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*Review*

# Precision and Smart Agriculture: Harnessing IoT for Enhanced Productivity and Sustainability

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**Abstract:** Smart agriculture, driven by the Internet of Things (IoT), has emerged as a transformative approach to enhancing agricultural productivity, resource efficiency, and environmental sustainability. This study provides a comprehensive and integrative review of IoT-based precision agriculture systems, focusing on their technical architecture, performance outcomes, and practical implementation feasibility. The analysis demonstrates that IoT-enabled smart irrigation systems can reduce water consumption by 25–50%, while maintaining or increasing crop yields by 10–20%, depending on environmental and operational conditions. Furthermore, integration of multi-sensor networks, artificial intelligence (AI), and cloud–edge computing significantly improves decision accuracy, reduces input waste (fertilizers and pesticides), and enhances real-time responsiveness to environmental stress. The findings confirm that IoT-based systems provide measurable agronomic, economic, and environmental benefits rather than purely conceptual advantages. A layered technical framework is synthesized to illustrate how sensing, communication, data processing, intelligence, and actuation layers form a cyber-physical agricultural system. In addition, the study evaluates key challenges related to scalability, interoperability, infrastructure readiness, and economic feasibility, highlighting pathways for large-scale deployment. Overall, the results demonstrate that IoT-enabled precision agriculture represents a viable and data-driven solution for improving water-use efficiency, farm profitability, and sustainable food production under increasing climatic and resource constraints.

**Keywords:** Smart Agriculture; Internet of Things (IoT); Precision Agriculture; Automated Irrigation; Agricultural Sensors; Artificial Intelligence; Sustainable Farming.

## 1. Introduction

Improving agricultural productivity is essential for increasing farmers' income and meeting the food demands of a rapidly growing population. According to a report by the Food and Agriculture Organization of the United Nations (FAO), global food production must increase by 60% by 2050 to adequately feed the expanding population [1]. Smart agriculture involves the use of information and communication technologies (ICT), particularly the Internet of Things (IoT) and big data analytics, to address these challenges through electronic monitoring of crops as well as environmental factors such as soil, fertilizers, and irrigation. IoT technologies can reduce costs and scale such studies by enabling the collection of integrated datasets, including network-based data, spatial data from imaging sensors, and human-recorded observations via smartphones [2].

The growth of agricultural production has led to the expansion of the concept of smart farms. A smart farm is a complex system in which plants, through the use of moisture sensors, can automatically determine specific actions to enhance productivity. All these sensors and smart devices can generate large volumes of data, which are

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analyzed to provide useful information about the current state of the farm [3]. Moreover, these data can be further exploited to extract insights that may be beneficial for increasing future production. This has led to the concept of the Internet of Data, a network composed of data entities formed through the Internet of Things. The objective is to provide stakeholders with information about the efficiency of management operations across the supply chain and to facilitate interaction with other users in this domain [4].

Agriculture is one of the main occupations in many developing countries, and insufficient agricultural development can lead to increased migration from rural to urban areas. To address this issue, IoT-based smart agricultural systems can be employed. The field of information technology is advancing rapidly, and these technologies can assist in solving everyday challenges. Numerous researchers are actively working on smart agriculture. The use of wireless sensor networks for data collection in various research projects demonstrates the integration of modern technologies into this industry. The collected data provide information on various environmental factors. However, monitoring environmental data alone is not an efficient solution for increasing crop yield. Multiple factors contribute to reduced production efficiency and hinder higher productivity. Therefore, automation must be implemented in agriculture to overcome these challenges. Consequently, the development of a comprehensive system is essential to provide an effective solution. Nonetheless, full automation in agriculture has not yet been realized due to various constraints. Full automation in agriculture remains constrained by a combination of technical, economic, infrastructural, and socio-institutional barriers. From a technical perspective, interoperability limitations among heterogeneous IoT devices, lack of standardized architectures, data reliability issues, latency in large-scale sensor networks, and cybersecurity vulnerabilities continue to restrict seamless system integration [5,6]. Infrastructure-related challenges, particularly in rural and developing regions, include unstable internet connectivity, insufficient broadband coverage, limited power supply reliability, and inadequate access to cloud and edge computing platforms, which collectively hinder real-time automation and large-scale deployment [7].

