

Artificial Intelligence Applications in Smart Agriculture for Enhancing Productivity and Promoting Sustainable Development for the Next Generation Worldwide

Kamal Prasad*

Privi Life Science, Research and Development, A-71, TTC Industrial Area, Thane-Belapur Road, Kopar Khairane, Navi Mumbai, Maharashtra, India

***Corresponding author:** Kamal Prasad, Privi Life Science, Research and Development, A-71, TTC Industrial Area, Thane-Belapur Road, Kopar Khairane, Navi Mumbai, Maharashtra, India

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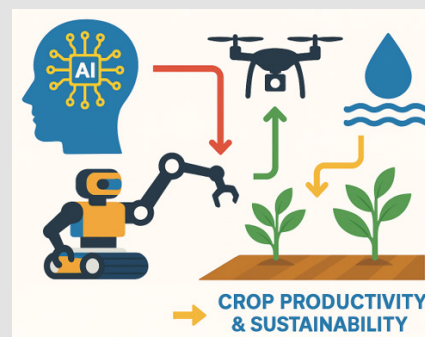
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ABSTRACT

Agriculture is a fundamental sector for global food security, economic development, and rural livelihoods. However, it faces increasing challenges such as climate change, soil degradation, water scarcity, pest infestations, and population growth, which threaten sustainable food production. Traditional farming methods are often insufficient, creating a need for innovative solutions. Artificial Intelligence (AI) has emerged as a transformative tool in modern agriculture, enabling data-driven decision-making, precision farming, intelligent crop monitoring, and predictive analytics. AI-powered smart agriculture integrates technologies such as machine learning, computer vision, IoT, drones, and robotics to optimize farming operations and improve productivity. These solutions support real-time monitoring of crop health, soil conditions, pest detection, yield prediction, and efficient resource allocation, reducing waste and environmental impact. This paper reviews key AI applications, including precision farming, smart irrigation, crop disease detection, yield estimation, agricultural robotics, drone-based monitoring, and supply chain optimization. It also highlights how AI contributes to sustainability by improving resource efficiency, conserving water, reducing chemical use, and supporting climate-resilient practices. Challenges such as high costs, limited infrastructure, and lack of technical expertise are discussed, along with future prospects (Graphical Abstract). Overall, AI-driven agriculture has the potential to enhance productivity, improve efficiency, and support sustainable and resilient farming systems to meet future food demands.

Keywords: Artificial Intelligence; Smart Agriculture; Precision Farming; Sustainable Development; Crop Yield Prediction; IoT

Abbreviations: AI: Artificial Intelligence; IoT: Internet of Things; GPS: Global Positioning Systems; CNNs: Convolutional Neural Networks; SVM: Support Vector Machines; ANN: Artificial Neural Networks; SDGs: Sustainable Development Goals



Graphic Abstract.

Note: AI → Drones → Smart Irrigation → Robotics → Enhanced Crop Productivity & Sustainability.

Introduction

Agriculture is a crucial sector for global economic development, food security, and rural livelihoods. With the world population projected to approach 10 billion by 2050, the demand for food is expected to increase substantially, necessitating a corresponding rise in agricultural production. Traditional farming, however, faces significant challenges, including unpredictable climate conditions, limited arable land, soil degradation, water scarcity, and pest infestations, all of which threaten crop yields and food security. These challenges highlight the need for innovative technologies that improve efficiency, reduce losses, and support sustainable agricultural practices. Recent technological advancements, such as precision farming, IoT devices, drones, and satellite imaging, have become instrumental in enhancing agricultural productivity. Among these, Artificial Intelligence (AI) has emerged as a transformative technology capable of converting conventional farming into smart agriculture. AI employs machine learning algorithms, computer vision, and data analytics to process large volumes of agricultural data, enabling informed decision-making in crop management, irrigation, fertilization, pest control, and yield optimization. By incorporating AI into farming operations, farmers can enhance efficiency, reduce resource wastage, and increase productivity while mitigating environmental impacts. Smart agriculture integrates AI with advanced technologies, including sensors, drones, satellite imagery, robotics, and IoT devices, to monitor field conditions in real-time and optimize farming practices.

For instance, AI-enabled sensors can measure soil moisture and nutrient content to determine precise irrigation and fertilization schedules. Drone-based imaging allows early detection of pest infestations and crop diseases, facilitating timely interventions. Predictive AI models can forecast crop yields and assess risks related to climate variability, enabling proactive farm management. These technologies promote sustainable practices by improving resource efficiency, minimizing excessive fertilizer and pesticide use, conserving water, and reducing environmental pollution. Additionally, AI-powered automation, such as robotic harvesting and autonomous machinery, decreases labour dependency while enhancing operational precision. Collectively, these innovations improve crop productivity and support climate-resilient, sustainable food production systems. The aim of this research paper is to explore the role of AI in smart agriculture, with a focus on its applications in precision farming, crop disease detection, smart irrigation, yield prediction, agricultural robotics, drone monitoring, sustainability, and future prospects. By examining these applications, the study highlights how AI enhances agricultural productivity, optimizes resource management, and promotes sustainable

development, positioning smart agriculture as a critical strategy for addressing global food security challenges.

Artificial Intelligence in Agriculture

Artificial Intelligence (AI) is one of the most transformative technologies of the 21st century, with rapidly expanding applications across sectors such as healthcare, education, manufacturing, and agriculture (Russell [1,2]). AI refers to computer systems capable of performing tasks that typically require human intelligence, including learning, reasoning, pattern recognition, and decision-making. In agriculture, AI has emerged as a powerful tool to enhance productivity, optimize resource usage, and Deep learning models promote sustainable farming practices. The agricultural sector faces significant global challenges, including climate change, soil degradation, water scarcity, pest infestations, and rising food demand driven by population growth (FAO [2,3]). Traditional farming often relies on manual observation and experience-based decisions, which may not always yield accurate results. AI technologies help address these challenges by analyzing vast amounts of agricultural data collected from sensors, satellites, weather stations, and farm equipment. The integration of AI with digital technologies enables the development of smart agriculture systems, where data-driven insights guide farming decisions. Such systems allow farmers to monitor crop conditions, predict yields, manage resources efficiently, and respond rapidly to environmental changes.

Artificial Intelligence Technologies in Agriculture

AI applications in agriculture primarily leverage technologies such as machine learning, computer vision, robotics, and the Internet of Things (IoT) (Liakos, et al. [4]). Machine learning algorithms analyze historical and real-time agricultural data to identify patterns and predict outcomes related to crop growth, soil fertility, and pest outbreaks. Computer vision enables AI systems to process images of crops captured by drones or field-installed cameras. These systems can detect plant diseases, nutrient deficiencies, and pest damage at early stages, allowing for timely interventions that reduce crop losses and minimize excessive pesticide use. Predictive analytics is another critical AI application in agriculture. By analyzing weather data, soil characteristics, and historical crop performance, AI models can forecast crop yields and recommend optimal planting schedules, helping farmers plan more effectively. AI-powered smart irrigation systems optimize water management by analyzing soil moisture, weather forecasts, and crop water requirements to determine precise irrigation needs. This approach conserves water while sustaining crop productivity (Shah [5]) (Figure 1).

