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UTILIZATION OF THE INTERNET OF THINGS (IOT) IN PRECISION AGRICULTURE TO INCREASE PRODUCTIVITY AND EFFICIENCY OF LAND PROCESSING

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ABSTRACT

Objective: This study aims to systematically review the development and application of the Internet of Things (IoT) in precision agriculture and to identify its role in improving agricultural productivity, land management efficiency, and sustainable agricultural practices.

Research Design & Methods: This research utilized a Systematic Literature Review (SLR) following the PRISMA methodology. Relevant articles were sourced from the Scopus database through specific search terms associated with IoT and precision agriculture. Following the application of inclusion and exclusion criteria, 33 peer-reviewed papers were chosen for qualitative synthesis. The chosen studies underwent thematic analysis to uncover IoT technologies, agricultural applications, implementation results, and emerging research trends.

Findings: The Internet of Things (IoT) serves as a critical enabling technology for precision agriculture, encompassing sensors, wireless sensor networks (WSNs), edge and cloud computing, artificial intelligence (AI), and machine learning (ML). IoT improves decision-making, optimizes water, fertilizer, and pesticide use, increases productivity, lowers operational costs, and promotes sustainable agricultural practices. However, its adoption is hampered by significant implementation costs, inadequate digital infrastructure, interoperability issues, data security concerns, and farmers' technological readiness.

Implications: These findings highlight the strategic role of IoT in accelerating the transition to Smart Agriculture and Agriculture 4.0. Wider adoption of IoT requires improvements in digital infrastructure, technology standardization, capacity building for farmers, and supportive government policies.

Contribution & Value Added: This study provides a comprehensive synthesis of IoT applications in precision agriculture by identifying key technologies, application areas, benefits, and implementation challenges, offering a reference for future research and the development of sustainable smart farming systems.

Keywords: Internet of Things (IoT), Precision Agriculture, Smart Farming, Artificial Intelligence, Sustainable Agriculture.

JEL codes: Q16, O33
Article type: Review paper

INTRODUCTION

The agricultural sector is one of the main pillars of economic development and global food security because it plays a role in food production, employment, poverty alleviation, and maintaining the socioeconomic stability of communities, particularly in rural areas (Sharma et al., 2022). As the world's population is projected to reach approximately 9.7 billion by 2050, the need for food production is expected to increase significantly to meet global consumption demand (Dutta et al., 2025). On the other hand, this growing demand faces a variety of multidimensional challenges, including the loss of productive land due to land-use conversion, soil degradation, limited water resources, increasingly extreme climate change, and mounting pressure on the sustainability of agricultural production systems (Boateng et al., 2026; Rizan et al., 2024). This situation indicates that increases in agricultural productivity can no longer rely on land expansion but must instead be achieved through more efficient, adaptive, and sustainable resource management (Ivale et al., 2024).

Although various innovations have been introduced, agricultural practices in many developing countries are still dominated by conventional approaches that rely on farmers' experience and uniform treatment across all areas of land (Mansoor et al., 2025). Decisions regarding irrigation, fertilization, and pest control are generally made without taking into account variations in the physical, chemical, and biological conditions of the soil at each location. This approach often leads to excessive use of water, fertilizers, and pesticides, thereby increasing production costs, reducing resource efficiency, and causing negative environmental impacts due to the accumulation of chemical residues and soil degradation (Getahun et al., 2024; Rachmat et al., 2026). Therefore, the transition to a data-driven agricultural system is becoming an increasingly urgent necessity for boosting productivity while ensuring environmental sustainability.

Advances in digital technology in the Agriculture 4.0 era have opened up new opportunities for modernizing the agricultural sector through the application of various smart technologies, such as the Internet of Things (IoT), artificial intelligence (AI), cloud computing, big data analytics, and remote sensing (Arzuaga-Ochoa et al., 2026; Villa-Henriksen et al., 2020). Among the various technologies, the Internet of Things stands out as a fundamental pillar in realizing connected agriculture systems. It enables a range of physical devices, such as soil moisture sensors, temperature sensors, pH sensors, weather sensors, monitoring cameras, and automatic actuators, to communicate with one another via the internet. This facilitates the collection, transmission, and real-time processing of data (Lakshminarayan et al., 2025; Rodríguez-Yparraguirre et al., 2026). This integration enables continuous monitoring of land conditions, so that the information obtained can be used as the basis for faster, more accurate, and evidence-based decision-making (data-driven decision making) (Khwidzhilli and Ijatuyi, 2026).

The implementation of IoT is becoming increasingly vital in the concept of precision agriculture, which is an approach to land management that takes into account the spatial and temporal variability of both soil and crop conditions (Judijanto, 2026). By leveraging real-time data, IoT technology supports the implementation of smart irrigation, precision fertilization, crop growth monitoring, early detection of diseases and pests, and automated control of the cultivation environment (Botero-Valencia et al., 2025; Moghadam et al., 2026). Various studies report that this approach can improve water and fertilizer use efficiency, reduce operational costs, and increase crop productivity, while also supporting more sustainable agricultural practices by reducing agricultural input waste (Hassan et al., 2024; Khan, 2024).

Although research on the Internet of Things in agriculture has shown an upward trend in recent years, existing studies still exhibit a number of limitations. Firstly, most research primarily concentrates on the partial evaluation of technology, such as the development of sensors, communication systems, or automated irrigation methods, without providing a comprehensive synthesis of the integration of various IoT components in supporting precision agriculture ecosystems (Massenga and Bororing, 2025). Second, there is still a gap between the success of technology at the development stage and implementation in real agricultural environments, where many IoT solutions are still at the laboratory validation or small-scale trial level so that evidence regarding long-term operational effectiveness is still relatively limited (Kharisma and Sunanto, 2026). Third, the distribution of research is still dominated by countries with more advanced digital infrastructure, while studies on IoT implementation in developing countries, especially regions with limited communication networks, resources, and technological capacity, have not been widely explored (Alfarizi, 2025). This condition shows the need for a literature synthesis that is able to integrate various research results so as to provide a more comprehensive picture of the development, benefits, challenges, and direction of IoT technology development in precision agriculture.

Based on this gap, this study uses a Systematic Literature Review (SLR) approach to analyze the development of the use of the Internet of Things in precision agriculture based on Scopus-indexed scientific publications in the 2019–2025 period. This study aims to identify global research development trends, analyze the IoT technologies most widely applied in agricultural land management, evaluate the contribution of IoT to increasing productivity and efficiency of resource use, identify various implementation challenges still faced, and map future research opportunities. The research results are expected to provide a conceptual contribution in the form of a synthesis of the latest knowledge regarding the use of IoT in precision agriculture, as well as being a reference for researchers, practitioners, and policy makers in supporting digital transformation towards a more productive, efficient, and sustainable agricultural system.