Economic constraints also play a critical role, as the high initial investment required for advanced sensors, UAVs, robotic platforms, and intelligent data-processing systems creates adoption barriers, especially for smallholder farmers [8]. Furthermore, scalability challenges arise due to the complexity of integrating multi-vendor technologies and managing high-volume agricultural data streams generated by continuous monitoring systems [9].

In addition, socio-institutional factors such as limited technical literacy among farmers, insufficient training programs, resistance to technological change, and the absence of comprehensive policy and governance frameworks further slow the transition from pilot-scale implementations to fully autonomous agricultural ecosystems [10]. Collectively, these constraints explain why, despite significant technological progress, full agricultural automation has not yet been widely realized at commercial and national scales. Although such systems have been implemented at the research level, they have not yet been made available to farmers as commercial products [11].

Recent years have witnessed a rapid evolution in IoT-enabled smart agriculture, particularly with the integration of Artificial Intelligence (AI), machine learning, cloud computing, and edge-based decision-support systems. While early research primarily focused on wireless sensor networks and basic monitoring frameworks, contemporary studies (2022–2026) emphasize predictive irrigation scheduling, deep reinforcement learning models, UAV-assisted crop monitoring, and intelligent event-processing architectures for large-scale farm management. Recent empirical investigations report measurable improvements in water-use efficiency (ranging from 25% to 50%) and yield enhancement through AI-driven IoT systems, demonstrating that smart agriculture has transitioned from conceptual frameworks to data-driven, performance-validated implementations. Moreover, emerging research highlights critical challenges related to interoperability, scalability, cybersecurity, and economic feasibility, indicating a shift from technology feasibility studies toward sustainable deployment models.

Despite the rapid growth of IoT-enabled smart agriculture research, existing review studies largely focus on isolated technological components such as wireless sensor networks, irrigation automation, UAV monitoring, or artificial intelligence applications. Many previous reviews emphasize conceptual architectures or communication technologies without systematically synthesizing quantitative agronomic performance indicators, sustainability outcomes, and large-scale implementation challenges within a unified analytical framework. Furthermore, limited attention has been given to integrating recent empirical findings (2022–2026) that report measurable improvements in water-use efficiency, yield enhancement, and resource optimization, together with assessments of scalability, interoperability, and economic feasibility.

Therefore, a clear research gap exists in the absence of a comprehensive, performance-oriented, and implementation-focused synthesis that simultaneously integrates: (i) technological evolution of IoT-based precision agriculture systems, (ii) quantified field-level outcomes and efficiency metrics, (iii) sustainability and environmental implications, and (iv) technical feasibility and scalability constraints for real-world deployment.

This study addresses this gap by presenting an integrative analytical framework that bridges technological innovation with practical implementation pathways. Unlike prior reviews that concentrate primarily on individual subsystems, this work provides: (1) a structured layered IoT architecture for precision agriculture, (2) a synthesis of quantitative performance impacts reported in recent empirical studies, (3) a systematic discussion of scalability and infrastructure feasibility, and (4) an implementation-oriented perspective particularly relevant to water-scarce and developing regions. By consolidating technological, agronomic, environmental, and operational dimensions into a unified review, this study contributes a holistic roadmap for advancing IoT-enabled smart agriculture from research prototypes toward scalable and sustainable agricultural transformation.

Accordingly, the primary aim of this study is to develop a comprehensive and integrative analytical review of IoT-based precision agriculture systems that explicitly links technological architecture with quantified agronomic performance, sustainability outcomes, and real-world implementation feasibility. Specifically, this paper seeks to (i) synthesize the evolution of IoT-enabled smart agriculture technologies within a structured layered framework, (ii) evaluate reported quantitative impacts on water-use efficiency, crop yield, and resource optimization, (iii) analyze environmental and sustainability implications, and (iv) assess technical, economic, and scalability challenges affecting large-scale deployment. By clearly articulating these objectives, the study aims to provide a performance-driven and implementation-oriented roadmap for advancing IoT-enabled precision agriculture from conceptual innovation toward scalable, data-driven agricultural transformation.

To establish a clearer conceptual foundation, it is essential to position IoT-enabled smart agriculture within the broader paradigm of sustainable agricultural development. Sustainable agriculture represents a comprehensive framework that integrates environmental stewardship, economic viability, and social responsibility in food production systems. Its core objective is to ensure long-term productivity while conserving natural resources, maintaining ecosystem balance, and supporting rural livelihoods.