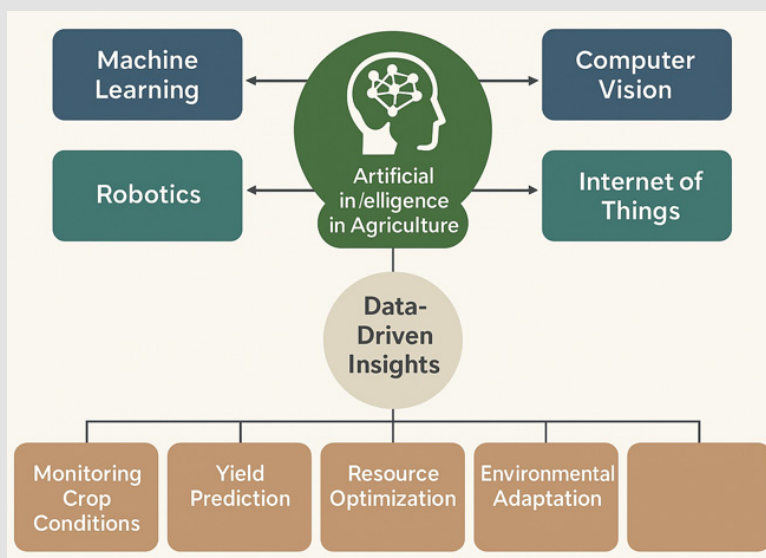


Figure 1: Systematic diagram for Artificial Intelligence application in Agriculture.

Benefits of Artificial Intelligence in Agriculture

The implementation of AI technologies in agriculture offers multiple benefits, enhancing both productivity and sustainability. One of the most significant advantages is precision farming, which enables the application of fertilizers, pesticides, and water only where required. This targeted approach reduces input costs and mitigates environmental pollution. AI also supports improved decision-making through real-time data analysis and automated recommendations. For instance, AI systems can alert farmers about potential pest infestations or adverse weather conditions, enabling preventive measures to minimize losses. Additionally, AI-powered agricultural machinery and robots can execute repetitive tasks such as planting, harvesting,

and weed control with high precision and efficiency. Automation decreases labour requirements and increases operational efficiency. AI also contributes to better supply chain management by analyzing market demand, transportation logistics, and storage conditions, optimizing the distribution of agricultural products. This reduces post-harvest losses and ensures timely delivery of food to consumers (Kamilaris, et al. [6]). In summary, AI in agriculture facilitates precision farming, enhances decision-making, improves resource management, and supports sustainable practices. By leveraging data-driven insights and automation, AI can help address the pressing challenges of modern agriculture while boosting productivity and efficiency (Figure 2).

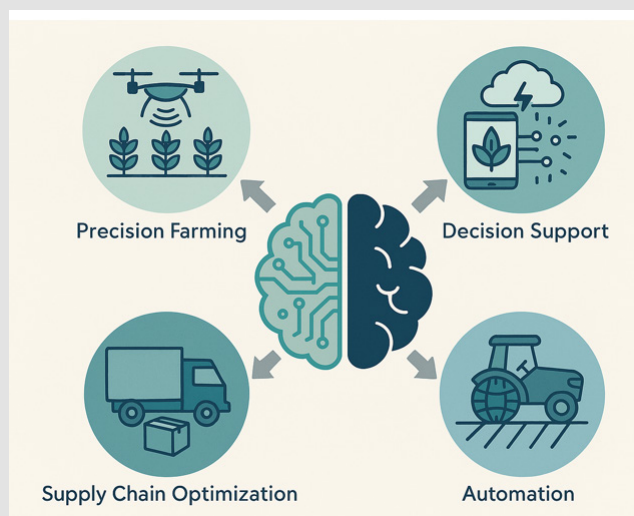


Figure 2: Systematic diagram illustrating the Benefits of AI in Agriculture.

Applications of Artificial Intelligence in Smart Agriculture

Precision Farming

Precision farming, also referred to as precision agriculture, is one of the most significant applications of Artificial Intelligence (AI) in modern agriculture. It involves leveraging advanced technologies such as AI, Global Positioning Systems (GPS), sensors, drones, and data analytics to monitor and manage agricultural fields with high accuracy (Liakos, et al. [4]). The primary goal of precision farming is to maximize crop productivity while minimizing the use of resources such as water, fertilizers, pesticides, and energy. Traditional farming often treats an entire field uniformly, applying the same amount of inputs across all areas, despite variations in soil fertility, moisture levels, and crop health within different sections of the field. Precision farming overcomes this limitation by using AI to analyze these spatial variations and provide site-specific recommendations. This approach enhances resource efficiency, increases crop yields, and reduces environmental impact.

Role of Artificial Intelligence in Precision Farming: AI plays a central role in precision farming by processing large volumes of agricultural data collected from sensors, satellite imagery, weather stations, and farm machinery. Machine learning algorithms identify patterns in soil conditions, crop growth, nutrient levels, and environmental factors to predict potential issues such as pest infestations or nutrient deficiencies (Kamilaris, et al. [6]). Early detection enables farmers to take preventive measures before problems escalate. Computer vision technology further enhances precision farming. Drones and field robots equipped with cameras capture images of crops, and AI algorithms analyze these images to detect diseases, weeds, or water stress. By identifying these issues early, farmers can apply targeted interventions, reducing the need for excessive pesticides and chemicals.

Technologies Used in Precision Farming: Several digital technologies support AI-based precision farming:

- **Soil Sensors:** Measure parameters such as moisture, temperature, and nutrient levels, transmitting data to cloud platforms for AI-based analysis.
- **GPS Technology:** Enables precise mapping of agricultural fields and guides automated machinery for accurate application of fertilizers, seeds, and pesticides.
- **Drones (UAVs):** Equipped with multispectral cameras, drones capture high-resolution images for crop health monitoring. AI software processes these images to generate detailed crop health maps.

Benefits of Precision Farming: Precision farming provides multiple benefits for farmers and the environment:

- **Enhanced Crop Productivity:** Applying inputs accurately improves crop growth and yield.
- **Efficient Resource Use:** Reduces overuse of water, fertilizers, and pesticides, lowering costs and environmental impact.
- **Improved Decision-Making:** Real-time monitoring and predictive insights allow timely interventions for issues such as drought stress or pest outbreaks (Shah [5]).

By combining AI with sensors, drones, and GPS systems, precision agriculture allows for data-driven field management, improving productivity while promoting sustainable practices. As technology advances, precision farming is expected to become increasingly accessible and affordable, supporting global food security.

Crop Disease Detection Using Artificial Intelligence

Crop diseases caused by fungi, bacteria, viruses, and pests represent a major challenge in agriculture, leading to significant reductions in yield and quality (Ferentinis [7]). Traditional disease detection relies on manual inspection, which is often time-consuming, less accurate, and unable to detect early-stage infections. AI has emerged as a powerful tool for improving crop disease detection through automated and precise analysis. AI-powered systems use machine learning, deep learning, and computer vision to identify plant diseases from images of leaves, stems, and fruits. Early detection allows farmers to take timely preventive measures, reducing crop losses and improving overall productivity.

AI Techniques for Crop Disease Detection: AI-based disease detection primarily relies on image processing and machine learning algorithms. Computer vision techniques analyze visual features of plants captured via cameras, smartphones, or drones. The systems compare these images against large datasets of healthy and diseased plants to identify disease symptoms. Deep learning models, particularly Convolutional Neural Networks (CNNs), have demonstrated high accuracy in detecting plant diseases. These models automatically learn patterns from thousands of images and classify diseases based on features such as color changes, spots, leaf deformation, and texture variations. Other machine learning algorithms, such as Support Vector Machines (SVM), Random Forest, and Artificial Neural Networks, are also employed for disease classification and prediction (Mohanty, et al. [8]) (Figure 3).

