American Journal of Agricultural Science, Engineering, and Technology (AJASET)

ISSN: 2158-8104 (ONLINE), 2164-0920 (PRINT)

VOLUME 8 ISSUE 3 (2024)

PUBLISHED BY: E-PALLI PUBLISHERS, DELAWARE, USA

American Journal of Agricultural Science, Engineering, and Technology (AJASET)

Volume 8 Issue 3, Year 2024
ISSN: 2158-8104 (Online), 2164-0920 (Print)
DOI: https://doi.org/10.54536/ajaset.v8i3.3843
https://journals.e-palli.com/home/index.php/ajaset

Exploring Artificial Intelligence and Machine Learning in Precision Agriculture: A Pathway to Improved Efficiency and Economic Outcomes in Crop Production

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Article Information

Received: September 24, 2024

Accepted: October 29, 2024

Published: November 11, 2024

Keywords

Artificial Intelligence, Internet of Things, Machine Learning, Precision Agriculture, Robotics

ABSTRACT

This review analyzes secondary data from academic databases, research articles, and case studies to explore the role of new technologies for precision agriculture (PA) and investigates the value addition that Artificial Intelligence (AI) and Machine Learning (ML) provide to resource use, crop yield, and economic performance. Accordingly, the most of the key applications of AI in PA were related to crop yield prediction, disease detection, and effective water usage. Operating models through AI will analyze much data in real time, thus providing insight into informed decision making by farmers for proactive action against crop challenges like drought or pest attack. Furthermore, IoT devices and remote sensing support continuous monitoring in the delivery of correct data about optimizations of resources with minimal environmental impact. AI-driven robotics further automates all tasks related to planting, harvesting, and pesticide application, improving labor productivity and operational efficiency. This would involve in other issues like implementation costs, data privacy, and general unawareness among farmers of developing areas. Equally important will be ethical issues like ownership of data and loss of jobs. Various case studies in India, China, the United States, and Africa reveal how AI could transform the future of agriculture if integrated into agricultural systems properly to gain higher productivity and sustainability. Improvements in data quality and ethical issues, and increased access by smallholder farmers, will also be part of future research. Eventually, integrating AI with IoT, robotics, and big data analytics could provide high potential to meet global food demand in a sustainable manner.

INTRODUCTION

Precision agriculture characterizes modern farming with the incorporation of advanced technological tools to enhance efficiency in crop production and optimal resource use. It thus aims at using real-time data from a wide range of sources to enable farmers to make proper decisions with the aim of boosting agricultural productivity and sustainability. With precision agriculture (PA), very advanced technologies such as Geographic Information System (GIS), sensors, drones, satellite images, and many more are being used to capture critical data regarding soil health, crop growth, weather, and resource availability (Sharma, *et al.*, 2023). It is expected that, by 2050, the world population will rise to about 9.7 billion people; besides, the area of arable land and water is limited. Both these factors mean that a huge challenge is in store for agriculture. Farmers are being put in an increasingly onerous position to produce more food with as little environmental impact as possible, with preservation of the natural resource base. However, the long-term effects still pose a challenge to food security. Agricultural production, in which a significant portion is crop production, depends mostly on weather conditions that ought not to vary so much from year to year. (Florentin & Barcellano, 2024). Precision agriculture is, therefore, important in solving some of these problems. This method includes input use efficiency, such as water, fertilizers, and pesticides, for better crop yields, minimizing waste, and degradation of the environment.

Precision agriculture has integrated the use of artificial intelligence (AI) and machine learning (ML) in agriculture, thus empowering farmers with better and more precise decision-making on the data that may be available to them. AI and ML algorithms can sift through huge datasets, look for patterns, and extract meaningful insights that may help farmers plan their agricultural business better. For example, AI-enabled systems can forecast crop yield, map pest outbreak probabilities, and suggest resource applications at exact timings when the weather conditions are congenial (Akhter & Sofi, 2022). Thus, considering the twin challenges of food production and management of resources with finiteness, the use of AI and ML in precision agriculture becomes all the more indispensable (Bhat & Huang, 2021). Therefore, the aspects of importance in effective and efficient precision agriculture, focusing on reliable, practical, and affordable techniques against their implementation on small farms, both currently and in the future should be discussed.

