlights the practical implications of AI technologies for real-world agricultural systems, demonstrating how they can be integrated to optimize farming practices.

Table 1
Comprehensive overview of AI applications and impact in agriculture.

Section	Key Concepts & Applications	Data & Case Studies
AI in Agriculture	Precision farming via GPS and IoT sensors. Machine learning for yield prediction. Robotics for automation.	IoT sensors monitor soil moisture and nutrient levels. Drones detect plant diseases in early stages.
Enhancing Crop Productivity with AI	Genetic modification for pest and disease resistance. Resource optimization for water and fertilizers.	AI identified genes for drought tolerance, aiding in creating resilient crops. AI systems in California vineyards led to a 25 % increase in yield and 20 % water savings.
Barriers to Adoption	High costs and infrastructural demands. Resistance from farmers, training needs. Regulatory and data privacy concerns.	Example of connectivity issues in rural areas impeding AI adoption.
Future Perspectives	Development of smart seeds. Integration with blockchain for transparency. Advanced robotic systems.	Predicted enhancements in real-time crop monitoring and efficient harvesting techniques.
Conclusion	AI as a transformative force for sustainable agriculture. Need for collaborative efforts among all stakeholders.	Emphasis on balancing productivity with sustainability to ensure long-term agricultural success.

- Proposed a roadmap for further development and scaling of AI technologies, focusing on their integration into global agricultural practices to meet future food security and sustainability challenges.
- By synthesizing key trends and challenges, we offer actionable insights for policymakers, technology developers, and agricultural stakeholders to drive the effective adoption of AI in agriculture.