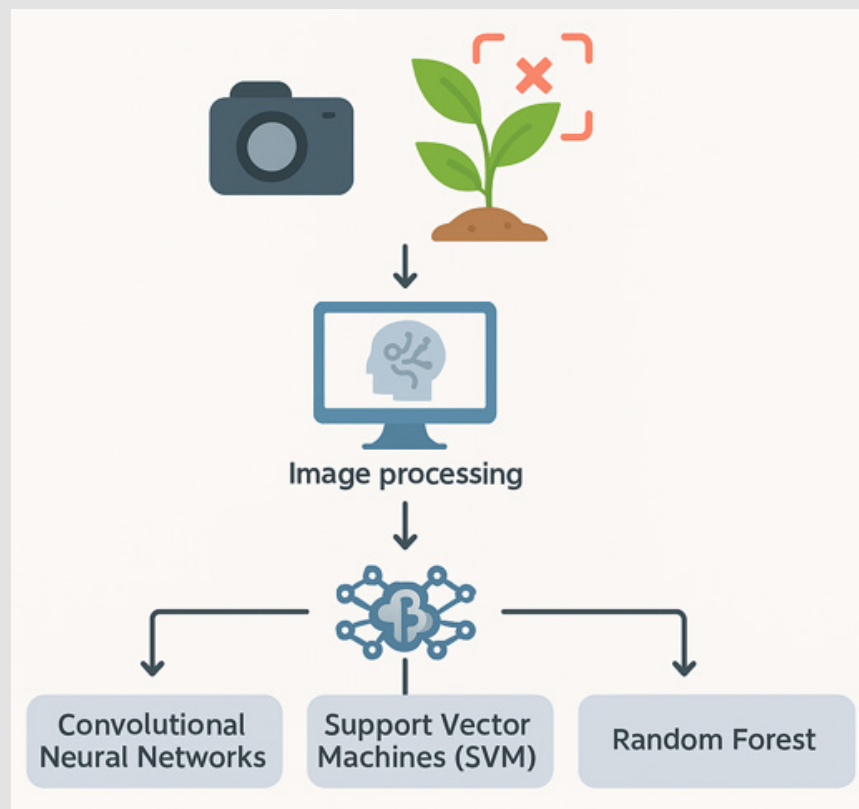


Figure 3: Systematic diagram of *Crop Disease Detection Using Artificial Intelligence*.

Role of Smart Devices and Drones: Modern disease detection systems integrate AI with smart devices and remote sensing technologies. Farmers can use smartphones to capture images of affected plants, and AI-powered mobile applications provide instant disease diagnoses along with treatment recommendations. Drones equipped with high-resolution or multispectral cameras monitor large fields, generating aerial images that AI systems analyze to identify infected areas. These systems produce crop health maps that guide precise interventions.

Benefits of Artificial Intelligence Based Crop Disease Detection: AI-based crop disease detection offers several advantages:

- **Early Disease Detection:** Enables farmers to control infections before they spread, reducing yield losses.
- **Reduced Pesticide Usage:** Targeted treatments minimize chemical application, lower costs, and decrease environmental impact.
- **Improved Decision-Making:** Real-time information allows farmers to monitor crops continuously and respond to potential disease outbreaks promptly.

By integrating AI with computer vision, machine learning, and drone technologies, modern agriculture can achieve automated, accurate, and efficient crop health monitoring. These innovations support sustainable farming, reduce losses, and enhance productivity. As AI technology evolves, crop disease detection systems are expected to become more advanced, affordable, and widely accessible, playing a key role in ensuring global food security.

Smart Irrigation Systems Using Artificial Intelligence: Water is a critical resource for agricultural production, yet increasing water scarcity poses a significant global challenge. Agriculture accounts for nearly 70% of the world's freshwater consumption, making efficient water management essential for sustainable farming (FAO [3]). Traditional irrigation methods often follow fixed schedules or rely on manual observation, which can lead to over-irrigation or under-irrigation. Both scenarios negatively impact crop productivity and resource conservation. Artificial Intelligence (AI) offers effective solutions for optimizing irrigation through the development of smart irrigation systems. These AI-based systems leverage technologies such as soil moisture sensors, weather forecasting models, Internet of Things (IoT) devices, and advanced data analytics to ensure crops receive the right amount of water at the right time (Shah [5]).

Role of Artificial Intelligence in Smart Irrigation: AI plays a central role in processing agricultural data and determining optimal irrigation strategies. Smart irrigation systems collect data from multiple sources, including soil moisture and temperature sensors, rainfall measurements, and weather forecasts. AI algorithms analyze these datasets to evaluate environmental conditions and crop water requirements. Machine learning models predict the precise water needs of crops based on factors such as soil type, crop growth stage,

temperature, and humidity. These models continuously learn from historical and real-time data, improving the accuracy of irrigation recommendations over time (Liakos, et al. [4]). AI-based irrigation systems can also automate the operation of irrigation equipment, such as pumps, valves, and sprinklers. When soil moisture levels fall below a predefined threshold, the system activates irrigation to supply water to crops. Conversely, if rainfall is predicted, the system can delay irrigation to prevent unnecessary water use (Figure 4).

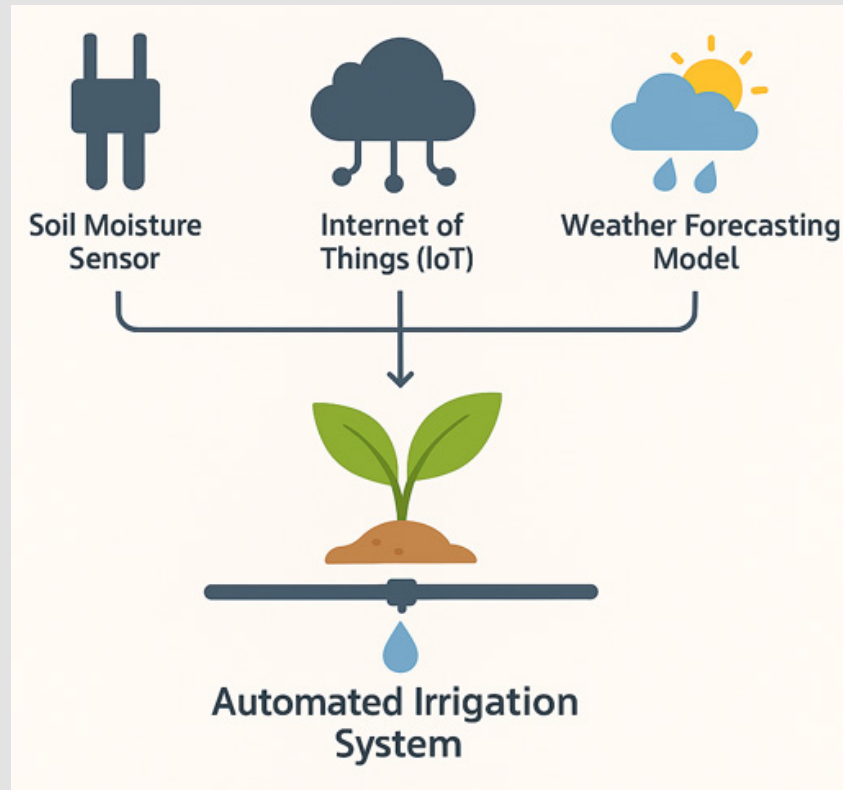


Figure 4: Systematic diagram for AI Technologies Supporting Smart Irrigation Systems.

Technologies Supporting Smart Irrigation: Smart irrigation integrates several modern technologies to optimize agricultural water management:

- **Soil Moisture Sensors:** Continuously measure water content in the soil and provide real-time data for AI-based irrigation decisions.
- **Internet of Things (IoT):** Connects sensors, irrigation equipment, and cloud-based platforms. IoT devices collect and transmit field data to AI systems for analysis, accessible via mobile or desktop applications.
- **Weather Forecasting Models:** AI analyzes rainfall probabil-

ity, temperature, and humidity to adjust irrigation schedules, reducing water wastage.

- **Automated Irrigation Systems:** Technologies such as drip and sprinkler irrigation can be integrated with AI platforms to ensure uniform water distribution and efficient crop growth.

Benefits of Smart Irrigation Systems: AI-based smart irrigation systems offer numerous advantages for farmers and sustainable agriculture:

- **Water Conservation:** Provides water only, when necessary, significantly reducing waste.