This review aims to provide a critical view of artificial intelligence and machine learning applications in PA, with the purpose of establishing how these approaches enhance crop yield optimization, efficiency in resource use, and economic returns. The goals of this paper are to present the benefits and challenges associated with integrating AI and ML into farming practices, its ethics, and probable future directions that may contribute

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toward ease of access and sustainability within global food production.

LITERATURE REVIEW

Overview of Precision Agriculture (PA)

PA is an advanced technological method of farming to increase more productivity on farmland, optimize resources, and create sustainability. Conventional methods cannot compete with food demand globally and depleted resources of the environment (Sharma *et al.*, 2023). The kind of precision agriculture being deployed with advanced technologies in AI, ML, and IoT devices has the capability to furnish actionable input on real-time soil health, crop growth, water needs, and data of pest and infestation on a continuous basis to the farmers for enabling them to take data-driven decisions ((Akhter & Sofi, 2022; Bhat & Huang, 2021). AI and ML go through massive datasets so that farm-specific interventions can be supported with precision. This aids in the improvement of crop yields and maximization of economic returns on one side, while it reduces the environmental footprint further (Karunathilake *et al.* 2023). Its adaptability across scales, from industrial farms to smallholders, underlines the potential of PA to drive a productive and sustainable future of agriculture.

Applications of Artificial Intelligence (AI) and Machine Learning (ML) in Precision Agriculture (PA)

Applications of AI and ML in precision agriculture are endless, with totally innovative solutions to traditional farming challenges. Both have totally changed the way of looking by farmers at crop management, resource allocation, and risk mitigation. Through analysis of data from several sources like sensors, drones, satellites, and more, AI and ML algorithms provide insights that enable farmers to make proper decisions in a timely manner. It is a shift from conventional farming to data-informed farming practices that improve productivity by cutting costs and increasing sustainability.

Probably the most important benefit which AI and ML bring into agriculture is processing a great amount of data, extracting necessary insights from the data that a human might miss. This can use AI to do environmental monitoring in real time, such as soil moisture, temperature, and humidity, to adjust the irrigation schedule or fertilization accordingly. Similarly, ML models are able to forecast the probabilities of pest infestations or disease outbreaks, considering historical data and current conditions, to develop proper preventive measures well in advance in order to avoid any damage. These technologies contribute not only to improved health of crops but also to better optimization of the use of resources, leading to improved economic returns to farmers (Akhter & Sofi, 2022). Moreover, AI and ML strengthen automation in the cumbersome tasks of planting, watering, and harvesting that reduces operational costs while increasing efficiency as well. Such automation releases farmers to divert their attention to other important aspects of farm management with a view toward ensuring the routine continues uninterrupted and with greater precision. The integration of AI and ML into precision agriculture can, therefore, turn out to be one of the causes for its paradigm shift toward intelligent and sustainable farming.

AI for Crop Yield Prediction

Precise forecasting of crop yield is one of the most critical features of farm management. It notifies farmers about the planning of resource allocation and the assessment of market demand necessary for food security. Traditional methods of yield prediction normally rely on historical data and personal experience, which are always uncertain due to shifting weather patterns, variable soils, and pest pressures. This can be furthered by AI models that bestow more accurate and reliable output on account of large and complex data they have analyzed, which capture a number of variables that affect crop yield (Adinarayana *et al.*, 2024). AI-based yield prediction models use some of the machine learning algorithms, such as artificial neural networks (ANNs), support vector machines (SVMs), and random forests, to analyze data emanating from many sources, including soil sensors, weather stations, and satellite imagery. These models look for complex interactions among variables that range from soil moisture and temperature to planting schedules, and even more precariously to advance predictions related to crop yield. It will therefore give farmers the most needed opportunity to decide upon in crop management when to plant and when to harvest, apply necessary and correct inputs like fertilizers and water on time (Shaikh *et al.*, 2022).

Besides inputs from terrestrial sensors, the applications of various remote-sensing technologies, including drones and satellites, also confer added strength on AI-based yield prediction models. With multispectral and hyperspectral cameras, drones can even monitor critical growth stages in far greater detail, capturing images that detail plant health, nutrient deficiencies, and other stresses of the plants. These images, in turn, will get processed with AI algorithms to predict yields in real time and, thus, enable farmers to act proactively toward the mitigation of any potential risks and managing their farms in general (Senoo *et al.*, 2024). AI models can also integrate historical data on yield, soil quality, and weather to predict future prospects. Because of this, farming has been much easier in areas getting extreme variability in environmental parameters as farmers can make easy decisions based on the situation. Application of AI for the forecasting of crop yield allows farmers to handle resources optimally, keep wastage low, and enhance profitability.