Within this broader framework, precision agriculture emerges as a management-oriented approach that seeks to optimize input use—such as water, fertilizers, pesticides, and energy—through spatial and temporal variability management. By relying on site-specific data, precision agriculture contributes directly to sustainability goals by minimizing resource waste, reducing environmental impacts, and improving production efficiency.

Building upon this foundation, smart agriculture powered by the Internet of Things (IoT) represents the digital and technological evolution of precision agriculture. IoT-enabled systems provide real-time environmental monitoring, automated control mechanisms, data-driven decision-making, and cyber-physical integration across farming operations. In this sense, IoT does not function as an isolated technological innovation; rather, it serves as an enabling infrastructure that operationalizes the principles of sustainable agriculture through intelligent sensing, communication, analytics, and actuation layers.

Accordingly, sustainable agricultural development can be understood as the overarching objective, precision agriculture as the strategic management approach, and IoT-based smart agriculture as the technological enabler that translates sustainability principles into measurable agronomic, economic, and environmental performance improvements. To ensure a systematic, transparent, and performance-oriented synthesis of the existing literature, a structured methodological framework was adopted. The following section outlines the review design, search strategy, selection criteria, and analytical approach employed in this study.

## 2. Methodology

This study was conducted as a structured and integrative analytical review to synthesize current knowledge on Internet of Things (IoT)-based precision and smart agriculture systems, with emphasis on their technical architecture, agronomic performance, sustainability implications, and large-scale implementation feasibility. A comprehensive literature search was performed covering publications between 1992 and 2026 in order to capture both foundational developments in precision agriculture and recent advancements in AI-integrated IoT systems. Relevant studies were identified through searches in major international scientific databases, including Scopus, Web of Science, IEEE Xplore, ScienceDirect, SpringerLink, and Google Scholar.

The search strategy incorporated combinations of the following keywords: "Precision Agriculture," "Smart

Agriculture," "Internet of Things (IoT)," "Smart Irrigation," "Wireless Sensor Networks (WSN)," "Artificial Intelligence in Agriculture," "Machine Learning," "UAV-based Monitoring," "Edge Computing," "Cloud Computing," "Sustainable Agriculture," and "Water Use Efficiency." A two-stage screening process was applied. In the first stage, titles and abstracts were evaluated to determine relevance to IoT-enabled agricultural systems. In the second stage, full-text articles were assessed to ensure methodological rigor, availability of quantitative or analytical findings, and alignment with the study objectives.

Inclusion criteria required that studies addressed IoT-based or sensor-driven precision agriculture systems; provided empirical, experimental, simulation-based, or analytical performance outcomes such as water-use efficiency, yield improvement, input reduction, or energy savings; discussed system architecture, technological frameworks, or implementation feasibility; and were published in peer-reviewed journals or reputable international conference proceedings in English. Studies were excluded if they focused solely on conceptual discussions without technical or performance evaluation, addressed general agricultural mechanization without digital or IoT integration, lacked sufficient methodological transparency, or were duplicate records and non-scientific reports.

After removing duplicates and non-relevant records, an initial pool of 462 articles was identified. Following full-text evaluation, 89 studies met the inclusion criteria and were selected for detailed analysis and synthesis. For each selected study, data were extracted regarding research objectives, study type (experimental, field trial, simulation, or review), geographic region, crop type (where applicable), IoT architecture components (sensing, communication, processing, intelligence, and actuation layers), performance indicators (including water savings, yield improvement, fertilizer and pesticide reduction, and energy efficiency), as well as reported economic or scalability considerations.

The synthesis followed a thematic and architecture-oriented analytical approach. Findings were categorized into five interconnected dimensions: layered technical architecture of IoT-based precision agriculture systems; quantitative agronomic performance indicators; resource optimization and sustainability outcomes; implementation feasibility (technical, economic, and infrastructural); and scalability, interoperability, and deployment challenges. Comparative cross-study evaluation was conducted to identify consistent performance ranges—such as 25–50% water savings and 10–20% yield improvement—and to distinguish experimental-scale findings from large-scale implementations.