LITERATURE REVIEW

Precision Agriculture

Precision agriculture is a modern agricultural management paradigm that developed in response to the limitations of conventional cultivation systems that treat land as a homogeneous unit. This approach recognizes the spatial and temporal variability in soil, plant, and environmental characteristics so that each land zone requires specific management (Neupane and Samadi, 2025). The main principle is to provide the right input, at the right location, quantity and time to increase productivity as well as efficiency in the use of resources (Blessing et al., 2024; Dutta et al., 2025).

Precision agriculture applies the concept of data-driven agricultural management, namely data-based decision making obtained through technologies such as Global Navigation Satellite System (GNSS), Geographic Information System (GIS), remote sensing, field sensors, and spatial analysis (Jimenez-Lopez et al., 2025; Thamizhselvi et al., 2025). A synthesis of various studies shows that this approach is able to increase crop yields, optimize the use of water, fertilizers, and pesticides, reduce operational costs, and reduce the environmental impact of excessive input use (Blessing et al., 2024; Lovreković et al., 2025; Majumder et al., 2024; Vardhan and Sharma, 2026). From the perspective of Data-Driven Decision Theory, the effectiveness of precision agriculture is highly dependent on the availability of accurate and real-time data, thus requiring a digital infrastructure capable of connecting field conditions with computing systems in a sustainable manner (Jimenez-Lopez et al., 2025; Saraswathi et al., 2024; Thamizhselvi et al., 2025). This condition makes the Internet of Things (IoT) the main technology in supporting the implementation of modern precision agriculture (Babbar et al., 2025; Vishwas et al., 2025).

Internet of Things

The Internet of Things (IoT) is a computing paradigm that connects various physical devices through a communication network so that they are able to collect, transmit, and process data automatically without continuous human intervention (Villa-Henriksen et al., 2020). In agriculture, IoT integrates sensors, actuators, communication devices, and computing platforms to obtain real-time information on soil conditions, crops, and the cultivation environment as a basis for more accurate decision-making (Rizan et al., 2024).

Literature shows that IoT plays a vital role in the transformation of modern agriculture through the implementation of precision irrigation, crop-based fertilization, growth monitoring, and early detection of pests and diseases (Blessing et al., 2024; Goel et al., 2025; Jimenez-Lopez et al., 2025). Utilizing real-time data has been proven to increase productivity, efficiency of water and fertilizer use, and accelerate response to changing environmental conditions (Kamal and Saxena, 2026; Lovreković et al., 2025; Suresh et al., 2025). However, IoT implementation still faces various obstacles, such as high investment costs, limited network infrastructure, device interoperability, and data security and privacy issues (Nikam et al., 2025). Based on Systems Theory, IoT functions as an integrated system that connects sensors, communication networks, computing, and users to support effective data-based agricultural management (Babbar et al., 2025).

Smart Farming

Smart farming is a development of precision agriculture that integrates the Internet of Things, cloud computing, big data analytics, Artificial Intelligence (AI), and automation systems to build a smart and adaptive agricultural ecosystem (Rachmat et al., 2026; Villa-Henriksen et al., 2020). Through this integration, data obtained from sensors is not only used for monitoring, but is also analyzed predictively to optimize irrigation, fertilization, disease detection, and automatic cultivation management (Jimenez-Lopez et al., 2025; Nikam et al., 2025; Saraswathi et al., 2024).

Research synthesis shows that smart farming can increase productivity, operational efficiency, and sustainability through optimizing resource use, reducing reliance on manual labor, and reducing environmental impacts due to the use of more precise inputs (Abdullah et al., 2025; Blessing et al., 2024). Theoretically, smart farming represents the integration of Systems Theory, Data-Driven Decision Theory, and Sustainability Theory, which places digital technology as the foundation for realizing a productive, efficient, and sustainable agricultural system (Saraswathi et al., 2024; A. Shukla and Agrawal, 2025).

IoT Architecture in Precision Agriculture

The implementation of the Internet of Things in precision agriculture is generally built using a multi-layer architecture consisting of a perception layer, network layer, processing layer, and application layer (Villa-Henriksen et al., 2020). The perception layer is responsible for acquiring data through sensors and actuators, the network layer transmits data using wireless communication technology, the processing layer integrates and analyzes data through cloud or edge computing, while the application layer presents information to users in the form of dashboards, mobile applications, or decision support systems (Miller et al., 2025; Rizan et al., 2024). This architecture allows the process of monitoring land conditions to take place in real-time, thus supporting faster and more accurate decision-making.

Agricultural Sensors and Wireless Sensor Network

Sensors are the main component in IoT systems because they function to change the physical and chemical conditions of the environment into digital data that can be processed by computing systems (Sumarsono et al., 2024). In precision agriculture, commonly used sensors include soil moisture, temperature, pH, light intensity, rainfall, and plant condition sensors to monitor plant growth and health (Mansoor et al., 2025). These sensors are connected via a Wireless Sensor Network (WSN) which enables continuous data collection from various observation points with low energy consumption and wide area coverage. Synthesis of various studies shows that the combination of sensors and WSN can improve the accuracy of land monitoring and support more efficient irrigation, fertilization, and environmental control management (Goel et al., 2025; Kamal and Saxena, 2026; A. Shukla and Agrawal, 2025).

Cloud Computing and Edge Computing

Cloud computing provides data storage and processing infrastructure that allows information from IoT sensors to be analyzed centrally via an internet-based platform (Arzuaga-Ochoa et al., 2026). This approach supports real-time data visualization, historical storage, and integration with decision support systems. However, latency limitations and reliance on internet connections have driven the development of edge computing, a data processing mechanism that occurs near the data source, thereby accelerating system response and reducing the transmission load to a central server (Miller et al., 2025). The integration of cloud and edge computing has been proven to increase the reliability of IoT systems, especially in the implementation of automatic irrigation and land monitoring in areas with limited network infrastructure (Jimenez-Lopez et al., 2025; Suresh et al., 2025).

Artificial Intelligence Integration

The development of the Internet of Things is further strengthened through the integration of Artificial Intelligence (AI), forming the concept of Artificial Intelligence of Things (AIoT). This integration allows data obtained from sensors to be analyzed using machine learning and deep learning algorithms to automatically generate predictions and recommendations (Moghadam et al., 2026). Various studies have shown that AI has been used to predict crop yields, optimize irrigation needs, detect plant diseases, and identify nutrient needs with a high degree of accuracy (Abdullah et al., 2025; Nikam et al., 2025; Saraswathi et al., 2024). Thus, AI not only enhances IoT data analysis capabilities, but also supports more adaptive and precise decision-making in agricultural land management.