Machine Learning for Disease Detection and Prevention

Crop diseases are among the most threatening factors to agricultural productivity on the global scale and, therefore, have the potential to cause widespread economic losses and food scarcities. Early detection of and preventive measures against disease in plants can bring crop losses to a minimum, with the added value of making production more viable and sustainable. Traditionally, plant disease has been detected by a farmer or agricultural expert through observation, which is many times cumbersome and sometimes prone to human error. ML models have given a better handle on this and thus have emerged as a successful alternative, as through recognition of images and analysis of patterns, they automate the detection of diseases (Sharma *et al*., 2020). Convolutional neural networks (CNNs) have been one of the most adopted ML algorithms in precision agriculture for disease detection. Their models are usually trained on substantial datasets comprising images of diseased and non-diseased plants. Analyzing minute visual appearances like leaf color, texture, and shape changes, a CNN can identify early symptoms of various plant diseases, sometimes way in advance before they might be observable by the human naked eye. This helps farmers practice precision in intervention, reducing the frequency and extensiveness of application of broad-spectrum pesticides and the detrimental impact on the ecosystem (Waseem *et al*., 2024).

For example, ML models have very successfully been in service at vineyards to recognize fungal infections such as powdery mildew and downy mildew. They detect early signs of infection from high-resolution images taken by drones or sensors, after which treatment can be conducted just where needed. Similar work on wheat, rice, and maize has also been performed where diseases identified by ML models included rust, blight, and leaf spot. Therefore, in disease prediction, ML models have the potential to consider environmental data other than mere image-based detection, such as soil moisture, temperature, and humidity. Such predictive models will use historical data in combination with active monitoring so as to afford farmers corrective action by adjustment in irrigation schedules or protective treatments against diseases before actual disease outbreaks occur (Sharma *et al*., 2020). An active approach towards disease control is effective in reducing crop loss but also acts towards increasing the efficiency of general farming operations.

AI in Optimizing Water Usage and Irrigation

Water scarcity is one of the most limiting conditions in agriculture, particularly in arid and semi-arid regions. Efficient water management makes for healthy conditions for crops and conserves this precious resource. Traditional irrigation systems, for a long time, have resulted in water waste through over-irrigation or poor distribution. AI-powered irrigation systems will thus involve determining the level of water usage based on the specific needs of every crop in real time, guided by soil moisture sensors and weather forecasts (Lakhiar *et al*., 2024). AI can process data about soil moisture, the water requirements for crops, and climatic conditions to assess how much water is required at any one given time. Such sensors, buried in the field for example, can monitor soil water continuously and send signals to AI-powered irrigation systems to adjust delivery accordingly. In this way, optimal water delivery to crops is assured with reduced waste, and under or over-irrigation will be avoided (Shaikh *et al*., 2022).

One of the strong benefits of AI-powered irrigation systems is their ability to predict water requirements in the future. These systems study weather forecasts and historical data and can estimate any period of drought or excessive rain well in advance to plan irrigation schemes. In cases where the system predicts a period of drought, it may reduce water use much earlier to avoid unnecessary wasting of water while still retaining adequate crop health (Adinarayana *et al*., 2024). Furthermore, AI-driven irrigation systems can be integrated with other technologies in precision agriculture, such as drones and satellites, to carry out large-scale monitoring of crop health and soil conditions. This integrated approach allows for finer-scale water management-particularly for fields containing variable soils or topographies. This can be achieved by optimizing water usage, which will reduce the bill for water usage; besides, natural resources can be conserved to increase crop yields, and thus contribute to economic and environmental sustainability (Lakhiar *et al*., 2024).

Internet of Things (IOT) and AI Integration in Precision Agriculture

Integrating IoT devices with AI systems is changing precision agriculture by equipping farmers with the capacity to monitor environmental conditions in real time and take data-driven decisions, which optimizes the use of their resources and productivity in crops. IoT devices include sensors, drones, and sensing tools, which capture critical information about soil moisture, temperature, humidity, and health status of plants. The consolidated data is relayed back to the AI systems, which then process it through machine learning algorithms to come up with workable insights to act on (Soussi *et al*., 2024). The biggest advantage of integrating IoT with AI in agriculture is continuous monitoring of the farm conditions and, in turn, adjusting the operations in real time. For example, IoT sensors planted in the soil can monitor the moisture levels to cue the AI-driven irrigation systems to decide how much water to be applied. This prevents water waste, avoids over-irrigation, and also ensures the right amounts for crop consumption for their survival (Sharma *et al*., 2023).