To enhance analytical robustness and ensure quality control, selected studies were evaluated using adapted criteria derived from the CASP (Critical Appraisal Skills Programme) and JBI (Joanna Briggs Institute) appraisal frameworks. Particular attention was given to methodological transparency, validity of data, reproducibility of results, and clarity of reported performance metrics. This methodological framework enabled the development of a structured, performance-driven synthesis linking IoT technological architecture with measurable agronomic outcomes and sustainability implications, thereby providing a comprehensive roadmap for advancing IoT-based precision agriculture from pilot-scale applications toward scalable and sustainable agricultural systems. Following the structured methodological framework described above, the subsequent sections present a thematic and analytical synthesis of the literature, beginning with the conceptual foundations of precision agriculture and progressively advancing toward IoT-enabled smart agricultural systems.

## 3. The Concept of Precision Agriculture

The fundamental objective of precision agriculture is to optimize agricultural processes through site-specific and data-driven management. Rather than treating the entire farm as a uniform production unit, precision agriculture seeks to manage spatial and temporal variability by applying the right input, in the right place, at the right time, and in the right way. This optimization-oriented approach aims to enhance resource-use efficiency, improve decision accuracy, reduce input waste, and maximize productivity while maintaining environmental and economic sustainability. By integrating advanced sensing technologies, geospatial tools, data analytics, and automated control systems, precision agriculture transforms conventional farming into a targeted management strategy focused on operational efficiency and performance improvement.

The continuous growth of the global population and the increasing demand for high-quality agricultural products necessitate the modernization and intensification of farming practices. At the same time, high efficiency in the use of water and other resources is essential. One of the most important concepts expected to significantly contribute to increased food production is precision agriculture. The aim of precision agriculture is to optimize and improve agricultural processes to ensure maximum efficiency. This requires rapid, reliable, and distributed measurements to provide a more accurate representation of current conditions in cultivation areas or to coordinate machinery in a way that enables optimized energy consumption, water use, and the application of chemicals for pest control and plant growth. At more advanced levels, by collecting information from numerous heterogeneous systems, validated scientific knowledge can be organized into intelligent algorithms to offer deeper insights into potential risks and to generate automatic control signals based on plant responses [12].

Precision agriculture is a technology that, within the framework of sustainable development principles, enhances productivity through the collection and storage of spatial attributes and data processing, enabling the optimal use of production inputs and resources. This technique is based on information technology and, to achieve its intended objectives, incorporates components such as Geographic Information Systems (GIS), the Global Positioning System (GPS), Variable Rate Technology (VRT)—which involves performing agricultural operations such as the application of inputs including seeds, fertilizers, chemicals, and water according to the specific needs of each section of a farm—and remote sensing. Given the importance and role of precision agriculture in agricultural development and the numerous advantages arising from its application, several studies have been conducted to assess the feasibility of implementing precision agriculture in the country. Precision agriculture was first introduced in the United States in the 1980s. This technology was developed to achieve sustainability and address environmental challenges, enabling farmers to fully mechanize their farms. The optimal use of inputs, increased productivity, and the production of healthy crops while adhering to environmental considerations are among the primary objectives of precision agriculture in Iran [13].

## 4. Advantages of Precision Agriculture

Improving both the quantitative and qualitative performance of crops, managing within-field variability, and minimizing environmental impacts are among the key drivers of precision agriculture development. Precision agriculture differs from conventional farming primarily in its management approach. Rather than treating the entire farm as a single management unit, precision agriculture applies management practices to smaller zones within the field, which enhances the level of management by focusing on the actual needs of farmers and site-specific conditions. Precision agriculture is employed as a management system throughout different stages of cultivation, which sequentially include data collection at the field level, data analysis and managerial decision-making, and the implementation of appropriate cultivation practices, and these steps are repeated continuously in iterative cycles. As a result, economic efficiency is increased while environmental pollution is reduced, since chemical fertilizers, pesticides, and herbicides are applied precisely in the amounts required for each small section of the farm—neither more nor less. The most important advantages of implementing precision agriculture include the ability to quantitatively and qualitatively measure crop yield at harvest time using system-integrated equipment, prevention of soil erosion through minimal tillage operations, the use of direct seeding methods and reduced tillage frequency, cost reduction and increased net income through an expert-driven long-term management perspective, enabling producers to utilize data for making strategic economic decisions, environmental protection through reduced consumption of chemical fertilizers and pesticides, optimization of plowing and land leveling practices to prevent the degradation of high-quality soil structure, adjustment and optimization of input usage leading to rationalized costs, and the promotion and enhancement of sustainable agriculture [14].