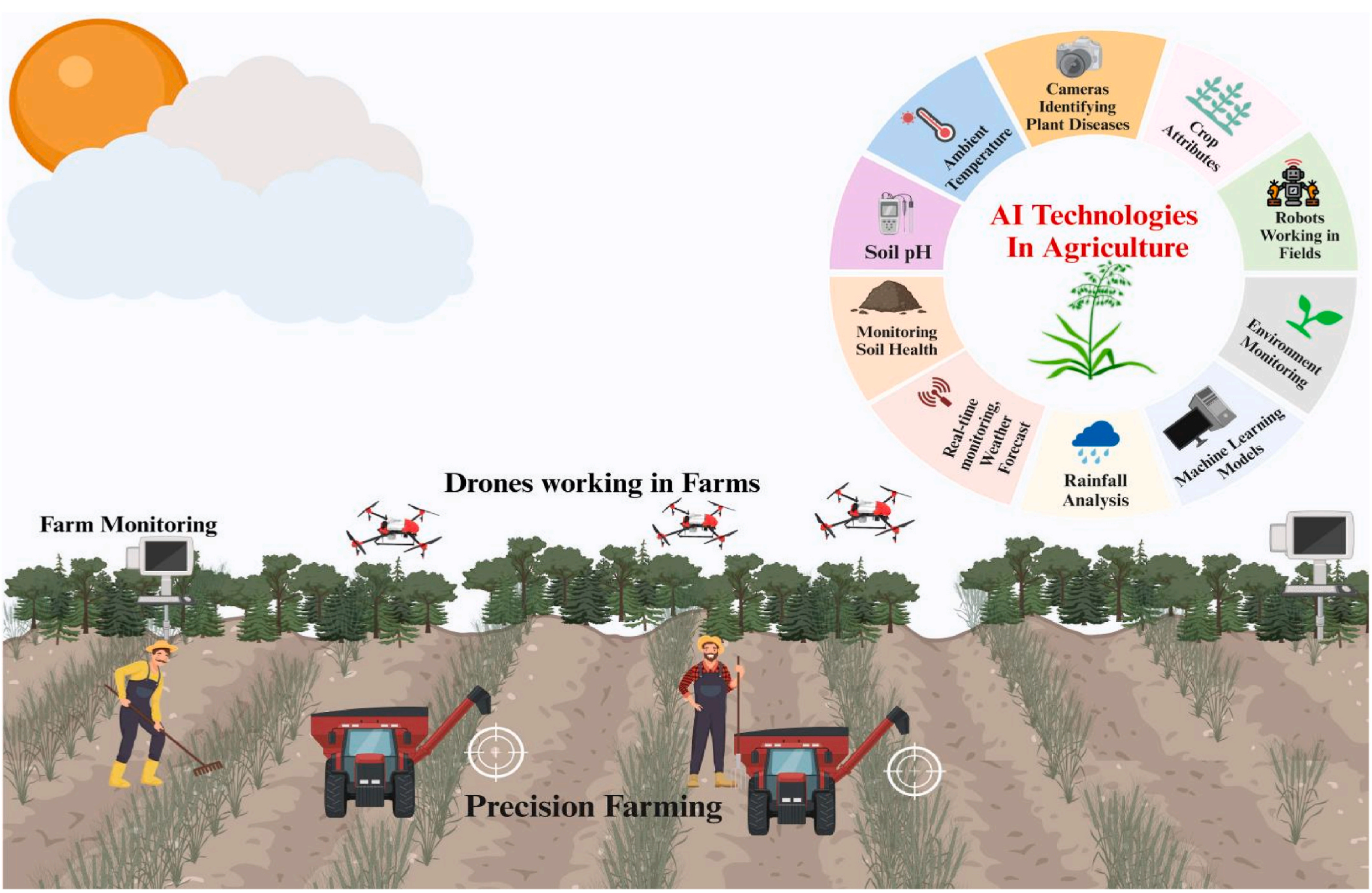

Fig. 1. Visual Representation of AI integration in agriculture: Monitoring, analysis, and precision farming.

The remainder of this paper is organized as follows: Section 2 provides an overview of AI in agriculture, focusing on precision farming, machine learning models, and the role of robotics in enhancing agricultural practices. Section 3 explores the impact of AI on crop productivity, covering AI-driven genetic modification, optimization of resource usage, and presenting case studies of successful AI integration in agricultural systems. Section 4 discusses various barriers to the widespread adoption of AI, including technological challenges, sociocultural factors, economic implications, and ethical concerns. Section 5 presents future perspectives on the advancement of AI technologies, emphasizing the importance of educational initiatives, collaboration among stakeholders, and the long-term impact of AI on global food security. Finally, Section 6 concludes the study, summarizing key findings and insights.

2. AI in agriculture

AI is changing the face of agriculture from environmental effect forecasts to efficient resource use and crop management. This section reviews three critical AI applications in agriculture for enhancing production and sustainability: agricultural robotics, machine learning, and precision farming Fig. 2.

2.1. Precision farming

Precision farming is one of the most prominent applications of AI, which was developed with an enhanced version of accuracy and control over agricultural techniques [21]. Abundant data have been collected from agricultural environments using GPS and IoT devices for precision farming [22]. This dataset was used to obtain the temperature, crop health, fertilizer availability, and soil moisture levels. AI algorithms assess these data to provide relevant and helpful recommendations to farmers regarding the sowing, irrigation, and harvesting of crops. AI-powered systems can recommend the optimum quantity of water and fertilizer to be treated on each field, reduce waste, and ensure proper crop development [16,23].

Fig. 3 shows the various key components and outcomes of these advanced agricultural practices. The core of precision farming is that it provides for the collection of data in real time through GPS and IoT devices for constant monitoring of key factors: soil condition, weather pattern, and health of the crop [24,25]. These real-time data form the backbone of AI algorithms that support decisions on variable resource applications, including the optimization of water, fertilizer, and pesticide applications. Among the key benefits identified from the figure is an overall reduction in the operational cost through the application of inputs only where and when they are required. This reduces waste and increases resource use efficiency.

Precision farming also seeks to protect vital resources, such as groundwater, by ensuring that the use of agriculture has minimal impact on water tables and ecosystems [26]. The figure points to the role of genomics and genetic modification in improving crop varieties, a role that supplements high-tech approaches to precision farming with enhancement in the resilience and productivity of crops. Such a combination, if based on advanced agricultural technology and elaborate data analysis, cannot enhance crop production. This means that the positive trends in increased yield with precision farming go hand in hand with sustainable agriculture [27]. These techniques minimize waste, preserve resources, and apply inputs in a more focused manner. These are again in line with the grand objective of contemporary agriculture, striking a proper balance between increasing food supplies and reducing environmental degradation.

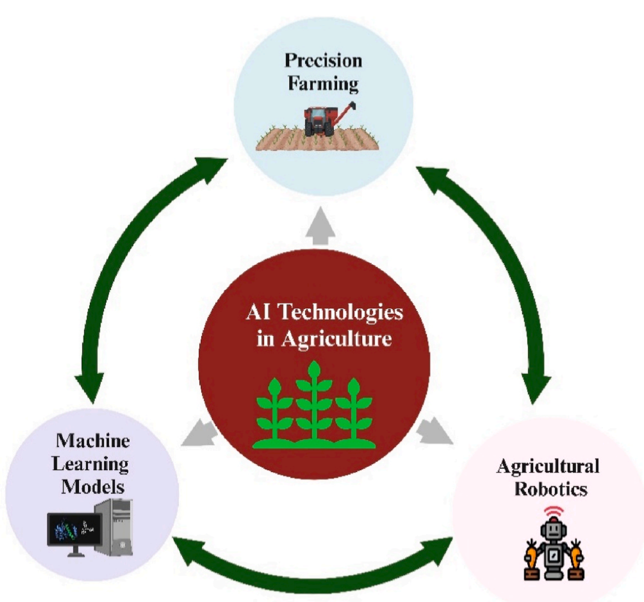

Fig. 2. Schematic Representation of AI-Driven technologies in modern agriculture.