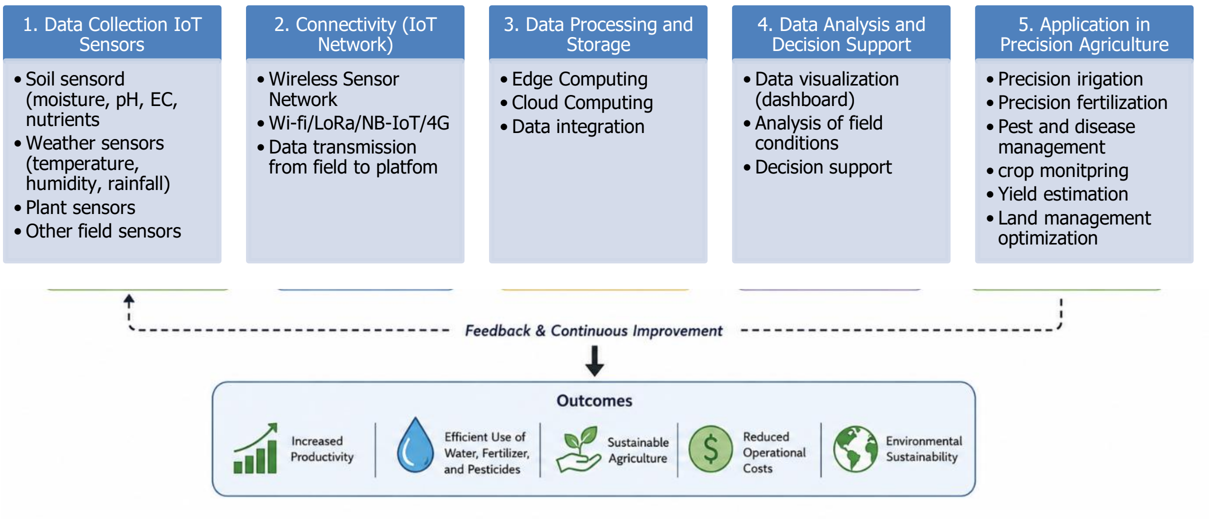

Figure 1. Conceptual Framework: IoT in Precision Agriculture

METHODS

Research Design

This study employed a Systematic Literature Review (SLR) method in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines. The SLR method was chosen because it allows for the identification, selection, evaluation, and synthesis of the literature to be conducted in a systematic, transparent, and replicable manner. This approach aims to provide a comprehensive overview of the development of Internet of Things (IoT) applications in precision agriculture, including the technologies used, areas of implementation, benefits for productivity and land management efficiency, and the challenges faced in their implementation.

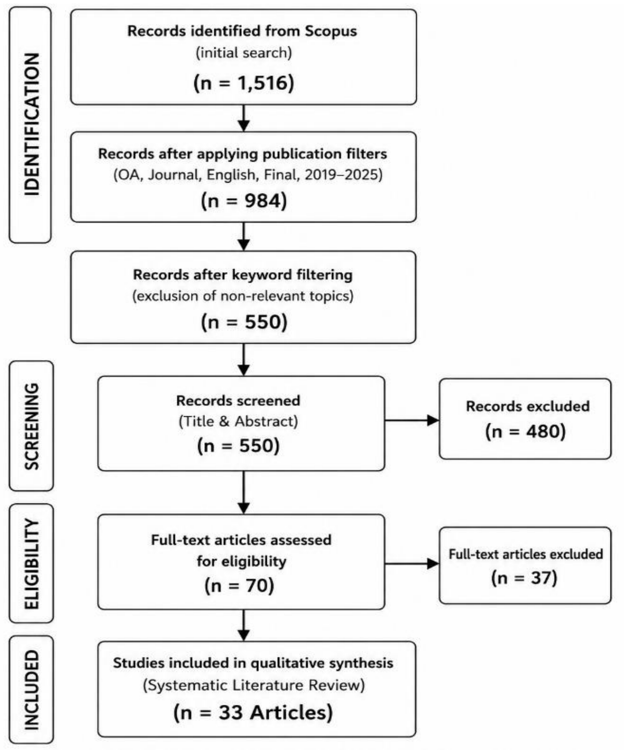

Figure 2. PRISMA 2020 Flow Diagram for Literature Selection on IoT in Precision Agriculture

This study employs the Systematic Literature Review (SLR) method, adhering to the PRISMA 2020 guidelines. A literature search was conducted on the Scopus database using a combination of keywords ("Internet of Things" OR "IoT") AND ("Precision Agriculture" OR "Smart Farming") AND ("Productivity" OR "Efficiency" OR "Land Management"). The search was limited to English-language journal articles and conference papers published between 2019 and 2025. The search results were then selected through the stages of identification, screening, eligibility, and inclusion, resulting in 33 articles that met the inclusion criteria. Subsequently, data were extracted based on publication characteristics, IoT technologies, system components, application areas, research methods, key findings, and research gaps. The data were analyzed using thematic analysis to identify technology trends, IoT implementation in precision agriculture, its impact on productivity and land management efficiency, as well as challenges and future research directions.

RESULT

Based on the classification of 33 articles, the Internet of Things (IoT) emerged as the most dominant technology, appearing in 30 articles (90.9%), indicating that IoT serves as a primary foundation for the implementation of precision agriculture. Frequently integrated supporting technologies include Artificial Intelligence (AI) with 10 articles (30.3%), Cloud Computing with 10 articles (30.3%), Machine Learning with 9 articles (27.3%), and Wireless Sensor Networks (WSN) with 6 articles (18.2%). Meanwhile, technologies such as Edge Computing, LoRa, UAVs, and Smart Irrigation each appeared in three articles (9.1%), whereas other technologies were utilized in only one or two studies as specific technologies. These findings indicate that the development of precision agriculture no longer relies on IoT as a standalone technology but is moving towards the integration of IoT with AI, Machine Learning, Cloud/Edge Computing, and WSN to establish systems for real-time monitoring, predictive analysis, and automated decision-making. This integration has proven capable of boosting agricultural productivity through the efficient use of water, fertilizers, energy, and other resources, while simultaneously supporting more sustainable land management.