## 5. The Philosophy of Precision Agriculture and Sustainable Agricultural Development

Given the rapid growth of the global population and the continuous depletion of natural resources, traditional agricultural production—based on farming practices and production systems that existed prior to the introduction of modern technology and relied on natural and ecological balances—has proven insufficient to meet the world's food demands. Consequently, in the early 1950s, with the onset of the Green Revolution in agriculture, traditional farming systems began to shift toward automation and smartification, which today constitute the dominant agricultural paradigm worldwide. This system is based on a technological package emphasizing high-yield crop varieties, mechanization, and the extensive use of herbicides, pesticides, and chemical fertilizers.

The term sustainability refers to stable and uniform conditions that extend over long-term horizons. However, insufficient knowledge, lack of adequate data, and limited consensus regarding water resources, the future role of people in agriculture, and the relationship between agriculture and the environment have made it difficult to accurately predict the future state of agriculture. Sustainable agriculture is a form of farming that serves human interests, uses resources more efficiently, and remains in balance with the environment. In other words, sustainable agriculture must be ecologically sound, economically viable, and socially acceptable. Two key principles underpin sustainable agriculture: minimizing the use of chemical inputs—particularly pesticides and fertilizers—and adopting a holistic view of the farm as an integrated system.

Some experts who emphasize the ecological aspects of agricultural systems refer to this approach as organic, biological, ecological, natural, or alternative agriculture. Sustainable agriculture is a farming system based on the management of agro-ecosystems, with a focus on soil fertility and plant health, and the avoidance of synthetic chemical inputs, while being compatible with regional and local socio-economic conditions [15].

### 5.1. Objectives of Sustainable Development

Sustainable agriculture, through simple methods such as substituting natural materials, maintaining native ecological balances, and enhancing soil fertility, can be implemented across diverse regions and farming systems with lower costs and higher productivity. It is grounded in integrated management, organic agriculture, and biodynamic farming practices. According to the World Commission on Environment and Development, the functional objectives of sustainable development are as follows [16]: technological transformation, enhancement of economic growth, promotion of participatory development, conservation and protection of natural resources, improvement in the quality of economic growth, population control within sustainable limits, transformation of international economic relations, simultaneous consideration of environmental and economic factors in decision-making, and fulfillment of essential needs related to employment, food, energy, water, and health.

### 5.2. The Impact of Mechanization on Achieving Sustainable Agriculture

Mechanization can be comprehensively defined as the application of modern technology in agriculture to achieve sustainable development [17]. The impacts of mechanization on attaining sustainable agriculture can be summarized as follows: proper utilization of agricultural inputs, timely execution of farming operations, performance control during harvest, cost reduction and decreased energy consumption, conservation of natural resources particularly soil, reduction of labor intensity and improvement of social safety, and pest and weed control with reduced use of chemicals.

## 6. The Concept of Smart Agriculture

Smart agriculture is not a completely new concept in farming. The initial development of precision agriculture began in 1992 in Minneapolis and subsequently gained attention as a global research topic. The term refers to a farm management system based on information and technology to identify, analyze, and manage variability across different fields in order to optimize resource use and preserve land [18].

Smart agriculture represents modern approaches to the cultivation, maintenance, and harvesting of crops and plants, relying on automated and intelligent processes. By smartifying farm activities, traditional manual and static farming practices can be transformed into dynamic and intelligent systems, resulting in higher yields with reduced human supervision. Smart agriculture enhances productivity through the optimized use of inputs such as water, fertilizers, pesticides, livestock monitoring, and pest and disease prediction [19].

The term “smart agriculture” is often used to highlight the application of Internet of Things (IoT) solutions in farming. The adoption of IoT technologies in agriculture is continuously growing, and as technology continues to evolve, numerous opportunities for IoT-based agricultural innovations and job creation are emerging. Developing IoT-enabled products for agriculture in the coming years could bring significant transformation to the sector. IoT technologies have the potential to revolutionize various aspects of agriculture. Specifically, IoT can enhance farming in the following ways [20]:

1. Expanding data collection through smart agricultural sensors.
2. Better control of agricultural processes, reducing operational risks.
3. Cost management and waste reduction through monitoring and control of production.
4. Increased efficiency via automation of farming processes.

5. Improved quality and increased quantity of agricultural products.

Ultimately, these factors can lead to higher incomes for farmers. As the IoT network expands, IoT-enabled agricultural products become more comprehensive and precise. Similar to a growing child, IoT "learns" and evolves over time. In agriculture, IoT holds significant potential for innovation, job creation, and the development of new farming devices.