- **Improved Crop Productivity:** Ensures crops receive sufficient moisture during critical growth stages, enhancing yield and plant health.
- **Reduced Labor and Operational Costs:** Automation minimizes the need for manual monitoring, allowing farmers to allocate resources to other tasks.
- **Enhanced Decision-Making:** Data-driven irrigation strategies improve planning and support precision agriculture practices (Kamilaris, et al. [6]).

By combining AI algorithms with sensors, IoT devices, and predictive weather models, smart irrigation systems optimize water management, enhance crop productivity, and promote sustainable farming practices. As water scarcity continues to challenge agriculture worldwide, the adoption of AI-driven irrigation technologies is becoming increasingly essential. Continuous technological advancements and broader accessibility will make smart irrigation systems pivotal for sustainable agricultural development and global food security.

Yield Prediction Using Artificial Intelligence

Crop yield prediction plays a crucial role in agricultural planning and management. Accurate forecasting of crop production enables farmers, policymakers, and agricultural organizations to make informed decisions regarding harvesting, storage, transportation, and market distribution. Traditionally, yield estimation has relied on manual field surveys and historical production data. However, these conventional methods often struggle to capture the complex interactions among environmental factors such as weather variability, soil fertility, irrigation practices, and pest infestations, resulting in limited prediction accuracy (Liakos, et al. [4]). Artificial Intelligence (AI) has emerged as a transformative tool for improving the precision and efficiency of crop yield predictions. By analyzing extensive agricultural datasets, AI systems can uncover patterns and relationships that are difficult to detect through traditional methods. Machine learning and deep learning models, in particular, evaluate historical agricultural data, weather trends, soil characteristics, and crop growth parameters to generate accurate yield forecasts. Such predictions allow farmers and agricultural experts to make proactive decisions that optimize production outcomes (Liakos, et al. [4]).

Role of Artificial Intelligence in Yield Prediction: AI-based yield prediction relies on data obtained from diverse sources, including satellite imagery, weather stations, soil sensors, and farm management platforms. Machine learning algorithms process this multi-source data to identify the key factors influencing crop growth and productivity. Based on these insights, AI systems can provide reliable yield estimates well before the harvesting season. Several machine learning techniques are commonly applied in yield prediction, including Artificial Neural Networks (ANN), Random Forest, Support Vector Machines (SVM), and advanced deep learning models. These

approaches analyze the relationships between environmental variables and crop productivity to forecast future yields. Deep learning models are particularly advantageous due to their capacity to handle large datasets and detect intricate patterns in agricultural information (Kamilaris, et al. [6,7]). Furthermore, AI systems increasingly incorporate remote sensing technologies such as satellite imagery and drone-based imaging to monitor crops throughout the growth cycle. These technologies provide detailed information about vegetation health, plant density, and developmental stages. AI algorithms can interpret this imagery to assess crop conditions and estimate potential yields with high precision (Wolfert, et al. [9]). AI-driven approaches enhance traditional yield prediction methods by integrating diverse data sources, analyzing complex environmental interactions, and delivering timely and accurate forecasts. Such innovations support evidence-based agricultural management and contribute to improved food security.

Factors Considered in Artificial Intelligence Based Yield Prediction: AI-based yield prediction models evaluate a variety of environmental and agricultural factors to estimate crop production accurately. Among the most influential are weather conditions, including temperature, rainfall, humidity, and solar radiation. These climatic variables directly impact crop growth and development. AI systems leverage historical weather datasets and seasonal forecasts to assess how variations in climate can influence yield outcomes (Zhang, et al. [10]). Soil characteristics represent another critical determinant of crop productivity. Parameters such as soil moisture, nutrient composition, pH level, and texture affect plant growth and overall yield potential. Real-time data from soil sensors are integrated into AI algorithms to provide a dynamic understanding of soil conditions, which improves the accuracy of yield predictions. Additionally, crop management practices such as irrigation schedules, fertilization strategies, planting density, and pest control measures play a significant role in determining crop performance. AI models incorporate these management variables alongside environmental and soil factors to generate more precise and actionable yield forecasts (Zhang, et al. [10]). By combining data on climate, soil, and agronomic practices, AI systems can provide comprehensive and reliable predictions that support decision-making for farmers and agricultural planners.

Benefits of Artificial Intelligence Based Yield Prediction: AI-based crop yield prediction offers numerous advantages for farmers, agricultural planners, and policymakers. One of the primary benefits is enhanced decision-making. Accurate forecasts allow farmers to plan harvesting schedules, allocate storage facilities, and manage transportation logistics efficiently, minimizing operational delays and post-harvest losses (Sharma, et al. [11]). Another key benefit is optimized resource management. By predicting crop performance, AI enables farmers to tailor irrigation regimes, fertilization plans, and pest management strategies to specific field conditions. This precision reduces unnecessary input usage, lowers production costs, and increases overall farm productivity (Kamilaris, et al. [6]). AI-driven yield pre-

diction also supports improved market planning. Early insights into anticipated crop output allow farmers and agricultural organizations to better anticipate supply and demand fluctuations, contributing to price stabilization and more efficient distribution channels (Wolfert, et al. [9]). Moreover, AI contributes to sustainable agriculture by promoting efficient resource utilization and minimizing environmental impacts. Data-driven decision-making enables the adoption of precision farming practices, reducing excessive chemical application, conserving water, and improving long-term soil health (Liakos, et al. [4]).

Overall, AI has become an indispensable tool in modern agriculture. By integrating diverse datasets including weather information, soil properties, crop growth patterns, and management practices AI systems generate reliable yield predictions that support strategic agricultural planning (Figure 5). As digital agriculture evolves, the integration of AI with remote sensing, IoT devices, and big data analytics is expected to further enhance the accuracy of yield prediction systems and advance sustainable farming practices (Sharma, et al. [11]).

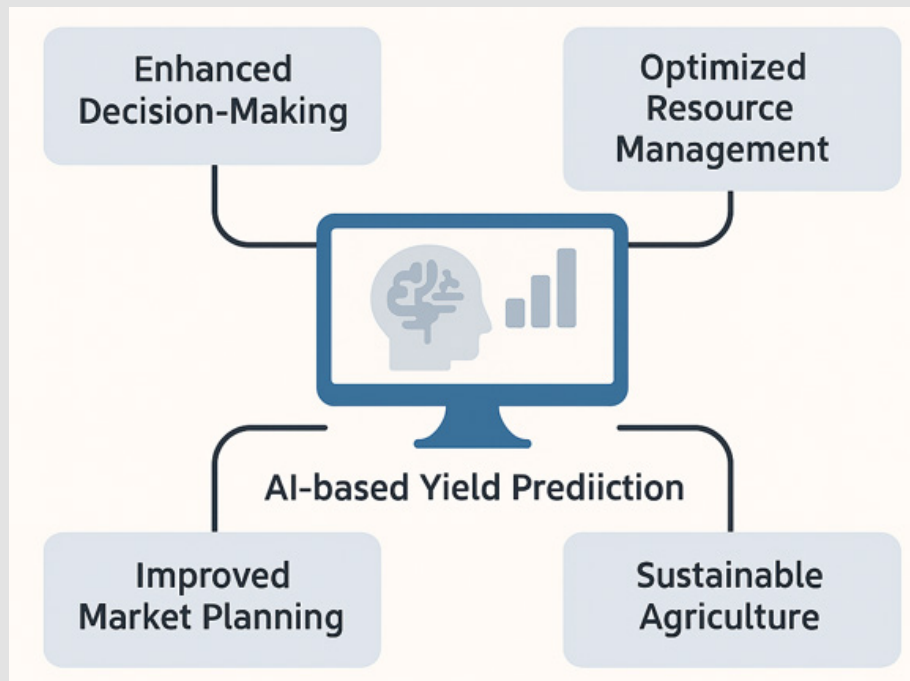


Figure 5: Systematic diagram for Benefits of AI Based Yield Prediction.