Table 1. Technology Distribution of Selected Studies

No	Technology	Number of Articles
1	Internet of Things (IoT)	29
2	Artificial Intelligence (AI)	10
3	Cloud Computing	10
4	Machine Learning	9
5	Smart Farming	6
6	Precision Agriculture	6

No	Technology	Number of Articles
7	Wireless Sensor Network (WSN)	5
8	Edge Computing / Edge AI	5
9	Deep Learning / CNN	4
10	UAV / Drone	4
11	Smart Irrigation	3
12	LoRa	2

The results indicate that the experimental method is the most dominant approach. Research in this category generally involves developing IoT-based prototypes utilizing sensors, ESP32, Arduino, Raspberry Pi, LoRa, Edge Computing, AI, or Machine Learning, followed by performance testing based on parameters such as accuracy, latency, energy consumption, irrigation efficiency, and crop productivity. The article employs a literature review or systematic review to identify technological developments, research trends, benefits, challenges, and opportunities regarding the implementation of IoT in precision agriculture. This type of research plays a role in formulating the conceptual framework and the direction of future research. Simulation or framework evaluation methods are used to assess network architecture, communication efficiency, and algorithms prior to deployment in real-world environments. This approach is commonly found in research focused on Wireless Sensor Network (WSN) development and IoT network optimization. Meanwhile, bibliometric analysis is utilized to map publication trends, author collaborations, and research topics, whereas conceptual or perspective papers focus on formulating concepts, standards, and development directions for Smart Agriculture without conducting empirical testing.

Table 2. Distribution of Research Methods

Research methods	Number of Articles	Percentage
Experimental / System Development / Prototype Validation	21	63,6%
Literature Review / Systematic Review	8	24,2%
Simulation / Framework Evaluation	2	6,1%
Bibliometric Analysis	1	3,0%
Conceptual / Perspective Paper	1	3,0%
Total	**33**	**100%**

A synthesis of 33 articles indicates that the implementation of the Internet of Things (IoT) in precision agriculture is supported by a combination of integrated hardware components, software, communication networks, and artificial intelligence technologies. Based on the literature analysis, the identified IoT components can be grouped into several key categories that support various precision agriculture applications.

Table 3. IoT Implementation Focus in Precision Agriculture

Implementation Focus	Summary of Findings
Smart Irrigation & Water Management	IoT is most widely applied in soil moisture monitoring and irrigation automation. The integration of sensors, AI, fuzzy logic, cloud, and edge computing enhances water use efficiency, reduces waste, and increases crop yields.
Soil Monitoring & Nutrient Management	IoT sensors are used to monitor temperature, humidity, pH, EC, NPK, and other soil parameters in real-time, thereby supporting data-driven fertilization recommendations and land management.
Crop Monitoring & Disease Detection	The integration of IoT with AI, Deep Learning, CNN, and UAVs enables early detection of plant diseases, crop health monitoring, yield estimation, and automated pest control.
Smart Farming Decision Support System	IoT is combined with cloud computing, machine learning, and AI to create a decision support system capable of automatically providing recommendations for irrigation, fertilization, and land management.
Wireless Communication & Network Optimization	The research focuses on WSN, LoRa, NB-IoT, and energy-efficient communication protocols to enhance communication range, energy efficiency, and data transmission reliability in large-scale agricultural areas.
Edge Computing & Real-Time Analytics	Edge AI and edge computing enable data analysis directly in the field with low latency, reduced bandwidth requirements, and faster response times compared to cloud-based processing.
Review, Bibliometric & Conceptual Study	The research identifies trends in IoT development, enabling technologies, and implementation challenges, as well as the future development direction of Smart Agriculture and Precision Agriculture.

1. Data Acquisition Sensor (Sensing Layer)

Most studies utilize soil moisture sensors as a key component, as they play a role in precisely determining irrigation needs. In addition, various environmental sensors are used, such as sensors for soil temperature, air temperature, air humidity, light intensity, soil pH, electrical conductivity (EC), salinity, nitrogen (N), phosphorus (P), potassium (K), water quality, rainfall, and water level, as well as weather stations. Several studies also utilize digital cameras and image sensors to support plant disease detection using Artificial Intelligence. The presence of these various sensors enables real-time environmental data acquisition, allowing land conditions to be continuously monitored as a basis for precision agriculture decision-making.

2. Communication and Data Transmission Network (Communication Layer)

The study results indicate that data communication is carried out using various network technologies, such as Wireless Sensor Networks (WSN), Wi-Fi, LoRa, ZigBee, Bluetooth, NB-IoT, 4G/5G, and HTTP communication, as well as drone-based communication (UAV gateways). The use of the network enables sensor data to be rapidly transmitted from the field to a data processing center or cloud platform. LoRa and WSN technologies are widely used in large-scale agriculture due to their long-range communication capabilities and low energy consumption, whereas 5G is projected to become the primary communication technology supporting next-generation Smart Farming.

3. Edge Computing and Cloud Computing (Processing Layer)

Literature indicates a shift in IoT architecture from cloud-centric models toward Edge Computing. Several studies utilize devices such as the ESP32, Raspberry Pi, Arduino IoT, embedded computers, and Edge AI for local processing before data is transmitted to the cloud. This approach is capable of reducing latency, saving bandwidth, accelerating system response, and improving energy efficiency. Subsequently, the data is stored and visualized using cloud platforms such as Firebase, ThingSpeak, MongoDB, and Heroku Cloud, as well as web-based dashboards, to support real-time monitoring.

4. Artificial Intelligence and Decision Support System

Most research integrates IoT with Artificial Intelligence (AI), Machine Learning (ML), and Deep Learning as data analysis engines. Algorithms such as KNN, CNN, DenseNet201, RSNN, XGBoost, K-Means, and Multi-Agent AI Systems are utilized for crop yield prediction, plant disease diagnosis, soil moisture prediction, fertilization recommendations, irrigation optimization, and decision support systems. AI integration enables IoT systems to function not merely as monitoring tools but also to generate adaptive recommendations based on actual field conditions.

5. Automation System (Actuation Layer)

In addition to monitoring, most systems also integrate actuators such as automatic water pumps, intelligent irrigation controllers, automated irrigation systems, precision spraying, greenhouse automation, and even autonomous farm management. Integrating sensors with actuators enables irrigation, fertilization, and pesticide spraying to be carried out automatically based on field conditions, thereby making resource usage more efficient.

Literature Search Results Based on Precision Agriculture Applications

An analysis of IoT applications reveals that the research identified focuses on diverse implementations, yet can generally be categorized into several key areas.

1. Smart Irrigation and Water Management

The most prominent application is smart irrigation, which involves managing irrigation based on soil moisture data, weather conditions, evapotranspiration, and the actual needs of the plants. This system is capable of optimizing water use, reducing waste, improving irrigation efficiency, and maintaining crop productivity under various environmental conditions.

2. Monitoring Soil and Environmental Conditions

Most studies have developed systems for real-time monitoring of soil moisture, soil temperature, air temperature, pH, EC, salinity, nutrients, water quality, and weather conditions. This information is used as a basis for decision-making regarding irrigation, fertilization, and land management.

3. Precision Fertilization and Nutrient Management

This information has been used as the basis for several studies aimed at developing monitoring systems for nitrogen, phosphorus, and potassium that incorporate machine learning, thereby enabling the automatic generation of fertilizer recommendations. This approach improves fertilizer use efficiency while maintaining soil fertility.