Furthermore, IoT devices integrated with AI systems enable farmers to automate activities that pertain to the control of pests and management of nutrients. IoT sensors detect variations in soil nutrient levels or the presence of pests, while AI models analyze data for recommendations on specific interventions. For example, it can recommend the application of a certain fertilizer if sensors detect any decline in nutrient levels within the soil to make sure crops receive just the right amount of nutrients at just the right time (Shaikh *et al*., 2022). Besides resource optimization, integration of IoT and AI increases the efficiency of large-scale farming through continuous insight into the performance of farms. In light of live field information, farmers can make proper decisions on the time for planting, irrigation, and harvesting of crops. Continuously adopted feedback through IoT and AI results in well-directed usage of resources directing for cost-cutting and improving of crop yield (Soussi *et al*., 2024).

Remote Sensing Technologies in Data Collection

Drones and satellites now are the requisite choice in large-scale data collection in precision agriculture. These technologies make farming efficient by providing quite accurate and high-resolution images of their fields, showing crop health, soil conditions, and environmental changes on an expansive area. The value of remote-sensing technologies lies in detecting even small variations in the health of plants not easily or clearly captured by the naked eye, such as nutritional deficiencies and water stress (Fuentes-Peñailillo *et al*., 2024). Drones equipped with multispectral or hyperspectral cameras will visualize images that highlight differences in plant health across the entire field. These images provide information on factors such as chlorophyll content, available water, and nutrient uptake to aid the farmer in decision-making regarding irrigation, fertilization, and pest management. AI models analyze these images to detect early signs of crop stress; therefore, the farmers are able to act before it begins to cause problems (Shafi *et al*., 2019).

Beside drones, satellite imagery offers a broad look into extensive areas of agriculture and can provide current data on soil moisture levels, temperature fluctuations, and weather patterns. Satellite data will be integrated with AI models that would forecast weather-related risks like droughts or frosts and optimal management strategies for crops. It might mean, for example, analyzing satellite data related to temperature and humidity conditions by AI systems, which would then make suggestions on the most appropriate dates of planting particular types of crops, when it is best to harvest and the improving crop yield in order to reduce the rate of loss under adverse weather (Shafi *et al*., 2019). Other important remote sensing technologies allow farmers to conduct monitoring on long-term trends in crop health and soil conditions. Through analytical examination, AI models can create a pattern from historical data acquired during several growing seasons and further predict the agricultural conditions that might persist in the future. This helps farmers for planning in upcoming seasons and making necessary changes to their farming methodologies as environmental factors shift (Fuentes-Peñailillo *et al*., 2024).

Machine Learning for Crop Health Monitoring and Soil Management

It has also emerged that ML is playing a vital role in precision agriculture now, mainly by offering advanced tools in crop health monitoring and soil fertility management. These technologies will eventually allow farmers to make decisions that improve agricultural productivity with sustainability. The main application of ML in precision agriculture is the prediction of soil fertility, which is one of the major factors that determines crop success (Sudhakar & Priya, 2023). ML models analyze vast data from historical and real-time soil information for predicting the fertility level of the land with high accuracy. These models help farmers in decision-making about type and quantity of fertilizers at any given time to optimize the condition of the soil without having a risk of nutrient imbalance. It ensures cost savings, reduced environmental impacts, and improved crop yields accordingly (Islam *et al*., 2023).

In addition to predicting soil fertility, the models of ML also find their applications in detecting nutrient deficiencies in crops. Nutrient deficiencies, such as those concerning nitrogen, potassium, or phosphorus, seriously affect the health and yield of a crop. Conventionally, nutrient deficiencies were diagnosed through visual inspections or by laboratory tests, which may involve delays. Although this would appear simple to the human eye, ML models trained on thousands of images of plants can detect such specific nutrient deficiencies through an analysis of plant features like leaf color and texture (Raza *et al*., 2023). Besides, ML algorithms will be increasingly applicable to generate full-profile soil health by integrating data from different types of soil sensors, weather stations, and remote sensing technologies. The profiles provide real-time insights into a selection of the basic parameters of the soil, including moisture levels, pH, and organic matter content, thus enabling farmers to make precise adjustments in irrigation and fertilization strategies. This increases efficiency in resource use and contributes toward sustainable farming practices (Diaz-Gonzalez *et al*., 2022).