Applications of Agricultural Robotics: Agricultural robots have found wide-ranging applications in modern farming, significantly enhancing efficiency, precision, and productivity. One key application is automated planting, where robotic systems place seeds at precise depths and optimal spacing. This ensures uniform crop emergence, improves germination rates, and supports higher yields (Wolfert, et al. [9]). Another important application is cropping monitoring. Robots equipped with high-resolution cameras and multispectral sensors can traverse agricultural fields to collect real-time data on plant health, soil moisture, nutrient levels, and pest activity. AI algorithms process this data to generate actionable insights, enabling informed decisions regarding irrigation scheduling, fertilization, and pest management (Wolfert, et al. [9]). Agricultural robots are also increasingly utilized for precision spraying of fertilizers and pesticides. Instead of blanket chemical application, AI-powered systems identify areas of

the field that require treatment and deliver inputs precisely where needed. This targeted approach minimizes chemical usage, reduces production costs, and mitigates environmental impacts (Liakos, et al. [4]). In addition, autonomous tractors and farm machinery are transforming large-scale farming operations. These machines use GPS guidance, AI-based navigation, and sensor feedback to perform tasks such as ploughing, seeding, and harvesting without human drivers.

By automating labor-intensive activities, autonomous farm equipment increases operational efficiency and enables the management of extensive agricultural areas with minimal workforce requirements (Zhang, et al. [13]). Through these applications, agricultural robotics combined with AI not only enhances productivity and operational efficiency but also promotes sustainable and data-driven farming practices.

Benefits of Agricultural Robotics: The adoption of agricultural robotics offers numerous advantages for modern farming systems. One of the most notable benefits is increased productivity. Unlike human labour, robots can operate continuously for extended periods without fatigue, enabling the timely completion of agricultural operations and improving overall farm efficiency (Liakos, et al. [4]). Another major advantage is the reduction of labor costs. Many agricultural regions face labor shortages due to urban migration and aging rural populations. Robotic systems automate labor-intensive tasks, mitigating the impact of workforce limitations and ensuring consistent farm operations (Kamilaris, et al. [6]). Precision and accuracy in farming practices represent additional benefits. AI-driven robots perform tasks with high consistency, enhancing crop management and supporting higher yields. Targeted interventions, such as precision spraying of fertilizers and pesticides, minimize chemical overuse and promote environmentally sustainable agricultural practices (Wolfert, et al. [9]).

The integration of AI with robotics transforms traditional agriculture into automated and data-driven systems. Agricultural robots can manage complex tasks such as planting, harvesting, weeding, and crop monitoring with minimal human intervention. These technologies optimize resource use, reduce dependency on manual labor, and enhance operational efficiency across the farm. As research and technological innovation continue, agricultural robots are expected to become more accessible and cost-effective for farmers worldwide. Widespread deployment of AI-powered robotic systems has the potential to address global food security challenges, improve farm sustainability, and support resilient agricultural development (Kamilaris, et al. [4,6]).

Drone Technology in Smart Agriculture

Drones, also known as Unmanned Aerial Vehicles (UAVs), are increasingly utilized in modern agriculture to enhance crop monitoring, precision farming, and field management. Equipped with AI-powered cameras, multispectral sensors, and GPS systems, drones provide a rapid, cost-effective, and highly efficient method for acquiring high-resolution aerial data over large agricultural areas (Liakos, et al. [4,13]). Traditional field inspection methods are often labor-intensive, time-consuming, and limited in spatial coverage, which can reduce the effectiveness of crop health monitoring and timely intervention. Drone technology overcomes these limitations by enabling real-time assessment of crop conditions, identification of pest infestations, detection of nutrient deficiencies, and evaluation of soil variability. This aerial perspective allows farmers to make data-driven management decisions and implement targeted interventions, improving both productivity and resource efficiency (Wolfert, et al. [9]). AI integration with drone systems further enhances their capabilities. Machine learning and computer vision algorithms can process the large volumes of imagery captured by UAVs to detect crop stress, classify plant species, and estimate yield potential. This combination

of AI and UAV technology supports precision agriculture by enabling site-specific management practices, reducing the overuse of fertilizers and pesticides, and promoting sustainable farming (Kamilaris, et al. [6]). Overall, drone technology represents a transformative tool in smart agriculture, providing farmers with actionable insights, reducing manual labor, and supporting efficient and sustainable farm management.

Role of Artificial Intelligence in Drone-Based Agriculture: The integration of AI with drone technology has transformed agricultural data collection and analysis, enabling more precise and timely farm management decisions. AI algorithms process multispectral, hyperspectral, and RGB imagery captured by drone-mounted cameras to detect variations in plant health, identify nutrient deficiencies, and monitor water stress across entire fields (Kamilaris, et al. [6,12]). Machine learning models analyze these datasets to identify patterns, classify crops, and detect early signs of pest infestations or disease outbreaks. By providing actionable insights, AI-powered drones allow farmers to implement targeted interventions, minimizing crop losses and optimizing resource use (Liakos, et al. [4]). AI also facilitates precision agriculture through the calculation of vegetation indices, such as the Normalized Difference Vegetation Index (NDVI) and the Soil Adjusted Vegetation Index (SAVI). These indices quantify plant vigor and photosynthetic activity, enabling field-level assessment of crop health. By mapping areas that require specific attention, such as targeted irrigation, fertilization, or pest management, AI-driven drones enhance both productivity and sustainability (Wolfert, et al. [9]). In addition, the combination of AI with UAVs supports predictive analytics by integrating temporal imagery and historical crop performance data. This allows farmers to anticipate stress factors before they significantly impact yield and make proactive, data-driven management decisions. Overall, AI-enabled drones provide a scalable, efficient, and cost-effective solution for modern precision farming, contributing to improved agricultural productivity and sustainability (Kamilaris, et al. [6,12]).

Applications of Drone Technology in Agriculture: Drones have become an essential tool in modern agriculture due to their ability to collect high-resolution spatial and spectral data and support AI-driven decision-making. Their applications span multiple aspects of precision farming, enhancing efficiency, sustainability, and crop productivity.

- 1. Crop Health Monitoring:** Drones capture high-resolution RGB and multispectral imagery of crops, which AI algorithms analyze to assess plant vigor, detect early signs of stress, and identify nutrient deficiencies. This enables timely intervention, reducing crop losses and improving overall productivity (Kamilaris, et al. [6,10]).
- 2. Pest and Disease Detection:** AI-enabled drones can identify areas affected by pests or pathogens by detecting abnormal plant patterns and spectral signatures. Targeted treatment

can then be applied precisely where needed, minimizing pesticide use and reducing environmental impacts (Wolfert, et al. [4,9]).

3. **Field Mapping and Soil Analysis:** Equipped with multispectral, thermal, or hyperspectral sensors, drones generate detailed maps of soil properties, moisture variability, and topography. AI algorithms process this information to implement site-specific management practices, including variable-rate fertilization, irrigation, and crop placement, thereby optimizing resource utilization (Kamilaris, et al. [6,12]).
4. **Monitoring Irrigation and Water Stress:** UAVs detect areas experiencing water stress, uneven irrigation, or drought conditions through thermal and multispectral imaging. By analyzing these data with AI models, farmers can adjust irrigation scheduling and water distribution to conserve resources while maintaining optimal crop growth (Wolfert, et al. [4,9]).

Through these applications, drone technology enables real-time, data-driven decision-making in precision agriculture, reduces labor requirements, and supports sustainable farming practices while improving productivity and efficiency.