2.2. Machine learning models

Models developed using ML represent an enormous step ahead in agricultural innovation, with wide-ranging functionalities in predictive analytics, disease identification, and pest management [28,29]. These models can predict agricultural output through the analysis of both historical and contemporary datasets. This analysis helps farmers to enhance their planning strategies and risk profiling associated with unpredictable weather conditions. Moreover, machine learning algorithms can detect trends indicative of illness or vermin, thereby triggering early intervention measures. For instance, image recognition software might look for anomalies in photographs of crops taken either from in-field cameras or drones to identify nutritional deficits or diseases [30].

In addition to predictive analytics and disease management, resource optimization can also be achieved using machine-learning models. These will go on to make full precision in irrigation and the application of fertilizers for better efficiency and sustainability, based on analyses of varied conditions of soil type, moisture content, and nutrient status. Furthermore, machine learning algorithms in concert with automated systems using drones or robotic machinery can accomplish focused interventions in real-time [31]. With the exponential growth of agricultural data, machine learning models are becoming increasingly important in the processing of data and actionable insights derived to improve crop yields and operational costs, including supporting sustainable agriculture.

2.3. Agricultural robotics

Agricultural robotics automates labor-intensive operations, reduces the involvement of human resource elements, and increases the operational efficiency [32,33]. AI-capable robots are being utilized in various applications such as harvesting and weeding seeds [34]. These autonomous machines can perform field navigation with a high degree of accuracy and operate 24 h a day under various weather conditions [34]. Besides speeding up agricultural processes, robotics also minimizes human error and increases the overall quality standards of agricultural produce [4]. For example, robotic harvesters may be programmed to pick ripe fruits only, guaranteeing homogeneous product quality and simultaneously reducing waste [35,36]. These AI are making changes in farming by establishing more intelligent, accurate, and productive agricultural activities with less use of resources. Increasingly, food production has undergone a facelift with such developments. A new revolution in agriculture worldwide is likely to be kick-started by the efficiency and productivity that the integration of these technologies