Economic Impact of AI in Crop Production

Farming with AI comes with great economic benefits. AI technologies allow for efficiency gains, lower operational costs, and higher yields. Such AI-powered systems allow farmers to apply resources such as water, fertilizers, and pesticides in the most optimal manner, keeping in view real-time data analysis from sensors, drones, and satellite images. This ensures better and efficient utilization of resources to reduce wastage and enhance profitability (Jessy *et al*., 2024). For instance, AI-powered irrigation systems deploy predictive models that understand the exact needs of water that crops require by considering soil moisture levels and current weather conditions. It cuts down on the wasting of water, hence reducing the account in terms of cost paid for water and, at the same time, ensures that crops get enough amounts of water meant for growth. Similarly, AI models can analyze levels of nutrients within the soil and recommend the amount of fertilizers to be applied and hence reduce input costs and minimize environmental impact caused by excessive application of inorganic fertilizers (Shaikh *et al.*, 2022).

AI technologies also tend to save labor costs by automating most of the tasks carried out by human labor in traditional farming. With the aid of AI-powered robots, farming is able to perform activities like planting seeds, monitoring crop growth, and even harvests much more precisely than human labor. This indeed diminishes the need for manual labor and saves labor costs, especially in large-scale farms that may be based on a high cost of labor as part of the total budget (Prajapati *et al.*, 2023). Apart from the cost savings, AI technologies provide for increased crop yield through offering real-time insights into crop health and thus enabling early prevention. By early detection of diseases and pests, an AI model is able to detect the earliest stages of disease and pest manifestation, as well as nutritional deficiencies, thus enabling the farmers to take early action before any great harm has been done. This leads to higher yields and better-quality produce, which, in turn, can receive better prices in the market (Karunathilake *et al.*, 2023).

MATERIALS AND METHODS

This review paper was developed by performing a critical analysis of secondary data sources and a review of various research previously published. A literature review process was performed through systematic searching within major databases-IEEE Xplore, ScienceDirect, SpringerLink, and Google Scholar-for recent works using the keywords of machine learning, robotics, internet of things, big data analysis, precision agriculture, artificial intelligence and GPS. This was partly achieved by limiting our review to just peer-reviewed articles, conference papers, technical reports, and case studies. The selection criteria emphasized recent research within the last five years. It showed recent advancement but also considered some foundational studies for background and contextual purposes.

This structured and multidisciplinary approach has allowed us to make a comprehensive balanced review of PA, underlining different facets of technology integration, economic impacts, and applications of AI. The methodology guarantees that insights will be based on reputable sources and in line with the area of expertise of each author, adding to the depth and reliability of the findings. This review further identifies limiting factors in the analysis of secondary data, including possible biases in studies that have already been conducted, and in the realm of changing nature of PA technologies that are constantly in need of updating. In a nutshell, this collaborative approach therefore gives a sound insight into the prevailing status of PA, its economic, and technological consequences that reshape modern agriculture with advanced AI and engineering solutions.

RESULTS AND DISCUSSION

Review of secondary data and studies previously published indicates that AI, ML, GPS-guided machinery, and IoT devices have been playing an important role in the attainment of efficient and effective PA. These aforementioned technologies enable real-time collection, analysis, and automation, hence giving a major fillip to agricultural practices compared to traditional methods. In addition, the economic benefits of PA are quite evident; very often, the use of PA technologies offers savings of wasted resources, improved crop yields, and reduces overall costs. Sustainability and resource efficiency represent further significant added values since PA systems allow for precisely applied water, fertilizers, and pesticides to minimize environmental impact. Emphasizing the importance of conserving energy, especially in terms of electronic devices, and fighting the false information or complications to the enactment of such would collectively contribute to an improvement in resource conservation (Masongsong, 2024). The review has also identified some challenges and ethical concerns, such as high implementation costs, data privacy issues, and job displacement in AI adoption in agriculture. These themes are undertaken in the paper that revisited some important case studies and success stories related to real-world applications of AI-driven PA and the adoption of robotics to automate laborious tasks. These findings give insight into both the transformative potential and complexities of upscaling PA. It was found that efficient and effective PA is an integrated system composed of many advanced technologies summarized in Figure 1.