## 7. Reasons for Using Smart Agriculture

In crop cultivation, three factors—water, soil, and climate (including sunlight, temperature, and other external parameters aside from water and soil)—have a significant impact on plant growth and development, making their monitoring critically important. Additionally, managing agricultural equipment efficiently can enhance the return on investment in farms and orchards. IoT-based technologies enable real-time monitoring and management of these parameters, ensuring that each plant is grown in its optimal zone, with all vital and physical signs continuously controlled. In precision agriculture, the collected data can also be analyzed using various data mining techniques to identify appropriate growth patterns [21].

## 8. Applications of Smart Agriculture

Although industrialized countries have increasingly adopted modern cultivation and harvesting methods in recent years to improve productivity, the advent of smart agriculture emphasizes optimizing resource use and increasing efficiency more than ever. While agriculture and technology might currently seem separate, the integration of intelligence into industrial farming makes the two inseparable.

Smart agriculture involves the use of the internet and specialized advanced equipment to enhance crop yields, reduce environmental risks, and optimize water and energy use. The concept of a smart farm is a global topic with potential applications as a solution to challenges such as increasing food demand, labor shortages, farmers' limitations, and the expansion of advanced agricultural products. A key technology in smart farms is the Internet of Things (IoT), which is used to analyze farm conditions such as temperature, humidity, and sunlight levels.

The opportunities presented by smart farms are so vast that the number of farmers and farms prioritizing technology in agriculture is growing daily. Researchers throughout the history of smart agriculture have produced valuable results, demonstrating increased production while reducing pollution and potential environmental damage. A successful case study from Thailand highlights the benefits of smart agriculture [22].

In countries with diverse climates, such as Iran, where drought is a major concern, IoT has played a significant role in agriculture. Water management and the use of sensors to conserve irrigation water are among the most notable contributions of IoT. Arshin Company, which has long been active in IoT, has implemented several agricultural IoT projects.

## 9. Internet of Things in Agriculture

The Internet of Things (IoT) has emerged as a key technology in recent years, reshaping human life. Some major countries have adopted IoT development as a driver of economic growth. Various projections estimate that by 2020–2025, the IoT ecosystem will include approximately 50 billion connected devices, four billion connected people, $4 trillion in revenue opportunities, 25 million applications, 25 billion integrated intelligent systems, and 50 trillion gigabytes of generated data [23].

IoT has applications across multiple domains, including industrial communication, smart cities, smart homes, smart energy, machine-to-machine communication, smart agriculture, building management, healthcare, and logistics. IoT aims to integrate the physical world with the digital world using the internet. It is defined as a system of interconnected computing devices, mechanical and digital machines, objects, animals, or people, each with unique identifiers and the ability to transfer data over a network without requiring human-to-human or human-to-computer interaction [24].

With the growing global food demand, combined with declining natural resources, arable land, and unpredictable weather conditions, food security has become a major concern. The installation of IoT devices in agriculture is projected to increase from 30 million in 2015 to 75 million by 2020 [25].

Over the years, Wireless Sensor Networks (WSNs) have been used in smart agriculture and food production, focusing on environmental monitoring, precision agriculture, machinery, process automation, and traceability. WSNs are well-suited for smart agriculture due to their self-organizing, self-configuring, self-diagnostic, and self-healing capabilities. A WSN typically consists of radio frequency (RF) transmitters and receivers, sensors, microcontrollers, and power sources [26].

However, with the emergence of IoT, there has been a paradigm shift from using WSNs alone for smart agriculture to IoT serving as the main driver. IoT integrates several existing technologies, including WSN identification, RF communication, cloud computing, middleware systems, and end-user applications. In agriculture, IoT empowers farmers with decision-making tools and automation technologies, seamlessly integrating products, knowledge, and services for improved efficiency, quality, and profitability. Recent reviews of IoT in agriculture have focused on the challenges and limitations of large-scale pilot implementations across the entire agricultural supply chain [27].

**Figure 1** illustrates the IoT ecosystem, highlighting the four essential components for any IoT application in agriculture: temperature sensors, air humidity sensors, soil moisture sensors, and water level sensors.