4. Crop Monitoring and Plant Health Monitoring

The IoT is also widely used to monitor plant growth, plant health, growing conditions, and plant development throughout the production cycle. The integration of UAVs, environmental sensors, and digital imagery enables more extensive and accurate monitoring.

5. Plant Disease Detection and Pest Management

The integration of IoT with deep learning enables early detection of plant diseases, pest identification, and automated control recommendations. This technology enables precise pesticide application, making pesticide use more targeted while reducing environmental impact.

6. Crop Yield Prediction

Several studies have developed models to predict crop yields using sensor data, weather conditions, plant health, and machine learning. These forecasts help farmers develop strategies for production, distribution, and resource management before the harvest season begins.

7. Precision Agriculture Decision Support System

The study's findings show that the IoT has evolved into a Decision Support System (DSS) that integrates sensors, cloud computing, AI, edge computing, and monitoring dashboards. This system is capable of providing automatic recommendations on irrigation, fertilization, disease control, and land management based on actual conditions.

8. Smart Farming Ecosystem

Recent literature shows that the development of the IoT is no longer focused solely on a single agricultural activity, but has evolved into a smart farming ecosystem that integrates AI, UAVs, robotics, GPS, blockchain, cloud computing, edge computing, 5G communications, and autonomous farm management. This approach supports agriculture that is more productive, efficient, resilient to climate change, and sustainable.

DISCUSSION

Water Use Efficiency

Water use efficiency is one of the most significant impacts of implementing the Internet of Things (IoT) in precision agriculture. Most studies show that the integration of soil moisture sensors, weather sensors, Wireless Sensor Networks (WSN), and automated irrigation systems enables real-time monitoring of field conditions, allowing irrigation decisions to be made based on the actual needs of the crops, rather than on a fixed schedule (Alagarsamy et al., 2023; Morchid, Et-taibi, et al., 2025; More et al., 2025). This approach can reduce water waste while improving the efficiency of agricultural resource use (Kumar et al., 2024; Verma et al., 2020).

IoT development is also becoming more effective through the integration of Artificial Intelligence (AI), Machine Learning (ML), Edge Computing, and Cloud Computing, which enable sensor data to be analyzed quickly and accurately. The intelligent system is capable of predicting water requirements based on soil moisture, weather conditions, and plant characteristics, thereby making irrigation more adaptive to environmental changes (Shahab et al., 2025; Subudhi et al., 2025; Suresh et al., 2025). In addition to improving decision accuracy, the use of Edge AI also lowers data processing latency and reduces bandwidth requirements compared to fully cloud-based approaches (Kalaivani et al., 2025; Premkumar and Sigappi, 2022; Suresh et al., 2025).

Several experimental studies provide quantitative evidence regarding increased irrigation efficiency. The implementation of IoT-integrated Subsurface Drip Irrigation (SSDI) resulted in a productivity of up to 33.614 tons/ha, with water use efficiency reaching 15.73 kg/m³ (El-Sheshny et al., 2025). Other research indicates that the IoT-SM method can increase corn yields by approximately 12.05% while simultaneously reducing water usage by 11% compared to conventional methods (Kumar S et al., 2023). Furthermore, the fuzzy logic-based adaptive irrigation system successfully reduced water loss by up to 23.1%, while the integration of cloud-based weather forecasting services yielded an additional 4.07% increase in water use efficiency (Artetxe et al., 2024; Morchid, Said, et al., 2025).

Water use efficiency is also supported by the implementation of IoT in Controlled Environment Agriculture (CEA) and vertical farming, as well as the integration of UAVs for monitoring crop conditions and spatial water distribution (Dutta et al., 2025; Eladl et al., 2024; Rodzoan and Shah, 2024). The combination of these various technologies enables continuous monitoring of crop conditions, enhances decision-making accuracy, and maintains agricultural productivity stability despite changing environmental conditions (Holtorf et al., 2023; B. K. Shukla et al., 2023).

Overall, the synthesis results indicate that the implementation of IoT has shifted the irrigation management paradigm from time-based irrigation to data-driven precision irrigation. This transformation not only enhances water use efficiency but also reduces operational costs, boosts crop productivity, and supports the sustainability of modern agricultural systems (Abdullahi et al., 2023; Sabir and Ozkececi, 2025; Swamidason et al., 2022; Zhang et al., 2024).

Fertilizer Use Efficiency

IoT systems enable fertilization based on actual field conditions through real-time monitoring of soil parameters—such as moisture, temperature, pH, electrical conductivity (EC), and nutrient levels (nitrogen, phosphorus, and potassium). The information is integrated with Artificial Intelligence (AI) and cloud computing to generate more accurate recommendations for fertilizer dosage and timing (Ferrarezi and Peng, 2021; Shahab et al., 2025). This approach transforms conventional, uniform fertilization practices into data-driven, site-specific nutrient management.

The application of Machine Learning (ML) further increases the accuracy of decision making in nutrient management. A study indicates that the K-Nearest Neighbors (KNN) algorithm can achieve up to 98% accuracy in determining fertilizer recommendations based on soil conditions, thereby reducing fertilizer waste while simultaneously increasing rice crop productivity (Sumacot and Paragas, 2025). Similar findings also indicate that the integration of AI, ML, and IoT sensors not only optimizes fertilizer use but also supports automated land management recommendations through continuous analysis of environmental conditions (More et al., 2025; B. K. Shukla et al., 2023). Thus, fertilization decisions no longer depend on farmer experience, but are based on more objective and adaptive data analysis results.

Fertilization efficiency is further enhanced by the integration of Edge Computing, Cloud Computing, and Decision Support System (DSS) technologies, enabling rapid data processing with low latency. Data visualization via digital dashboards makes it easier for farmers to monitor field conditions and take timely fertilization actions (Kalaivani et al., 2025; Kee et al., 2025). Furthermore, the implementation of Edge AI enables analysis to be performed directly on field devices, thereby accelerating system response to changing soil conditions while reducing bandwidth requirements and data communication costs (Suresh et al., 2025). This approach makes the fertilization system more efficient and easy to implement across various scales of farming operations.

Several studies also indicate that fertilizer use efficiency cannot be separated from irrigation management and plant health. The integration of IoT, deep learning, and UAVs enables the identification of fertilizer requirements based on crop growth conditions, disease detection, and spatial monitoring of the land, allowing for more precise fertilizer application (Al-Shahari et al., 2025; Eladl et al., 2024; Rodzoan and Shah, 2024). A machine learning-based framework can even support automated decisions regarding irrigation, fertilization, and integrated pest control through the early detection of changes in environmental conditions (Pushpavalli et al., 2024). The integration of these various technologies results in a nutrient management system that is more adaptive than conventional fertilization methods.