Sustainability and Resource Efficiency in Precision Agriculture

Sustainability nowadays is really at the heart of modern agriculture, and AI technologies are really an important integral part in achieving such sustainable activities. Probably among the most important contributions of AI to sustainability is in optimizing the usage of such vital resources as water, fertilizers, and pesticides. These inputs, when applied over and above the optimum requirement by methods of conventional farming, are

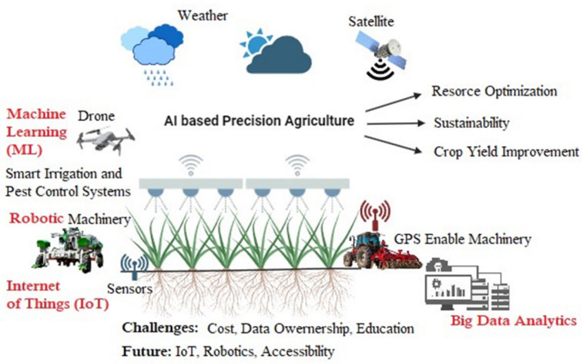

Figure 1: An AI-powered model

generally associated with environmental degradation through soil erosion, water contamination, and loss of biodiversity. Such AI-driven systems allow farmers to apply resources with greater precision, reducing waste and minimizing environmental damage (Sharma *et al.*, 2023). For instance, AI-powered irrigation systems analyze soil moisture, weather forecast, and crop water requirements for optimum water usage. Several studies have proved that such systems can reduce water usage by up to 30%, increasing the health and yield of crops in the process (Lakhiar *et al*., 2024). This is important in cases where the water supply is low, but the AI systems help farmers conserve this vital commodity while ensuring productivity.

Similarly, AI-driven systems let pesticides be applied more accurately only to the targets. Rather than applying pesticides throughout entire fields, AI systems can identify exact areas where pests are present and only apply pesticides in those areas. This reduces the overall application of chemicals, shields beneficial insects and biodiversity, and mitigates negative impacts on farming and the environment in general (Nath, 2024). AI technologies also streamline fertilizer use efficiency by analyzing soil health, weather conditions, and crop nutrient requirements. The predictions from AI models on proper timing, location, and quantities applied have the potential to reduce the risk of over-application and subsequent runoff of nutrients into water bodies. In this context, optimization of fertilizer use by AI systems results in environmentally favorable farming practices, decreasing the ecological footprint of agriculture (Sharma *et al*., 2023). Further, AI improves the sustainability of agriculture by increasing resource use efficiency and reducing farm operational expenses. With AI, relying on real-time monitoring of crop health and soil conditions, farmers make data-driven decisions by minimizing the application of resources while maximizing their productivity. This makes it possible for farmers to achieve the twin goals of improving agricultural yields without being exploitative of the environment for the benefit of future generations (Raman *et al*., 2024).

Challenges and Ethical Concerns in AI Adoption

While AI utilization in agriculture has many benefits, it equally brings about several challenges and ethical issues that need to be addressed. Probably the foremost issue is the knowledge gap among farmers, especially in developing regions. Most of the farmers lack the technical skills to implement and manage such AI-driven systems effectively; hence, they cannot take full advantage of these technologies. However, farmers' actual skills in implementing and using these AI tools show a significant gap. Training programs and educational resources should, therefore, be implemented to bridge this gap in farmers' skills (Gikunda, 2024). The other challenge is expensiveness of these AI technologies. Infrastructures that support AI systems, like IoT devices, storage, and connectivity, may be ridiculously too expensive to deploy, especially among smallholder farmers in developing countries. Large-scale farms that can accommodate such technologies are often at an advantage over their smaller, resource-constrained counterparts, which may hardly compete with them (Lassoued *et al*., 2021).