Benefits of Drone Technology in Agriculture: Drone technology offers significant advantages for modern agriculture by enabling rapid, accurate, and large-scale data collection. Compared to traditional manual inspection methods, drones can efficiently survey extensive farmland, saving both time and labor. When integrated with AI algorithms, drones provide real-time data analysis, allowing farmers to make timely, informed decisions (Kamilaris, et al. [4,6]). One of the primary benefits is the facilitation of targeted interventions. AI-enabled drones can implement precision spraying of fertilizers and pesticides, site-specific fertilization, and timely irrigation management. These practices reduce resource wastage, lower operational costs, and minimize environmental impacts, contributing to more sustainable farming (Wolfert, et al. [9]). Drone-based monitoring also improves yield prediction and farm management. By continuously capturing data on crop growth stages, plant health, and field conditions, drones provide actionable insights that support optimized resource allocation and decision-making. This real-time monitoring enhances overall farm efficiency, increases productivity, and supports sustainable agricultural practices (Zhang, et al. [12,13]). Furthermore, the integration of AI with UAV technology enables predictive analytics by identifying early signs of stress, nutrient deficiencies, or pest infestations. Farmers can respond proactively, reducing potential crop losses and improving both quality and quantity of yield. As drone technology continues to evolve, it is poised to become an indispensable tool in precision agriculture, helping farmers worldwide implement data-driven, environmentally sustainable farming strategies (Kamilaris, et al. [4,6]).

Artificial Intelligence and Sustainable Development in Agriculture

Sustainable agriculture aims to meet current and future food demands without compromising the capacity of future generations to produce food. With growing global populations, limited natural resources, and environmental challenges such as climate change, adopting sustainable farming practices has become essential. AI plays a transformative role in promoting sustainable agriculture by optimizing resource use, reducing environmental impacts, and enhancing productivity. By integrating AI with precision farming, smart irrigation, crop disease detection, robotics, drone technology, and supply chain management, farmers can develop more efficient, resilient, and environmentally responsible agricultural systems (Kamilaris, et al. [4,6]).

Artificial Intelligence for Resource Optimization

A key contribution of AI to sustainable agriculture is resource optimization. AI-based decision support systems process real-time data from soil sensors, weather stations, and crop monitoring devices to provide precise recommendations for irrigation, fertilization, and pesticide application. By applying inputs only where and when needed, farmers maintain high yields while minimizing environmental pollution. Reduced chemical usage prevents soil degradation, water contamination, and negative impacts on surrounding ecosystems, promoting long-term agricultural sustainability (Wolfert, et al. [4,9]). Smart irrigation systems further enhance resource efficiency. AI integrates soil moisture sensors, weather forecasts, and crop water requirements to determine optimal irrigation schedules. Automated irrigation ensures that crops receive sufficient water for growth without wastage, conserving water resources and reducing energy consumption associated with pumping and distribution systems (Kamilaris, et al. [6]).

Climate-Resilient Agriculture

Climate change poses substantial risks to agriculture through irregular rainfall, droughts, floods, and extreme temperatures. AI contributes to climate-resilient farming by analyzing historical climate records, real-time weather data, and soil conditions to provide actionable insights for farmers. Predictive models can recommend optimal sowing dates, suitable crop varieties, and adaptive irrigation schedules tailored to anticipated climatic conditions. These AI-enabled strategies enhance resilience against climate variability, reducing risks of crop loss (Liakos, et al. [4,13]). AI-powered crop monitoring and disease detection also support climate resilience. Early identification of stress caused by drought, pests, or disease allows timely interventions, protecting yields and ensuring food security (Wolfert, et al. [9]).

Artificial Intelligence in Supply Chain and Post-Harvest Management

Sustainable agriculture extends beyond production to include efficient food distribution and reduced post-harvest losses. AI-driven supply chain management optimizes logistics, storage, and transportation of agricultural products. Machine learning algorithms predict market demand, monitor storage conditions, and schedule deliveries, thereby reducing spoilage and ensuring timely availability of food (Kamilaris & Prenafeta-Boldú [14]). Integration of AI with robotics and automation in harvesting and sorting further enhances efficiency. AI-powered robots handle repetitive tasks accurately, minimizing post-harvest damage. Combined with optimized logistics, these technologies ensure agricultural products reach consumers with minimal waste, supporting environmental sustainability and food security (Liakos, et al. [4,9]).

Environmental and Socioeconomic Impacts

The adoption of AI in agriculture has broader environmental and socioeconomic benefits. Reduced fertilizer and pesticide use lowers greenhouse gas emissions and prevents water contamination, contributing to ecological conservation. Precision irrigation and resource management reduce pressure on natural resources, ensuring availability for future generations (Zhang, et al. [13]). Socioeconomically, AI empowers farmers with real-time insights that improve decision-making and productivity. Smallholder farmers can leverage AI-enabled mobile applications to adopt precision agriculture practices, reduce reliance on manual labor, and improve livelihoods. Ad-

ditionally, AI-driven market analysis enables access to fair prices and more stable incomes (Liakos, et al. [4,14]). AI is a powerful enabler of sustainable development in agriculture. By optimizing resource use, reducing chemical inputs, conserving water, enhancing climate resilience, and improving supply chain efficiency, AI supports environmentally responsible and economically viable farming systems. Integration of AI with modern agricultural technologies including precision farming, smart irrigation, crop monitoring, robotics, and UAVs—ensures high productivity while minimizing environmental impacts. As AI technologies continue to advance and become more accessible, their widespread adoption will be critical to achieving global sustainable agriculture goals and ensuring food security for present and future generations (Wolfert, et al. [9,10]).

Challenges of Artificial Intelligence Adoption in Agriculture

Artificial Intelligence (AI) has shown significant potential to transform agriculture through precision farming, smart irrigation, crop monitoring, robotics, and supply chain optimization. Despite its benefits, the widespread adoption of AI in agriculture faces several critical challenges, including financial constraints, inadequate digital infrastructure, limited technical knowledge among farmers, and difficulties in integrating AI with existing farming practices (Figure 6). Addressing these obstacles is essential for AI technologies to contribute effectively to sustainable and productive agriculture (Liakos, et al. [4,14]).

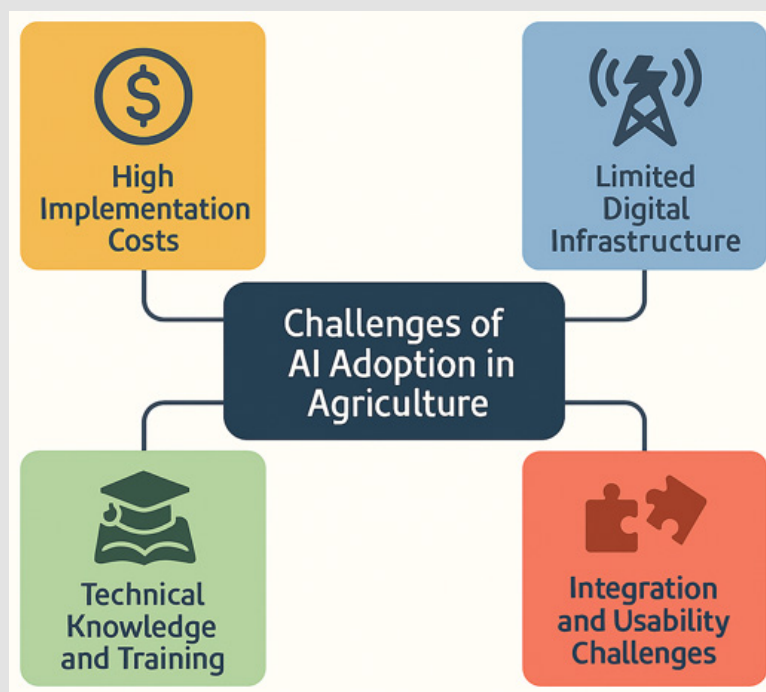


Figure 6: Systematic diagram for Challenges of AI Adoption in Agriculture.

High Implementation Costs

A major barrier to AI adoption is the high cost of advanced technologies, such as UAVs, IoT-enabled sensors, automated machinery, and AI software platforms. Smallholder and marginal farmers often lack the financial resources to invest in such equipment. The initial capital required for purchasing devices, installing digital monitoring systems, and maintaining AI platforms can be prohibitive, delaying adoption and limiting access to precision agriculture solutions (Kamilaris [13,14]).