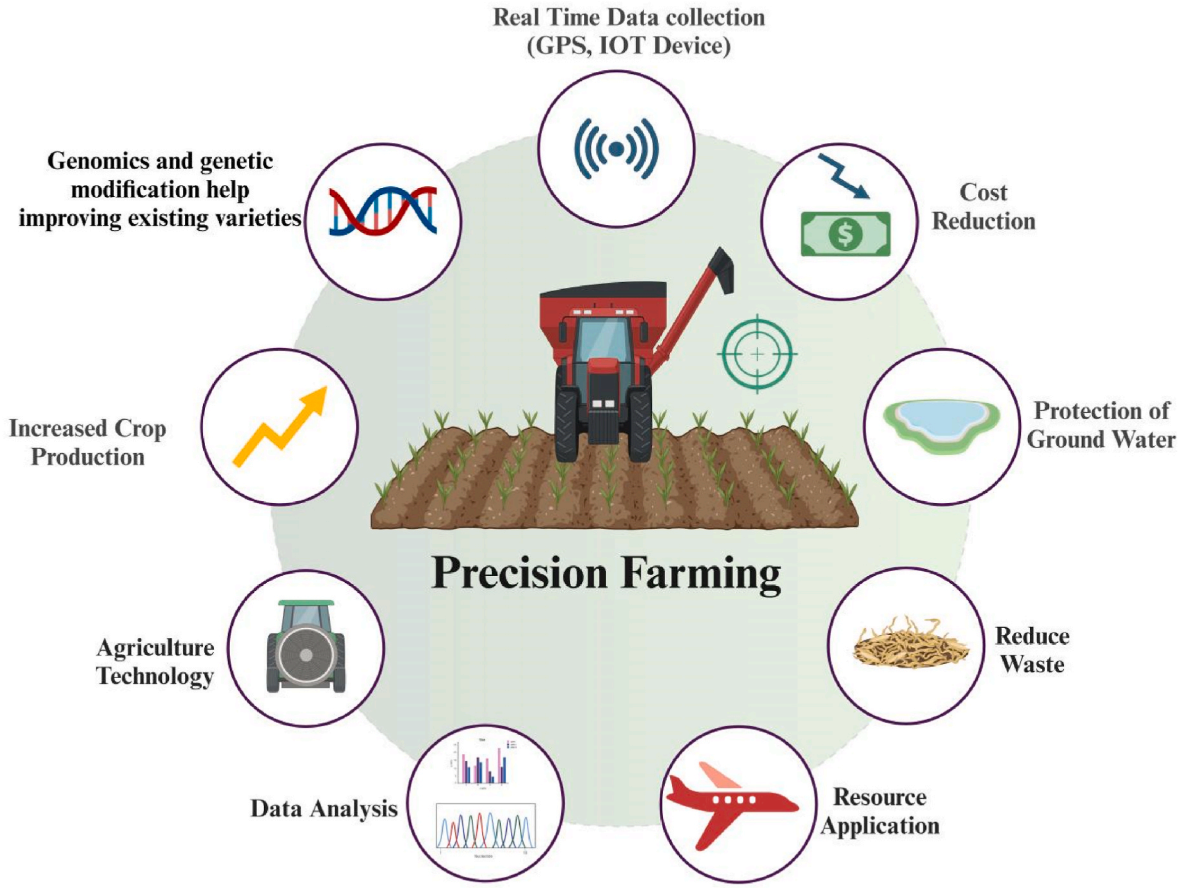

Fig. 3. Components and benefits of precision farming: Leveraging real-time data and genomics for sustainable agriculture.

into standard farming practices is likely to yield with maturation and advancement.

Moreover, scalability in agricultural robotics will continue to enable efficient large-scale farming, in which such machines will be able to monitor and manage vast areas with minimal human intervention. The integration of AI with robotics into precision agriculture creates smart farming ecosystems, where autonomous robots work with other technologies, including drones and sensors, to monitor crop health, evaluate soil conditions, and act in precise interventions. In this holistic approach, productivity increases while labor shortages are alleviated, especially in regions where agricultural workers are scarce [37]. With ongoing technological advancement in the future, there will be a reduction in the carbon footprint from farming, with energy usage well optimized or waste eliminated for farming methods with low environmental impacts. Most likely, the future of farming relies heavily on the further development and integration of such AI-driven robotic systems.

3. Enhancing crop productivity with AI

AI is a key factor that influences future agricultural productivity is AI. This can significantly improve farming efficiency. In this regard, the mechanisms through which AI results in genetic improvement, efficient use of resources, and practical applications help to increase crop yields and further enhance resistance.

3.1. AI-driven genetic modification and breeding

AI is an important aspect of crop breeding and genetic modification, because it can develop crops that can sustain various diseases, pests, and environmental extremes [38,39]. Analysis of large databases of genetic information and interactions with the environment will enable AI systems to predict the likeliest changes to succeed in crop production [40]. This will hasten the breeding process and enhance the possibility of viable crops. Such techniques using AI (AI) can help identify the genes responsible for drought resistance and support crop engineering in areas formerly unsuitable for agriculture, thereby improving agricultural productivity [41].

In addition to drought resistance, AI-based genetic analysis can also identify other desirable attributes, such as enhanced nutrition, faster growth rates, and reduced requirements for chemical inputs, such as pesticides and fertilizers. Hence, new hope is emerging for the development of more sustainable and nutritious crops adapted to variable conditions. Coupling AI with gene editing technologies, including CRISPR-in crops, enables the development of resilient and in-demand foods worldwide [42]. It will be feasible to grow high-yielding climate-resilient crops in areas that are usually not conducive for farming or have otherwise been inefficient, further driving global food security.

3.2. Optimizing resource use

AI has been influential in the agricultural sector, especially in terms of increasing the efficiency of resource use, including water, fertilizers, and pesticides. Such AI systems leverage data obtained from indicators of crop health, meteorological predictions, and soil sensors to determine application timing and quantity [23,43]. It is through such a meticulous approach to farming that crop health and yield are maximized at the same time as the minimization of waste and environmental impacts. For instance, AI-powered irrigation systems can automatically adjust the quantity of water supplied to crops according to the relative moisture in the soil to ensure that crops obtain the exact amount of moisture required for healthy growth [44].

More importantly, AI-driven systems ensure far more precise application of fertilizers and pesticides, further reducing the likelihood of overuse, which often results in soil degradation and water pollution. With current levels of soil nutrients and infestations from pests, for instance, AI can recommend exactly how much input is needed in each section in a given field to enhance efficiency in resource use. This narrowcasting not only saves precious resources, but also makes farming more sustainable to keep the ecological footprint as low as possible. As these technologies continue to improve, AI systems will likely further refine the balance between optimizing productivity and environmental care in agriculture and contribute to the long-term sustainability of global food production [45].

3.3. Case studies: successful AI integration

Various case studies have explained how AI can be successfully integrated to increase agricultural productivity. One of the most telling examples is provided by an experiment conducted in California that used AI to manage nitrogen and irrigation applications in growing grapes. The move resulted in a 25 % increase in production while using 20 % fewer water resources [46]. Another example of the use of AI in India has been in predicting the best planting times and crops to grow based on market demand and weather patterns, which has significantly improved crop yields and farmers' incomes [47,48]. Such tangible examples demonstrate the power of AI in promoting agriculture and further prove its potential to transform traditional farming methods into more profitable, sustainable, and effective operations. In the coming years, through the development and application of AI in agriculture, it will be possible to meet the global food demand continuously on the rise, while maintaining both environmental sustainability and farmers' economic viability on a global scale.