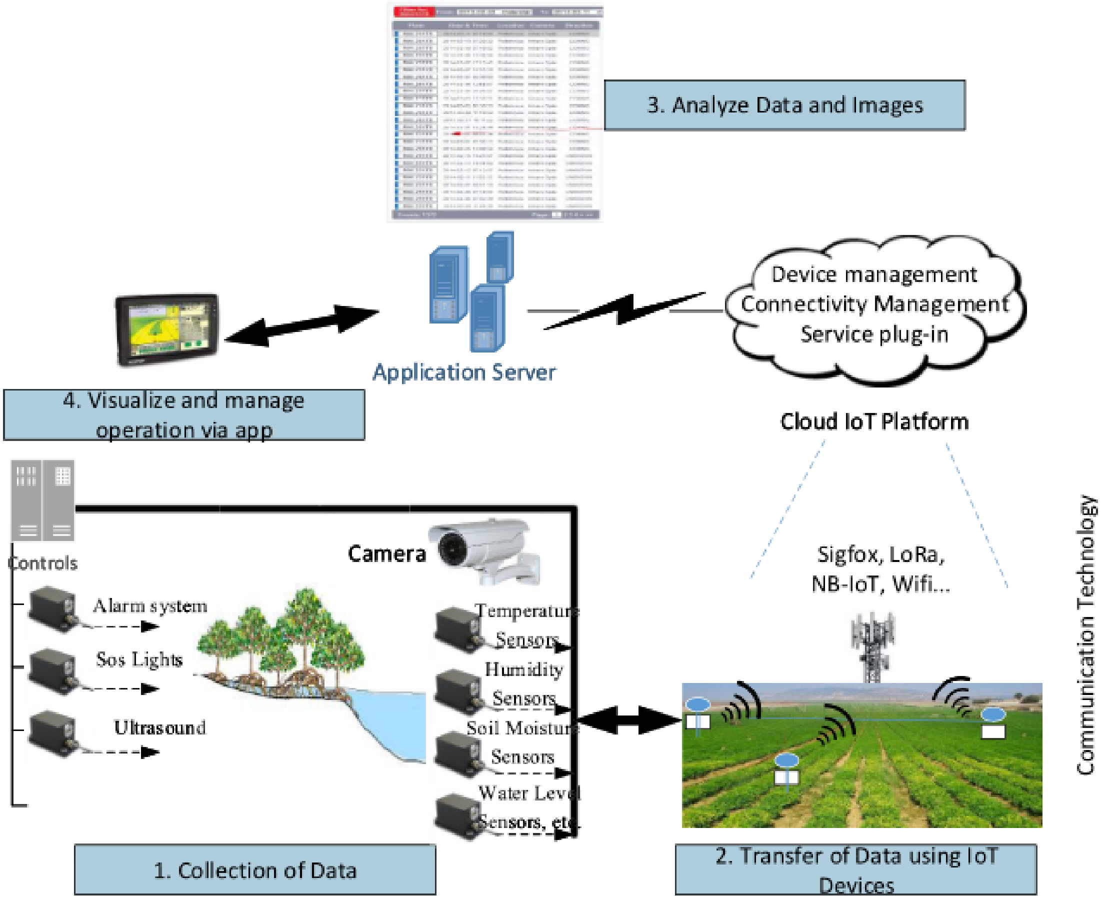

**Figure 1.** An Image of the IoT Ecosystem for Agriculture.

## 10. Precision-Smart Agriculture and the Internet of Things

Agriculture is one of humanity's greatest concerns, as most of the world's food is produced through farming. Currently, many people, particularly in Africa, suffer from hunger due to food scarcity. In 2016, chronic hunger affected over 800 million people worldwide, and more than 10 million people died as a result. Clearly, increasing food production is an effective strategy to eradicate hunger and poverty. However, agriculture in most developing countries remains far from modernized, leading to low food production.

Recently, smart agriculture has been proposed to promote farming and increase food production. Smart agricultural systems incorporate advanced computing and information technologies, such as artificial intelligence (AI) and cloud computing, into agricultural production. The Internet of Things (IoT) and AI are two primary techniques for developing smart agriculture systems. IoT is typically used to collect agricultural data and transmit it to data centers. Large volumes of agricultural data must be processed and analyzed quickly.

These systems integrate advanced information technologies, especially AI and cloud computing, with agricultural production to enhance food output. A particularly important AI model is deep reinforcement learning in the cloud layer, which supports immediate, intelligent decision-making, such as determining the optimal irrigation water quantity to improve the crop growth environment [28].