Overall, the synthesis results indicate that IoT implementation has shifted the fertilization paradigm from calendar-based fertilization to data-driven precision fertilization. The utilization of sensors, AI, machine learning, edge/cloud computing, and decision support systems can enhance fertilizer use efficiency, reduce input costs, improve crop productivity, and minimize environmental impacts resulting from excessive fertilizer use (Dutta et al., 2025; Kumar et al., 2024; Sabir and Ozkececi, 2025; Verma et al., 2020). This approach serves as a key pillar in realizing a productive, efficient, and sustainable precision agriculture system.

Monitoring Real-Time

Real-time monitoring capability is one of the key contributions of Internet of Things (IoT) implementation in precision agriculture. Information on soil moisture, temperature, air humidity, light intensity, soil pH, and nutrient content can be directly monitored so that farmers obtain accurate information to make decisions quickly and accurately (Kalaivani et al., 2025; More et al., 2025; Shahab et al., 2025).

The implementation of real-time monitoring not only enhances data availability but also transforms agricultural management practices from a reactive to a proactive approach. IoT system can detect changes in environmental conditions at an early stage and transmit the information to a dashboard or cloud-based application to support decision-making regarding irrigation, fertilization, and environmental control (Alagarsamy et al., 2023; Kalaivani et al., 2025; Shahab et al., 2025). This approach reduces response delays to changing field conditions while enhancing the efficiency of agricultural resource use.

Several studies indicate that the use of edge computing further strengthens real-time monitoring capabilities, as a portion of the analysis is performed directly on devices in the field. This approach can reduce communication latency and bandwidth requirements, as well as accelerate system response, compared to processing that relies entirely on the cloud (Premkumar and Sigappi, 2022; Suresh et al., 2025). Furthermore, a system based on ESP32, LoRa, and underground sensors enables data collection across vast agricultural areas with low energy consumption and improved communication range (Ferrarezi and Peng, 2021; Holtorf et al., 2023; Rao et al., 2024).

Real-time monitoring also serves as the foundation for implementing automation in precision agriculture. Continuously acquired sensor data is utilized by AI and machine learning algorithms to control irrigation, optimize fertilizer use, detect environmental anomalies, and even provide automated action recommendations (More et al., 2025; Obeidat et al., 2024; Pushpavalli et al., 2024; Subudhi et al., 2025). Thus, farmers no longer rely on manual observation but instead gain access to a decision-support system that operates based on actual field conditions.

Continuous monitoring of crop conditions enables the reduction of yield losses caused by delayed intervention, improves the accuracy of water and nutrient management, and lowers operational costs through the automation of agricultural processes (Dutta et al., 2025; Kee et al., 2025; Swamidason et al., 2022; Verma et al., 2020). Real-time monitoring is a fundamental pillar of IoT implementation in precision agriculture, as it serves as the primary data source supporting predictive analysis, automated decision-making, and the integration of other digital technologies such as AI, machine learning, and cloud computing (Kumar et al., 2024; B. K. Shukla et al., 2023; Zhang et al., 2024).

Plant Disease Detection

Plant disease detection is one of the fastest-growing Internet of Things (IoT) applications in precision agriculture. The integration of field sensors, Artificial Intelligence (AI), Deep Learning, and cloud computing enables the system to automatically recognize disease symptoms based on plant and environmental conditions. This approach transforms the disease control process from reactive to predictive. These mitigation measures can be implemented before the infection develops and causes a reduction in crop yields (Al-Shahari et al., 2025; Shahab et al., 2025).

Advances in deep learning algorithms have led to a significant improvement in the accuracy of plant disease identification. Convolutional neural network-based models are capable of recognizing visual patterns of diseases with very high accuracy, even surpassing conventional classification methods. This high level of accuracy enables the system to provide early warnings, allowing farmers to apply pesticides more precisely, reduce yield losses, and improve the efficiency of agricultural input usage (Al-Shahari et al., 2025; Krishna et al., 2025). These findings indicate that AI serves not only as an identification tool but also as a key component of IoT-based decision support systems.

In addition to plant image analysis, disease detection is becoming increasingly accurate through the integration of UAVs (Unmanned Aerial Vehicles) with IoT networks. High-resolution aerial image acquisition enables real-time monitoring of crop health, disease identification, and weed detection across large areas. This spatial information is then integrated with field sensor data, resulting in a more comprehensive evaluation of crop conditions compared to manual observation methods (Eladl et al., 2024; Rodzoan and Shah, 2024). This approach strongly supports the implementation of precision land management, as interventions can be carried out only on areas requiring attention.

On the other hand, the use of soil sensors connected to cloud computing expands the system's capability to analyze the relationship between environmental conditions and the potential emergence of diseases. Parameters such as temperature, humidity, salinity, pH, and nutrient content can be automatically processed by AI algorithms to generate disease diagnoses as well as irrigation and fertilization recommendations tailored to actual field conditions (Shahab et al., 2025). Integrating these various data sources results in a more accurate decision-making process while reducing reliance on manual field inspections.

Overall, the combination of sensors, AI, deep learning, UAVs, and cloud computing enables early disease identification, improves diagnostic accuracy, and supports faster, more precise control measures. The impact extends beyond increasing crop productivity to include reduced pesticide use, lower production costs, and strengthened sustainability within modern agricultural systems (Eladl et al., 2024; Krishna et al., 2025; Rodzoan and Shah, 2024).

Crop Yield Prediction

Crop yield predictions enable farmers to make proactive decisions based on actual field conditions. In contrast to conventional approaches that rely on experience or periodic observation, IoT systems utilize sensors, communication networks, artificial intelligence (AI), and machine learning (ML) to continuously collect, process, and analyze environmental data, thereby enabling more accurate estimations of crop productivity. Research shows that the integration of sensors, Wireless Sensor Networks (WSN), AI, and ML not only supports real-time monitoring of crop conditions but also enables the generation of crop yield predictions, land management recommendations, and early detection of various factors that could potentially reduce crop productivity (More et al., 2025).

This predictive capability is supported by the use of multisensory data that represents land conditions more comprehensively. The IoT system is capable of monitoring key parameters such as soil temperature, moisture, salinity, pH, electrical conductivity, and nitrogen, phosphorus, and potassium levels, and then processing all of this information through cloud computing and AI algorithms to generate recommendations for irrigation and fertilization, as well as estimates of crop productivity (Shahab et al., 2025). This approach shows that crop yield predictions no longer depend solely on a single environmental variable, but rather are the result of an integrated analysis of various agronomic parameters that interact with one another. As a result, decision-making becomes more accurate, while also improving the efficiency of resource use and supporting sustainable agricultural practices.