Case study 1: John Deere [49,50], a global leader in agricultural equipment, has integrated AI and machine learning into its precision farming solutions. The company has developed autonomous tractors and combine harvesters equipped with sensors that collect real-time data on soil conditions, crop health, and field conditions. These machines use machine learning algorithms to analyze this data, enabling farmers to make data-driven decisions on irrigation, fertilization, and pesticide applications. This technology reduces resource waste, improves yields, and minimizes environmental impact.

Impact: John Deere's AI-powered equipment has helped farmers increase crop yields while reducing costs and environmental damage. The use of precision farming also enhances operational efficiency and supports sustainable agricultural practices.

Case study 2: Plantix is a mobile app developed by AgriTech startup PEAT to help farmers detect crop diseases [51]. The app uses AI and image recognition to diagnose diseases based on photos taken by farmers with their smartphones. Plantix's machine learning models analyze the images, identifying diseases, pests, or nutrient deficiencies and providing treatment recommendations [52].

Impact: Plantix has helped smallholder farmers in India and other developing countries increase crop yields by enabling early detection and treatment of diseases, reducing the need for costly chemical interventions and improving food security.

Case study 3: The Climate Corporation, a subsidiary of Bayer, uses AI to help farmers optimize irrigation [53]. Through its Climate FieldView platform, the company combines weather forecasts, field data, and soil moisture levels to provide farmers with precise irrigation recommendations. This system uses machine learning models to predict water requirements based on current conditions and forecasts, enabling farmers to use water more efficiently [54].

Impact: The use of AI-powered irrigation management has helped farmers conserve water, reduce energy consumption, and optimize irrigation costs while maintaining crop health, especially in water-scarce regions.

Case study 4: Monsanto (now part of Bayer) [55] uses AI and CRISPR gene editing technology to accelerate crop breeding [56]. By analyzing vast amounts of genomic data, AI algorithms identify genes associated with desirable traits such as drought resistance, pest resistance, and higher yields. AI helps streamline the traditional breeding process, enabling the development of genetically modified crops that can thrive in diverse climates and resist diseases.

Impact: Monsanto's AI-driven genetic modification has led to the development of more resilient and higher-yielding crop varieties, helping to meet the demands of a growing global population and improve food security.

Case study 5: Cainthus, an agri-tech startup [57], uses computer vision and AI to monitor livestock behavior in real time. Using cameras installed in barns, AI algorithms analyze the animals' movements, health, and feeding patterns. The system can detect early signs of illness, monitor feeding habits, and track the overall health of livestock. This data is sent to farmers, enabling them to take timely actions and improve animal welfare.

Impact: Cainthus' AI-driven precision livestock farming system helps farmers increase milk production, reduce veterinary costs, and improve the overall health of their herds, leading to higher productivity and sustainability in livestock farming.

4. Barriers to adoption

The implementation of AI-integrated agricultural systems encounters several obstacles, notwithstanding the significant opportunities that AI presents to the farming sector. To maximize the capacity of AI to enhance crop yields, these challenges can be classified into three main categories: technological, social, and regulatory impediments. However, it is imperative to address these issues.

4.1. Technological challenges

AI adoption in agriculture requires a huge technological infrastructure, which can be unaffordable to most farmers, especially those from developing countries. This includes sensors, sophisticated robotics, and data analysis [19,58]. Given that AI systems are complex, they require data processing power and reliable access to the Internet, which are not always available in rural areas or places far from cities [59]. Challenges related to technological system reliability and maintainability exist; quite often, AI frameworks need to be continuously modified and fixed to become painful within harsh electronic device environments.

Besides, access to and maintenance of these systems in AI are very expensive, let alone the training that farmers must know in the use of these systems. Again, this would be the case for smallholder farmers and those in the developing world, where they might not enjoy this privilege if their governments or private organizations do not make huge investments in closing the digital divide. With the increased dependencies of agricultural operability on digital platforms for storing and processing data via cloud-based services, other challenges arise, such as cybersecurity and data privacy [32]. However, one key factor in the successful adoption of AI in agriculture will be to make the solutions scalable, affordable, and easy to maintain to work equally well in areas with less technological advancement. These challenges will require cooperation among the providers of the technology, governments, and other stakeholders involved in agriculture to ensure that the advantages of AI become available to every type of farmer, irrespective of their geographical or economic conditions [60].