Limited Digital Infrastructure

AI-based agricultural systems rely on real-time data collection, cloud computing, and internet connectivity. In many rural and remote regions, the lack of reliable digital infrastructure restricts the deployment of AI technologies. Without stable internet access, data from drones, sensors, and farm management systems cannot be transmitted or processed efficiently, limiting farmers' ability to obtain timely insights and implement precision farming practices (Wolfert, et al. [4,9,15]).

Technical Knowledge and Training

Effective utilization of AI in agriculture requires familiarity with data-driven decision-making, operating automated machinery, and interpreting AI-generated insights. Many farmers, particularly in developing regions, lack the technical expertise needed to adopt these technologies, reducing their ability to fully benefit from AI solutions. Capacity-building programs, training workshops, and user-friendly interfaces are critical to equip farmers with the necessary skills to implement AI-based agricultural practices (Kamilaris [13,14]).

Integration and Usability Challenges

Integrating AI systems with existing farm operations presents additional hurdles. AI platforms often need to be compatible with farm management software, digital sensors, and mobile applications. Systems that are complex or unintuitive can discourage adoption. There is a need for affordable, scalable, and user-friendly AI solutions that are adaptable to different farm sizes, crop types, and local agricultural practices (Liakos, et al. [4,9]).

Opportunities and Future Prospects

Despite these challenges, ongoing advancements in digital technologies and supportive policies for smart agriculture are improving AI accessibility. Low-cost sensors, mobile-based AI applications, and cloud computing platforms are making precision agriculture increasingly viable for small and medium-scale farmers. User-friendly interfaces allow real-time insights to be delivered directly to smartphones or tablets, facilitating better crop management decisions (Kamilaris [4,14]). Continuous research and innovation are expected to reduce

costs, improve connectivity, and enhance technical literacy, gradually overcoming adoption barriers. Over time, AI is likely to become a cornerstone of sustainable agriculture, supporting productivity, resource efficiency, and global food security (Wolfert, et al. [4,13]). Addressing financial, infrastructural, and educational challenges is essential to unlock the full potential of AI, enabling farmers worldwide to adopt efficient, sustainable, and productive agricultural practices.

Future Scope of Artificial Intelligence in Agriculture

Artificial Intelligence (AI) is rapidly reshaping modern agriculture by supporting precision farming, smart irrigation, robotic automation, UAV-based monitoring, and crop yield prediction. The future scope of AI in agriculture is highly promising, driven by continuous advancements in machine learning, deep learning, robotics, data analytics, and digital technologies. As AI technologies become more accurate, cost-effective, and accessible, they are expected to further enhance agricultural productivity, sustainability, and climate resilience. Predictive AI models will increasingly enable farmers to forecast yields, anticipate pest and disease outbreaks, and optimize resource use at field and farm scales. The integration of AI with remote sensing, IoT devices, and big data analytics will allow for real-time monitoring of crop growth, soil conditions, and environmental factors, improving decision-making and operational efficiency (Kamilaris [9,14]). Robotic and automated systems powered by AI will continue to evolve, enabling autonomous planting, weeding, harvesting, and post-harvest processing. These technologies will reduce labor dependency, lower operational costs, and ensure precision in farming operations. Similarly, AI-driven drones will provide more sophisticated multispectral and hyperspectral imaging capabilities, allowing early detection of plant stress, nutrient deficiencies, and water stress, which will enhance yield and resource optimization (Liakos, et al. [4,13]).

Furthermore, AI has the potential to transform supply chain management, market analysis, and post-harvest logistics. Machine learning algorithms can predict market demand, optimize storage and transportation, and minimize post-harvest losses, thereby improving the economic sustainability of agricultural operations. In the longer term, AI may also facilitate climate-smart agriculture by integrating historical and real-time climate data to recommend adaptive farming strategies, including crop selection, sowing times, and irrigation management tailored to changing environmental conditions. Such innovations will be crucial in enhancing the resilience of agricultural systems to climate variability and global food security challenges (Wolfert, et al. [9,14]). Overall, the future of AI in agriculture lies in holistic, data-driven, and automated farming systems that integrate precision agriculture, robotics, drones, IoT, and AI-powered analytics. As technological barriers decrease and adoption expands, AI is poised to become a cornerstone of sustainable, efficient, and productive global agriculture (Figure 7).

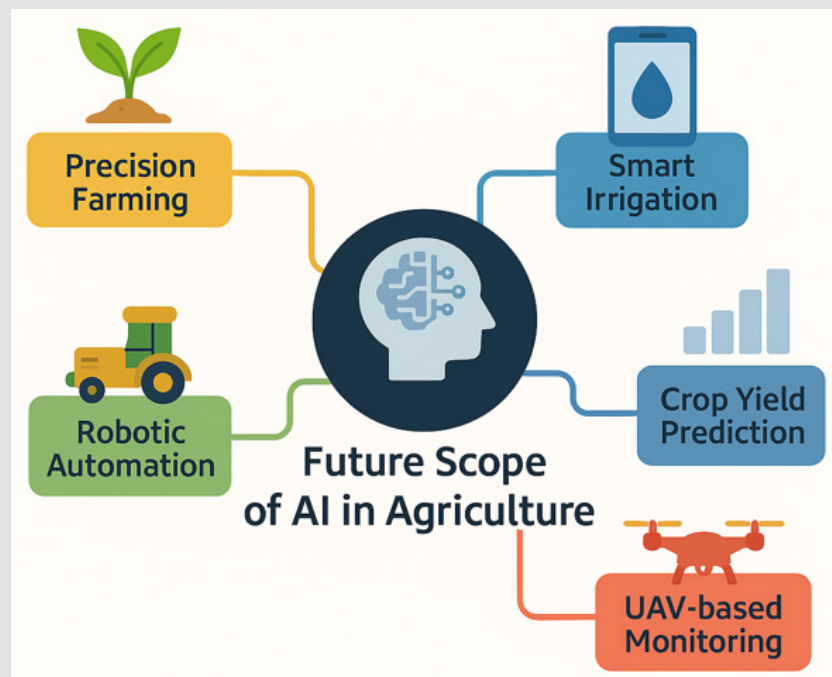


Figure 7: Systematic Sketch for Future Scope of AI in Agriculture.

Enhanced Decision Support Systems

AI-based decision support systems (DSS) are expected to become increasingly sophisticated, offering farmers highly precise recommendations for crop selection, irrigation management, fertilization, and pest control. Advanced machine learning and deep learning models will process and analyze large volumes of data from soil sensors, drones, satellite imagery, and weather stations, providing predictive insights that enable real-time, data-driven decision-making. These capabilities allow farmers to maximize crop yields while minimizing input costs, reducing resource waste, and mitigating environmental impacts [Kamilaris [4,14]]. Future AI-based DSS will also integrate multiple variables simultaneously, including soil characteristics, local climatic trends, crop varieties, and market demand, to create holistic agricultural planning tools. By combining environmental, biological, and economic data, these systems will support multi-dimensional analyses that optimize resource allocation, enhance farm efficiency, and minimize losses from pests, diseases, or suboptimal management practices [Wolfert, et al. [9,13]]. In addition, AI-enabled DSS will be capable of adaptive learning, continuously refining recommendations based on incoming field data and historical outcomes.

This will allow farmers to implement precision agriculture at scale, improving sustainability, productivity, and resilience against climate variability. As these systems become more accessible and user-friendly, both smallholder and commercial farmers will benefit

from actionable insights that support efficient, environmentally responsible, and profitable farming practices [Kamilaris [4,14]].