Besides the technological challenges, there are certain ethical considerations with respect to data privacy and ownership. AI systems operating on agriculture garner a substantial set of data on soil conditions, crop health, and farm management practices from farms. It then raises questions concerning who owns the data and how it is used by third-party technology providers. Farmers may also not have much to say in deciding how their data are collected, stored, and transmitted. They may also be subjected to the risk of being exploited and losing their competitive advantage (Ryan, 2023). There is much concern about the social effects that might result from the use of AI in agriculture. While AI-based automation cuts labour costs and increases efficiency, it could also lead to unemployment among those agricultural workers who are landless and of low skills. This would have a significant economic and social consequence for those economies where agriculture is one of the main sources of employment. It is also now imperative that the sharing of benefits, arising from the adoption of AI, be done in an equitable manner, while alternative livelihoods for the workers so displaced are readily available to go on and reduce the adverse socio-economic impacts of AI in agriculture.

There are legal and regulatory challenges related to the use of AI in agriculture as well. The current regulatory framework might not be ready to deal with the peculiar challenge that AI presents to them, such as questions of liability and accountability. For instance, if an AI system incorrectly predicts and this leads to crop failure, it is uncertain in the present circumstances who will be held responsible: the farmer, the technology supplier, or the AI system. As stated above, developing clear legal frameworks is definitely an aspect that points out accountability and responsibility when taking part in AI technologies, and it is of importance for their ethical and fair adoption (Costa *et al*., 2023).

Case Studies and Success Stories in AI-Driven Precision Agriculture

There are numerous successful examples of the transformative potential of AI-driven precision agriculture across very diverse regions and farming systems, showcasing economic benefits, improved efficiency of resources, and productivity.

The "Sowing App" of Microsoft and the International Crop Research Institute for the Semi-Arid Tropics (ICRISAT) uses AI-powered models to help farmers in India which decides the best sowing dates based on the current weather conditions, soil moisture levels, and insights from historical information of crops. Results from pilot programs show that the app has increased crop yields by 30%, allowing farmers to avoid losses due to erratic weather conditions and thus optimize their planting schedules accordingly (Lakhiar *et al*., 2024). This case study points out that AI can increase productivity and economic outcomes in areas with harsh environmental conditions. In China, equipped with image recognition technologies, AI-enabled drones are revolutionizing the precision application of pesticide and crop health monitoring. Its capability for real-time identification of diseased or infected crops and pests enables the drones to spread pesticides only within those parts of their flight path where the crops have become diseased or infected, reducing use by up to 50% and minimizing environmental impact. The economic estimates also indicate that these AI-driven precision farming techniques of China will increase the net income of farmers by 20% (Rhoads, 2023). This is a very good example of how AI-enabled targeted application has encouraged economic and environmental benefits.

John Deere's See & Spray technology uses AI-powered computer vision to make a real-time distinction between crops and weeds in the United States. This system applies herbicides only onto the weeds, hence offering a reduction by up to 90% in chemical usage and thus a great saving in costs to farmers (Ahmed *et al*., 2024). The precision of AI-powered herbicide application, besides reducing weed competition and increasing crop yield, decreases the ecological footprint of large-scale farming.

AI-driven precision farming tools are a game-changer for smallholder farmers in Africa. Systems, like Zenvus and an AI-based agritech deploy sensors that track soil moisture, nutrients, and temperature to provide real-time feedback on when to water or add fertilizers which improve resource efficiency and crop yields. In the countries with limited resources where these tools have been deployed, such as Kenya and Nigeria, water and fertilizer usage has been reduced by 40% and helped small-scale farmers to be more productive and profitable (Javaid *et al*., 2023).

The AI is used in Australia to help with viticulture to improve the crop management and wine production. Applying ML algorithms to satellite images, an AI system can predict crop quality and yield of grape fruits based on variables like temperature, soil health, and moisture levels. Improvement in grape quality due to efficient irrigation scheduling and pest management through AI systems has resulted in improvement of 15-20% which fetch better market prices, thereby expected to enhance profitability among wine producers in South Australia (Shet & Shekar, 2020).