4.2. Sociocultural barriers

There are societal obstacles to AI integration into agriculture. Many farmers who are skeptical of new technologies and use old farming methods frequently oppose this [61]. Such a shift towards AI-driven techniques requires gradual, challenging adjustments in practice and mentality alike [62]. Moreover, farmers require considerable knowledge and training to acquire the skills necessary to efficiently employ AI. Adoption would also be low in the event of a lack of knowledge and confidence in the created systems.

In addition to skepticism, attachment to traditional farming techniques and practices may further frustrate acceptance of AI. Many rural communities pass down farming techniques over generations, making it difficult to convince farmers to apply novel, unfamiliar systems. There is also a generational gap in technology adoption, where older farmers may not be as willing to adopt AI solutions as tech-savvy farmers [63]. Sociocultural barriers will be surmounted through educational programs and outreach initiatives. Showing the real benefits of AI in crop yield and reducing labor would be more likely to build trust and confidence in the technology through success stories from locals. Similarly, it is important that AI systems be designed in a user-friendly interface that ensures accessibility for all farmers, irrespective of their technical background.

4.3. Regulatory and ethical concerns

Another main barrier to AI adoption in agriculture is AI-related regulation. Agriculture often involves sensitive information that farmers may not feel like sharing with other people, corporations, or governments. In addition, ethical concerns linked to the use of AI in genetic engineering and breeding might even result in new regulations. Unless there is wide-ranging testing together with long-term effect assessments, governments do not approve GMOs created with the help of AI [64]. Delays such as these can tamper with the implementation of potentially useful technology.

In addition, data privacy legislation and agricultural data ownership are concerns that have grown equally because most AI systems require extensive data from farms for efficient operation [65]. Hence, farmers may be very concerned with who owns this data and how it is used, calling for stricter data protection measures. Another ethical aspect has to do with the use of AI in the manipulation of genetic material, which many say creates questions about the impacts this could have in the longer term on biodiversity, food security, and the balance of ecosystems [66]. This may trigger debate concerning the sustainability of AI-driven genetic modifications and lead to the development of control over the use of genetic modifications [67]. There needs to be a clear regulatory framework regarding the use of AI that considers ethical concerns and issues related to data privacy without being harmful to innovation. In this light, direct discussions with farmers, policymakers, and other experts within the agricultural sphere constitute the first step toward framing guiding principles that weigh the benefits of AI against social and ethical responsibility.

4.4. Economic implications

The most noteworthy are economic constraints, which may involve high capital investment at the beginning and long periods to recoup the ROI. Such economic considerations may reduce the appeal of these advanced technologies to producers of agricultural produce, and more so for smallholder farming practitioners. Moreover, economic justifications for resisting automation and mechanization can be derived from employment repercussions for conventional agriculture-dependent rural communities [68].

Apart from the already high upfront costs, maintenance and general upgrades over time can also be financially costly to farmers in developing areas. In a wider sphere, the economic effects of adopting AI are felt within labor markets through increased automation of tasks traditionally done by human labor; consequently, job losses particularly affect rural populations whose livelihoods depend on agriculture [69]. AI can also create new jobs in farming that are related to managing, operating, and developing these technologies if proper training and education are available. This being the case, meeting these economic challenges may require governments and other institutions to provide subsidies or fiscal incentives to make such adoptions easier for farmers and encourage the creation of new jobs within this evolving industry.

4.5. Overcoming the barriers

Overcoming such challenges requires the combined efforts of government entities, technology companies, and academic institutions. Some of the more successful means by which farmers can help overcome financial obstacles include subsidies or other substitute financial incentives. Further confidence and skill building for all farmers is possible through comprehensive training programs with follow-up [70,71]. Appropriate regulatory frameworks need to be developed to address respect for data privacy and ethical considerations, while ensuring innovation. By addressing these issues, farming can achieve a more productive and sustainable future, driven by AI [72–74].

Further, collaboration among these stakeholders could also result in more accessible and affordable AI for the needs of smallholder farmers or rural farmers beyond those provided by financial and training support [75]. The simplification of user interfaces and making AI tools adaptable to different agricultural systems will encourage wider adoption. This will also ensure that best practices and successful stories of AI applications in agriculture are shared internationally, instilling confidence and calming skepticism. Policymakers can stimulate innovation through public-private partnership models in such a way that the technologies being developed address all farmers, regardless of economic status. Ultimately, addressing these barriers will accelerate the integration of AI in agriculture through a combined effort that will contribute to the resilient, efficient, and sustainable development of the world's agricultural sector.

5. Future perspectives

The potential of AI in agriculture is very large; it not only has the capability of changing the face of agriculture, but also increasing crop output. AI-powered solutions are envisioned to further infiltrate with the advancement of technology and its affordability, bringing about radical changes in food production, processing, and delivery. The subsequent section examines upcoming advancements in AI, their implications for policymaking, and their broader societal effects through incorporation in the agricultural sector Fig. 4.