Integration with Emerging Technologies

The future of AI in agriculture is strongly associated with its integration with other emerging technologies, which can enhance efficiency, transparency, and sustainability across the food production system. One prominent example is the combination of AI with block chain technology, which can improve traceability, accountability, and transparency in agricultural supply chains. AI algorithms can monitor the journey of produce from farm to consumer, track storage and transportation conditions, and forecast market demand. This integration reduces post-harvest losses, ensures quality control, and strengthens food security and supply chain reliability [Wolfert, et al. [9,13]]. In addition, AI-powered climate modeling and predictive analytics enable farmers to anticipate and adapt to changing environmental conditions. By analyzing historical weather data, soil moisture levels, crop growth metrics, and climatic trends, AI systems can recommend resilient farming strategies that minimize risks associated with droughts, floods, or pest outbreaks. These predictive tools support climate-smart agriculture, helping farmers make data-driven decisions for crop selection, irrigation scheduling, and resource allocation while mitigating the impacts of climate variability [Kamilaris [4,14]]. Furthermore, the integration of AI with IoT devices, remote sensing, robotics, and big data analytics is expected to create fully interconnected and autonomous agricultural systems.

These technologies will enable real-time monitoring, automated interventions, and optimized resource management, resulting in higher productivity, reduced environmental impact, and more sustainable agricultural practices. Such convergence of technologies positions AI as a central enabler of future smart farming ecosystems, capable of addressing both production efficiency and environmental sustainability challenges (Wolfert, et al. [9,13]).

Robotics and Autonomous Farming

The future of agriculture will increasingly rely on AI-driven robotics and autonomous machinery to perform essential farming operations, including planting, harvesting, weeding, and precision spraying. Autonomous tractors, robotic harvesters, and AI-enabled planters are designed to operate with high accuracy and efficiency, significantly reducing labor dependency while ensuring precise execution of field tasks (Kamilaris [4,14]). These systems can optimize planting depth, spacing, and harvesting schedules, improving crop uniformity, yield quality, and overall farm productivity. Moreover, the integration of AI with swarm robotics and coordinated drone fleets allows for real-time monitoring and intervention across large-scale farms. Swarm robotics enables multiple autonomous units to collaborate, distributing workloads efficiently and covering extensive areas for tasks such as targeted pesticide application, weed removal, and soil analysis. Simultaneously, AI-powered drones can collect multispectral and high-resolution imagery to provide dynamic feedback, which informs adaptive control of robotic systems (Wolfert, et al. [9,13]). These technologies not only enhance productivity but also support environmentally sustainable practices. Precision spraying and targeted fertilization minimize chemical usage, while autonomous irrigation systems optimize water application, reducing resource waste.

By combining robotics, AI, and real-time sensing, farms can transition toward fully automated, intelligent, and eco-efficient agricultural systems capable of meeting the increasing global food demand while maintaining ecological balance (Kamilaris [9,14]).

Accessibility and Digital Literacy

To fully harness the potential of AI in agriculture, affordability and accessibility of technologies are essential. Collaboration among governments, research institutions, and technology providers is required to develop cost-effective AI solutions that are suitable for smallholder and marginal farmers. Innovations such as mobile-based AI applications, cloud computing platforms, and low-cost IoT devices can enable broader adoption of AI-driven agricultural practices, allowing farmers to benefit from real-time insights, predictive analytics, and precision farming techniques regardless of farm size or location (Kamilaris [4,14]). Equally critical is digital literacy among farmers. Effective use of AI technologies requires understanding data-driven decision-making, operating smart devices, and interpreting AI-generated recommendations. Structured training programs, workshops, and agricultural extension services are necessary to equip farmers

with the skills to use AI tools efficiently. Enhancing digital literacy will not only accelerate AI adoption but also empower farmers to implement precision agriculture practices, optimize resource use, and improve both productivity and environmental sustainability (Wolfert, et al. [9,13]). By improving accessibility and fostering digital literacy, AI can become a transformative tool for inclusive, efficient, and sustainable farming, ensuring that farmers of all scales can leverage technological innovations to meet the growing global food demand.

Artificial Intelligence Contribution to Sustainable Development

AI holds substantial potential to advance sustainable agriculture and global food security. Through optimized resource utilization, precision irrigation, targeted pest and nutrient management, and efficient supply chain operations, AI can significantly reduce environmental impacts, conserve water, and minimize the use of chemical inputs. These improvements support environmentally responsible farming practices while maintaining or enhancing crop productivity. By promoting efficient and resilient agricultural systems, AI contributes directly to achieving the United Nations Sustainable Development Goals (SDGs), particularly those focused on zero hunger (SDG 2), responsible consumption and production (SDG 12), and climate action (SDG 13) (Wolfert, et al. [4,9]). The future scope of AI in agriculture is broad and dynamic. Advances in predictive analytics, robotics, autonomous machinery, UAV-based monitoring, blockchain-enabled traceability, and climate-adaptive farming tools will further enhance the efficiency, sustainability, and resilience of agricultural systems. Continued research, technological innovation, and collaboration among governments, private sector stakeholders, and research institutions will make AI solutions more affordable, accessible, and user-friendly, enabling widespread adoption among both large-scale and smallholder farmers (Kamilaris [13,14]). Moreover, combining AI with emerging technologies and digital literacy initiatives empowers farmers to implement smart agriculture practices, optimize decision-making, and increase farm productivity while minimizing ecological footprint.

By facilitating data-driven, sustainable, and climate-resilient farming, AI can play a pivotal role in addressing global food security challenges, promoting environmentally sustainable practices, and supporting the long-term viability of agricultural systems worldwide (Wolfert, et al. [4,9]).

Conclusion

Artificial Intelligence (AI) is rapidly transforming modern agriculture by improving productivity, efficiency, and sustainability. AI-driven technologies including precision farming, crop disease detection, smart irrigation, agricultural robotics, drone-based monitoring, and yield prediction provide farmers with advanced tools to make data-driven decisions, optimize resource use, and manage crops more effectively. By analyzing large volumes of data on soil conditions, weather patterns, crop health, and market trends, AI generates ac-

tionable insights that enable smarter and more efficient farming practices. The integration of AI into agricultural systems supports higher crop yields while reducing environmental impact. Precision irrigation minimizes water waste, AI-assisted fertilization prevents over-application of chemicals, and automated pest and weed management reduces reliance on harmful inputs. In addition, AI-enabled robotics and drones streamline operations, reduce labor demands, and ensure timely interventions for crop care. Collectively, these technologies contribute to sustainable farming practices, enhancing productivity while conserving natural resources. Despite its benefits, the adoption of AI in agriculture faces significant challenges, such as high implementation costs, limited digital infrastructure in rural areas, and insufficient technical knowledge among farmers. Overcoming these challenges requires continued technological innovation, supportive policies, and education initiatives.

Mobile applications, cloud platforms, and cost-effective sensor devices are helping make AI more accessible to smallholder and marginal farmers, while training programs and extension services equip farmers with the skills needed to utilize these technologies effectively. Looking ahead, the future of AI in agriculture is highly promising, especially when combined with emerging technologies. AI can be integrated with systems such as block chain for improved supply chain transparency, predictive climate modeling for adaptive farming strategies, and autonomous robotics and drone fleets for efficient large-scale operations. These capabilities allow for optimized resource management, climate-resilient farming, and reduced post-harvest losses, strengthening the overall sustainability and resilience of the agricultural sector. In conclusion, AI-powered smart agriculture represents a major shift from traditional to intelligent, data-driven farming systems. It enables farmers to increase yields, conserve resources, and improve operational efficiency. While challenges related to cost, accessibility, and technical skills remain, ongoing innovation, supportive policies, and training programs are expected to accelerate adoption. As a result, AI-driven agriculture will play a critical role in meeting the rising global food demand, promoting sustainable development, and enhancing the resilience of agriculture for future generations.

Declarations

Competing Interests

The author of this manuscript confirms that there is not any conflict of interest associated with the manuscript.

Ethical Approval

Not applicable.

Consent to Participate

Not applicable.

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