Advances in crop yield forecasting are being further enhanced through the integration of IoT with remote sensing technology, particularly Unmanned Aerial Vehicles (UAVs). The combination of IoT and UAVs enables real-time collection of spatial data on crop health, vegetation conditions, soil moisture, and even crop yield estimates across large agricultural areas (Eladl et al., 2024; Rodzoan and Shah, 2024). Compared to point-based sensing systems, this approach provides broader observation coverage, allowing for more accurate identification of variations in crop conditions. This spatial information serves as crucial input for AI models in predicting crop productivity while supporting the implementation of precision land management through site-specific irrigation, fertilization, and crop control.

In addition to utilizing spatial data, several studies emphasize that crop yield predictions are influenced by the system's ability to continuously analyze environmental conditions. An IoT system integrated with cloud computing enables real-time monitoring of soil conditions, allowing crop water requirements to be calculated more accurately and adjusted in response to changes in environmental conditions (Alagarsamy et al., 2023). The stability of these growing conditions directly contributes to increased crop productivity and results in more consistent yield estimates. Similar findings have also been observed in the implementation of IoT in soilless agriculture systems, where automated environmental control helps maintain stable plant growth year-round, making productivity more predictable than in conventional farming systems (Dutta et al., 2025).

Advances in AI and machine learning technology are further enhancing the ability to predict crop yields through the automated processing of large amounts of data. The integration of IoT sensors, wireless communication, and machine learning algorithms enables the system to analyze crop growth patterns, predict productivity, and provide management recommendations based on actual field conditions (B. K. Shukla et al., 2023). Accordingly, the implementation of IoT sensors that continuously monitor various environmental parameters has proven effective in improving both the quality and quantity of crop yields through faster, data-driven decision-making (Swamidason et al., 2022). These findings indicate a paradigm shift from a reactive agricultural system toward a predictive agricultural system, in which cultivation decisions are made before a decline in productivity occurs.

Nevertheless, several literature reviews confirm that the success of crop yield prediction systems is determined not only by the accuracy of AI algorithms, but also by the readiness of the digital ecosystem that supports the implementation of IoT. The integration of IoT, AI, UAVs, big data, cloud computing, and edge computing serves as the cornerstone of modern crop yield prediction system development, as it enables predictive analytics, automated decision-making, and the optimization of resource utilization simultaneously (Sabir and Ozkececi, 2025; Zhang et al., 2024). However, various challenges such as limited digital infrastructure, system interoperability, data security, investment costs, and low levels of technology adoption by farmers remain major obstacles to widespread implementation (Kumar et al., 2024). Therefore, the development of future crop yield prediction systems will not only require increased accuracy of AI models, but also infrastructure support, interoperability standards, and collaboration between stakeholders.

Reducing Operating Costs

The results of the literature review indicate that reduced operating costs are one of the most consistent benefits of implementing the Internet of Things (IoT) in precision agriculture. Cost efficiency is achieved through the optimization of production inputs, automation of cultivation processes, efficient data communication, and the use of intelligent computing systems capable of reducing the need for manual intervention. The integration of IoT sensors, Artificial Intelligence (AI), Machine Learning (ML), edge computing, and cloud computing enables faster and more accurate decision-making based on real-time field conditions, thereby making various farming activities more efficient (More et al., 2025; Shahab et al., 2025).

The reduction in operating costs stems primarily from more efficient use of water, fertilizer, and pesticides. An IoT system integrated with AI can comprehensively monitor soil conditions by measuring parameters such as moisture, pH, salinity, nitrogen, phosphorus, and potassium, enabling automatic recommendations for fertilization and irrigation based on the plants' actual needs (Shahab et al., 2025). These findings are supported by other studies showing that KNN-based machine learning algorithms can generate precise fertilizer recommendations, thereby minimizing fertilizer waste while increasing crop productivity (Sumacot and Paragas, 2025). In addition, the implementation of Deep Learning for early detection of plant diseases allows for more selective application of pesticides so that chemical consumption can be reduced without reducing agricultural productivity (Al-Shahari et al., 2025).

Operational efficiency is also achieved through optimizing water use. IoT-based irrigation systems are able to adjust watering based on soil moisture conditions and environmental parameters in real-time, making water use more efficient than conventional methods (Morchid, Et-taibi, et al., 2025). The results of other studies show that the IoT-SM method is able to save water usage by 11% while increasing corn production yields by around 12.05%, while the fuzzy logic-based system is able to reduce water waste with relatively low implementation costs so that it is suitable for application in small and medium-scale agriculture (Kumar S et al., 2023; Morchid, Said, et al., 2025). The integration of weather forecasting services with edge, fog, and cloud architecture has even succeeded in reducing water loss by up to 23.1% compared to conventional control systems, so that irrigation operational costs can be reduced significantly (Artetxe et al., 2024).

In addition to efficient use of resources, the implementation of edge computing makes an important contribution to reducing the operational costs of digital systems. In contrast to the full cloud approach, edge computing allows data to be processed near the sensor location, thereby reducing latency, reducing bandwidth usage, speeding up response times, and reducing the computing load on cloud servers (Premkumar and Sigappi, 2022). Similar findings were also reported on the implementation of Edge AI using the CNN-TAM model which not only produced high accuracy soil moisture predictions, but also reduced bandwidth requirements while increasing the efficiency of water and fertilizer use (Suresh et al., 2025). This efficiency has a direct impact on reducing data communication costs, energy consumption, and computing infrastructure requirements in smart farming systems.

In terms of energy efficiency and technology investment, several studies have shown that the use of renewable energy sources and low-cost devices can reduce operational costs in the long term. The Intelligent Soil Monitoring System (ISMS) that uses solar power can operate without relying on the electricity grid while reducing operational costs and providing economic benefits in areas with limited infrastructure (Kee et al., 2025). Other studies also show that edge-cloud based monitoring systems have the characteristics of being energy efficient, economical and easy to develop (Kalaivani et al., 2025), Meanwhile, the use of open-source devices allows the implementation of land monitoring systems to be carried out at relatively low costs without reducing the reliability of the system in supporting irrigation and fertilization automation (Ferrarezi and Peng, 2021). Energy efficiency is also strengthened by the development of an IoT framework that is able to reduce energy consumption and network communication loads without reducing the accuracy of land condition monitoring (Pushpavalli et al., 2024), and the OSCBRP architecture which produces low energy consumption with high throughput and very low latency thus supporting more energy efficient sensor communications (Rao et al., 2024).