5.1. Advancements in AI technologies

This will lead to more complex and tailored use in the agricultural domain. Examples include the improvement of robotic systems for planting and harvesting, the enhancement of genetic engineering methodologies, as supported by AI analytics, and the fine-tuning of algorithms for immediate monitoring of the crop, along with the immediate forecasting of diseases [58,76,77]. For instance, it may be possible for AI to enable smart seeds to automatically modify their growth behaviors with environmental inputs. AI can further enhance agricultural productivity and resource management by integrating more recent technologies, such as blockchain for supply chain transparency and drone technology for improved field analysis [78,79].

In accumulation, new developments in the area of predictive models

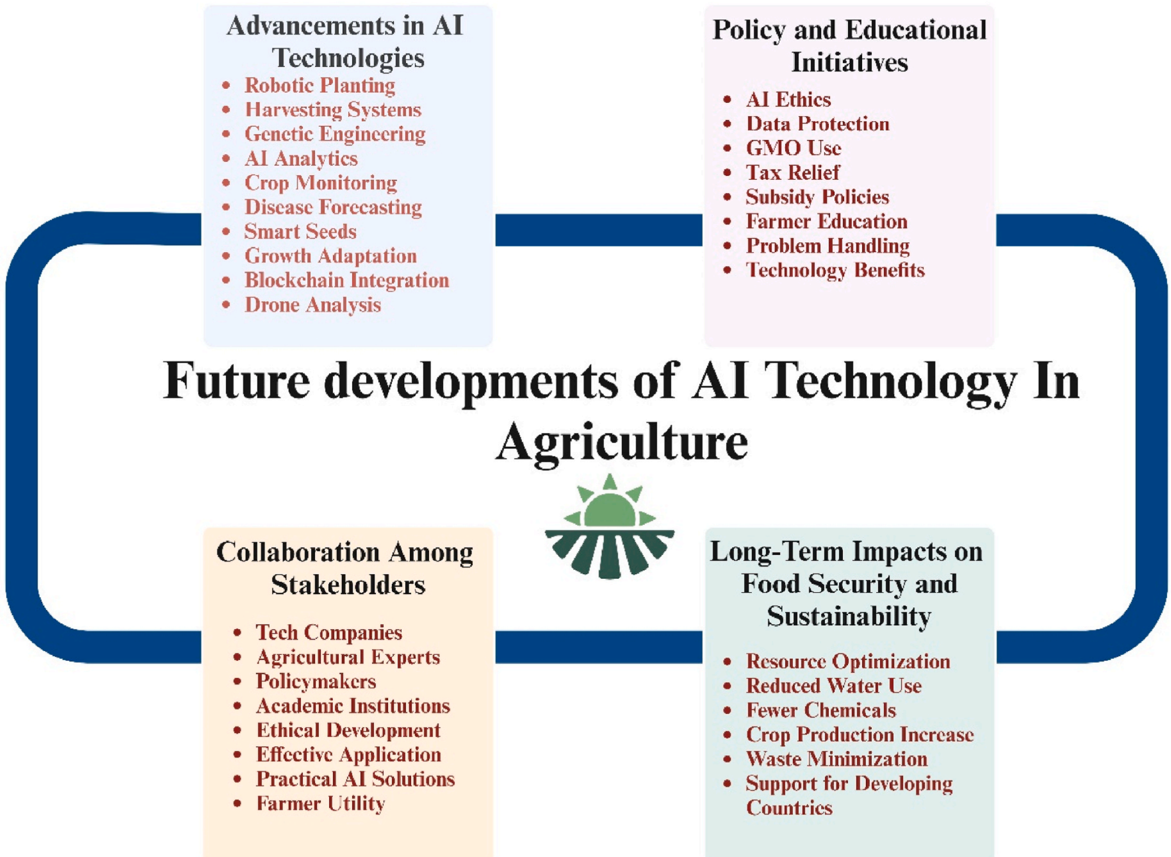

Fig. 4. Exploring the future of AI in agriculture: Technological advancements, policy frameworks, and sustainability impacts.

with AI make climate and weather forecasting more accurate and help farmers take much-needed precautions against extreme weather conditions, enabling them to adjust the planting and harvesting schedule. The integration between AI and IoT devices allows for better communication among the various systems of a farm in terms of collection and analysis in real time [12]. With further development, AI will permit the development and deployment of even more sophisticated systems capable of autonomously managing the entire farming process, from planting the seeds right through to the distribution of the crops. The shift will not only affect farming efficiency but also ensure food security and sustainability because of optimized resource use, minimal food waste, and traceability throughout the value chain.