Future Trends and Research Directions

The future of precision agriculture is directly linked with the advancements in AI and ML, whereby several emerging trends are foreseen to further transform the sector. Probably the biggest of them all is developing AI-powered robotics and automated systems that are being developed for precision tasks such as planting, irrigation, and harvesting. Whereas AI algorithms are becoming ever more clever, in the near future, such systems are likely to carry out the job with increased precision and efficiency, raising crop yields while using the fewest resources possible (Shaikh *et al*., 2022). One of the other promising areas of development involves the integration of IoT technologies with AI in real-time monitoring and decision-making in agriculture. The sensing devices incorporated with IoT will be able to collect huge volumes of data on soil conditions, crop health, weather patterns, and use of water. Combined with AI, these devices will enable real-time processing of big data and predictive analytics to optimize resource use and limit waste. For example, AI algorithms analyze data from soil sensors for inferences on when and how much watering of crops is to be done, thereby increasing the efficiency of water use by many folds (Friha *et al*., 2021). Such incorporation of IoT and AI has the potential to bring about a complete transformation in farm management itself by automating those tasks which required human intervention earlier.

Another area where deep learning will see very rapid growth in agriculture is: deep learning models, which work in exactly the same way as the neural networks in the human brain, greatly outperform all other forms while dealing with complex data patterns, such as in identifying diseases of crops or yield outcomes of crops. These models apply to be particularly effective in recognition tasks of drone and satellite imagery, such as observing weeds and pests or deficiencies in the uptake of nutrients (Oliveira & Silva, 2023). Hence, with deep learning algorithms still in the process of evolution, they will be summoned to center stage for precision agriculture in the enrichment of higher predictive accuracy and pace for the decision-making process. Agriculture 5.0 is an emerging concept of smart farming in which AI, IoT, robotics, and big data analytics integrate fully in completely autonomous farming systems. Agriculture 5.0 is oriented toward sustainability, productivity, and a circular economy to optimize the complete value chain of agricultural supply from farm inputs through farm production and storage to food distribution (Shaikh *et al*., 2022). More fundamentally, researchers consider the different ways through which AI and machine learning could be used to further enhance crop protection, precision pest management, and optimize resources with the help of cloud-based platforms.

While AI has excellent prospects in agriculture, several challenges still exist, hence opening new frontiers for research. Among the main directions of research, much attention should be given to increase the quality and homogeneity of data fed to AI models. At the moment, a lot of models have incomplete or incoherent data, which results in not very good predictions. By a review (Qazi *et al*., 2022) shows that future research is warranted to provide standardized protocols on how data are collected and processed from diversified regions and farming systems. Improved data quality would offer better output from AI algorithms, offering more accurate recommendations for farmers. Furthermore, there is a growing need for research into the ethical implications of AI in agriculture, especially regarding data privacy and ownership, but not limited to concerns about data quality. Whereas IoT devices and AI systems capture copious volumes of information from farms, it is still a point of discussion by stakeholders to determine who exactly owns the information and how that information ought to be applied. The research, therefore, should be directed toward the development of frameworks for responsible data management in ways that farmers are not exploited by third-party technology providers and retain full ownership of their data (Pugliese *et al*., 2021). Lastly, future research urgently needs to address the issue of accessibility, concerning AI technologies, in particular for the smallholder farmer level in developing regions. Despite the possibility given by AI to drastically enhance the output of agriculture, high cost and technical expertise required for the installation of these technologies are still considered major deterrents to adoption. Therefore, research should focus on making AI technologies more accessible and user-friendly to support a wider diffusion in agriculture that allows for smallholder farmers to become beneficiaries of those innovations (Araújo *et al*., 2023).

CONCLUSION

Analysis of secondary data indicates that integrating AI and ML into precision agriculture has the potential to support modern farming through increased efficiency, sustainability, and economic viability. These technologies optimize resource use, reduce environmental impact, and improve crop yields through data-driven decision-making and automation of the most labor-intensive tasks. However, high cost of adoption, issues related to data privacy, and requirement of farmer education are critical. Continued progress in AI, IoT, and robotics will be tantamount to increasing innovation in precision agriculture as scalable solutions for global food security continue to advance with sustainable agricultural methods. For the future, research also needs to go in the direction of increasing access to those technologies, particularly to small-scale farmers in developing regions, to effectively distribute the benefits of precision agriculture more widely and equitably.

Authors' Contribution

All authors have contributed to this review by adding different sections according to their expertise. Accordingly, K.P.G.D.M. Polwaththa and A.A.Y. Amarasinghe contributed to agriculture, precision agriculture, and the technologies introduced for precision farming. S.T.C. Amarasinghe dealt with the aspects of economic benefits, ethical issues, and case studies of precision agriculture. A.A.Y.D. Amarasinghe contributed by discussing artificial intelligence and other engineering technologies proposed and implemented in precision and smart agriculture.

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