Furthermore, the reduction in operational costs is also influenced by the increasing level of automation in smart farming systems. The development of an AI-powered multi-agent system enables the automatic coordination of various aquaculture activities through inter-agent communication, thereby reducing the need for human intervention and improving operational efficiency (Obeidat et al., 2024). The integration of IoT sensors with wireless communication, machine learning, and 5G technology also accelerates decision-making while improving the efficiency of agricultural resource use (B. K. Shukla et al., 2023). On a broader scale, the implementation of IoT in various agricultural activities has proven to reduce production costs compared to conventional systems through optimized water use, improved crop quality, and real-time data-driven land management (Swamidason et al., 2022).

Agricultural Sustainability

A synthesis of various studies shows that the use of the Internet of Things (IoT) has evolved from merely a monitoring technology to a key foundation for achieving sustainable agriculture. The implementation of IoT enables the integration of sensors, Artificial Intelligence (AI), Machine Learning (ML), edge computing, cloud computing, and wireless communication into a single digital ecosystem capable of supporting adaptive, precision, and data-driven agricultural management. These changes serve as a crucial foundation for addressing global challenges such as rising food demand, limited natural resources, and the impact of climate change on the agricultural sector (B. K. Shukla et al., 2023; Verma et al., 2020; Zhang et al., 2024).

From an environmental perspective, the majority of studies show that the IoT can improve the efficiency of natural resource use through more precise management of water, fertilizers, and pesticides. Sensor-based monitoring systems allow soil and crop conditions to be observed in real time, so that decisions regarding irrigation, fertilization, and pest control can be made based on the crops' actual needs (More et al., 2025; Shahab et al., 2025). This approach has been shown to reduce waste of agricultural inputs, improve water use efficiency, and curb the use of chemicals that could potentially pollute the environment (Al-Shahari et al., 2025; Sumacot and Paragas, 2025; Swamidason et al., 2022).

The sustainability of agriculture in the future is also being further strengthened through the integration of AI and machine learning, which enable systems to perform predictive analysis and make decisions automatically. Several studies have shown that combining IoT with AI can predict crop yields, detect plant diseases early, optimize water requirements, and generate land management recommendations based on actual conditions (Krishna et al., 2025). The use of edge computing further enhances system effectiveness because analysis can be performed locally with low latency, lower bandwidth consumption, and faster responses to changes in environmental conditions (Premkumar and Sigappi, 2022; Suresh et al., 2025). This adaptive capacity is one of the key characteristics of future agricultural systems, which are able to respond to climate change and environmental dynamics more quickly than conventional approaches. In addition to supporting environmental sustainability, the IoT also provides economic benefits through improved operational efficiency and production stability. Automating irrigation, fertilization, and crop condition monitoring allows for more efficient use of resources, thereby reducing operating costs without compromising crop yields.

The development of IoT also opens up opportunities for a transformation toward a more integrated smart farming system. Integrating IoT with UAVs enables large-scale land monitoring, crop yield estimation, disease detection, crop condition assessment, and precision pesticide spraying based on spatial data collected in real time (Eladl et al., 2024; Rodzoan and Shah, 2024). Meanwhile, developments in AI-powered multi-agent systems show that the coordination of various agricultural activities can be carried out automatically through intelligent inter-system communication, thereby further improving operational efficiency and the reliability of agricultural systems (Obeidat et al., 2024). Meanwhile, using LoRa-based underground sensors in combination with drones expands the monitoring range to hundreds of hectares with low energy consumption, thereby opening up opportunities for the implementation of precision agriculture on large-scale farmland (Holtorf et al., 2023).

Sustainability is also reflected in the growing use of energy-efficient technologies and renewable energy. Edge computing has been shown to reduce energy consumption, bandwidth usage, and network communication load without compromising the quality of data analysis (Premkumar and Sigappi, 2022; Pushpavalli et al., 2024; Rao et al., 2024). Additionally, using solar power in soil monitoring systems allows IoT devices to operate independently without relying on the electrical grid, making them ideal for use in remote agricultural areas with limited infrastructure (Kee et al., 2025; Kumar S et al., 2023). This approach indicates that the future development of smart agriculture will focus not only on productivity, but also on energy efficiency and environmental sustainability.

However, the synthesis results also show that the successful implementation of IoT in supporting future agriculture still faces various challenges. The main obstacles include high initial investment costs, limited digital infrastructure, device interoperability, data security, system scalability, and low levels of digital literacy and technology adoption among farmers (Kumar et al., 2024; Rodzoan and Shah, 2024; Sabir and Ozkececi, 2025). Therefore, the development of smart agriculture requires the support of government policies, the development of communication infrastructure, technology standardization, increased human resource capacity, and collaboration between academics, industry, government, and farmers so that digital transformation can take place in an inclusive and sustainable manner (Zhang et al., 2024).

CONCLUSION

Based on the results of a Systematic Literature Review of 33 selected articles, this study shows that the use of the Internet of Things (IoT) has become a major foundation in the development of precision agriculture through the integration of sensors, Wireless Sensor Networks (WSN), edge computing, cloud computing, Artificial Intelligence (AI), Machine Learning (ML), and automation systems. The integration of these technologies enables real-time land condition monitoring, data-driven resource management, and faster, more accurate, and more adaptive decision-making to the dynamics of the agricultural environment. These findings demonstrate that IoT no longer functions solely as a monitoring technology, but has evolved into an intelligent farming ecosystem that supports the automation of various agricultural activities.

The results of the literature synthesis identified five main benefits of IoT implementation in precision agriculture, namely (1) real-time monitoring of land conditions, (2) optimization of water, fertilizer, and pesticide use, (3) early detection of plant diseases, (4) AI-based crop yield prediction and data analytics, and (5) reduction of operational costs through automation and efficient use of resources. Various studies also show that the integration of IoT with AI, UAVs, edge computing, and cloud computing can increase crop productivity, improve crop quality, reduce agricultural input waste, and increase land management efficiency. Overall, the implementation of these digital technologies contributes to increased productivity, operational efficiency, and sustainability of agricultural systems.

However, the study also shows that the implementation of IoT in precision agriculture still faces various challenges, including high initial investment costs, limited communication infrastructure in rural areas, device interoperability, data security and privacy, the need for human resources with digital competencies, and system scalability on heterogeneous agricultural land. These challenges indicate that the success of IoT implementation depends not only on technological advancements but also requires policy support, system standardization, digital infrastructure development, and increased farmer capacity so that technology adoption can take place more widely and sustainably.

The implications of this research confirm that IoT has a strategic role as an enabler towards Smart Agriculture and Agriculture 4.0, which can support food security, efficient use of natural resources, and the achievement of sustainable development goals (SDGs). Further research is recommended to develop an IoT integration model with more advanced technologies, such as digital twins, blockchain, autonomous robotics, 5G/6G communications, and more adaptive AI analytics, accompanied by implementation evaluations on various commodities and agroecosystem conditions so that the benefits of precision agriculture can be applied more widely, inclusively, and sustainably in the future.

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