5.2. Policy and educational initiatives

Robust policy frameworks and well-funded educational programs can facilitate widespread implementation of AI in the agricultural sector. This would probably require governments and international organizations to develop policies and guidelines for AI ethics, data protection, and the use of GMOs [80]. Additionally, the implementation of AI was made possible through an incentivization approach involving tax relief and subsidy policies [81]. More importantly, training programs should focus on educating experienced and newcomer farmers on the use of AI. Such programs should cover the most common problems and challenges in the implementation of technology while singling out the most direct benefits in the form of increased crops and lowered labor expenses [82,83].

Further, there is an immediate need for better coordination among government bodies, educational institutions, and technology-developing organizations, and customized curricula must be designed to specifically cater to the particular requirements of diversified farming communities. Some such programs could include training activities, workshops, and on-the-farm demonstration visits where farmers could experience the impact of AI. In addition, extension services might play a very important role in reaching rural and remote areas, so that small-scale farmers are not excluded from this new technological wave. In terms of policy, it is also important to have international cooperation on standards for the regulation of AI in agriculture to allow cross-border innovation and trade [84]. However, when combined with appropriate education, financial incentives, and enabling policy, AI adoption into agriculture will be equally pervasive and include many more to urgently solve problems of global food security.

5.3. Collaboration among stakeholders

Stronger collaboration among technology companies, agricultural experts, policymakers, and academic institutions is expected to give full assurance to the ethical and effective development and application process of AI. These collaborative efforts align technological advancements with the real needs of the agricultural sector; therefore, AI solutions will be practical and useful for farmers [85].

Moreover, collaborative models can help foster more localized and adaptable AI solutions that address highly specific problems facing different regions or types of agriculture. For example, direct engagement with farmers helps technology companies better understand practical difficulties on the ground and refine tools to be more user-friendly and cost-effective. Policymakers can provide the necessary regulatory support and financial incentives for scaling up such innovations, and academic institutions may provide insights into important research and training programs that will ensure that the solutions are truly effective and widely available. Therefore, this calls for a collective effort by all players to ensure that AI farming not only takes root faster but also in a bid to ensure sustainable farming and equal access to the changing face of agricultural technology across all parts of the world [86].

5.4. Long-term impacts on food security and sustainability

AI could dramatically improve environmental sustainability and global food security in the long term. AI could optimize the ecological impacts related to agricultural practices by reducing resource use, particularly water and chemical inputs. Improving crop production increases and waste minimization processes will be mandatory to feed the growing world population, especially in developing countries with limited food resources [28,53,54].

In addition, AI are useful for reducing the impacts of climate change through resilient agricultural practices. In this regard, AI enables real-time monitoring of environmental conditions to allow for early warning systems against climate-related risks, such as drought, floods, and extreme temperatures, for timely and effective responses [87]. Such proactive action could not only ensure that the crops were safe, but also end up utilizing better land use, reducing the environmental footprint of agriculture. Moreover, the integration of AI with precision farming and genetic engineering may introduce crops with enhanced resistance to pests and diseases, further ensuring food supplies in unfavorable conditions [88]. As AI continues to develop, it will play a crucial role in the formulation of global food security and sustainability in addressing population growth demands in an environmentally sensitive manner.

6. Conclusion

In this paper, we explored the transformative potential of AI in agriculture, highlighting its ability to enhance crop production, optimize resource usage, and address critical challenges such as environmental sustainability and global food security. Through a detailed analysis of AI applications, from robotics and machine learning to precision farming, we demonstrated how AI can improve yield outcomes, increase operational efficiency, and reduce environmental impact. Furthermore, we discussed the challenges that must be overcome for the full deployment of AI in agriculture, including technological, societal, and regulatory barriers. In addressing these challenges, we emphasized the need for collaboration among policymakers, technology developers, agricultural stakeholders, and educational institutions. Such collaboration is essential to creating an enabling environment for AI while managing ethical concerns and privacy issues. Our paper also provided insights into the future of AI in agriculture, stressing the importance of continuous innovation, learning, and adaptation to emerging technologies. We believe that AI has the potential to revolutionize the agricultural industry by fostering a more sustainable and efficient farming ecosystem. To fully realize this potential, stakeholders must seize the opportunity to advocate for a fair and sustainable farming environment, ensuring that agriculture can meet the challenges of the future while contributing to global food security and environmental health.

CRediT authorship contribution statement

Nazish Aijaz: Writing – review & editing, Writing – original draft, Investigation, Formal analysis, Data curation, Conceptualization. **He Lan:** Writing – review & editing, Writing – original draft, Project administration. **Tausif Raza:** Writing – review & editing, Writing – original draft. **Muhammad Yaqub:** Writing – review & editing, Visualization, Formal analysis. **Rashid Iqbal:** Formal analysis, Writing – review & editing. **Muhammad Salman Pathan:** Writing – review & editing, Investigation, Funding acquisition.

Declaration of competing interest

The authors declares that there are no conflicts of interest.

Data availability

No data was used for the research described in the article.

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