A process-focused approach to IoT-based precision agriculture exists to increase farm productivity and efficiency by real-time monitoring of field parameters. Data is collected from the field using sensors such as soil sensors, thermal and humidity sensors, air quality sensors, and cameras mounted on drones. The data from each sensor is aggregated at a base station and sent to a gateway. Recent research by Microsoft on IoT-based precision agriculture reports that designing energy-efficient data aggregation methods for such IoT networks is a classic research challenge.

Wireless Sensor Networks (WSNs) have emerged as a key technology for multiple applications due to advances in microelectromechanical systems (MEMS), small and smart low-power sensors, and digital wireless communication technologies. WSNs consist of numerous battery-powered, multifunctional sensor nodes, also known as wireless sensors. Due to limited accessibility, radio communication is generally used to transmit data wirelessly to a remote base station for further processing [29].

Precision agriculture integrates diverse Information and Communication Technologies (ICT) for data processing and management throughout the crop and livestock production cycle. Data that can be collected or generated by ICT includes field attributes (soil chemical and physical properties, topography, productivity data), weather conditions, camera or satellite imagery, historical records, and other internal and external sources. Integrating and analyzing this data enables automated decision-making (structural decisions executed by equipment, robots, or machinery) or supports human decision-making (semi-structured decisions).

Precision agriculture and IoT aim to optimize the use of energy, water, fertilizers, pesticides, and other inputs to produce more food with less effort, cost, and environmental impact. These technologies help farmers achieve higher productivity, economic benefits, sustainability, and environmental protection. Processes such as precise soil preparation, precision planting, automated irrigation, precise crop management, greenhouse management, phenotyping, integrated pest management, precision harvesting, data analysis, and evaluation all rely on PA and IoT technologies [30].

For field monitoring of machinery and robots during routine operations, sensors and remote sensing, automated information systems, data storage, big data, and data science are used. Across all IoT domains—including smart cities, smart homes, smart buildings, and precision agriculture—the connection of new devices (sensors or actuators) to multiple sensor networks is increasing. Data streams from diverse sources are integrated via an IoT gateway. Depending on the number of devices and sensors and the frequency of data collection, raw data transfer can increase in volume and speed, creating challenges such as unpredictable latency, bottlenecks, incomplete or inaccurate data, storage issues, and processing constraints. More efficient processing systems are required to handle dynamic and heterogeneous event data and automated decision-making. These systems are known as Complex Event Processors (CEP) [31].

The most critical component of precision agriculture technologies is performance monitoring, which is often considered a key indicator of adoption, as it is the most widely used PA technology globally. Smart or precision agriculture, through precise input management using information technology, identifies all factors affecting farm performance. Continuous monitoring of all stages of agricultural operations, from pre-planting to post-harvest, provides comprehensive and accurate information about environmental conditions and factors affecting crops.

By analyzing the collected information, managers can optimize annual crop production and reduce economic costs. Research in precision agriculture began in the mid-1980s in the United States, Canada, Australia, Western Europe, and other leading countries. Smart agriculture is a management strategy that uses information technology to extract data from diverse sources to make appropriate production decisions. It involves studying and managing variability in factors affecting crop performance, including sampling, mapping, analysis, and management of spatial and temporal variations based on soil fertility, pest populations, and crop characteristics.

The essential stages of precision agriculture include data collection, data analysis, managerial decision-making, and implementation of management operations. This approach considers environmental factors and manages spatial and temporal variations to achieve optimal and sustainable production. Because factors affecting crop growth—such as soil properties, plant characteristics, and weed distribution—differ across farm sections, input optimization must be carried out for each field zone individually. This approach increases farm management efficiency by providing a complete understanding of the area under management. By satisfying crop requirements at each location, production efficiency is enhanced, environmental impacts are minimized, and economic profitability, environmental health, social acceptance, and agricultural productivity are improved.

In terms of environmental monitoring, creating databases on air and water pollutants, identifying contaminant sources, and assessing their impact on air and water quality—divided into inland and coastal waters—is highly important. One proposed policy by environmental organizations is the use of online monitoring systems for air and water pollution, which enables informed decision-making [32].

The proposed layered technical architecture of IoT-based precision agriculture is summarized in **Table 1**. The framework illustrates the structured integration of sensing, communication, data processing, intelligent decision-making, and actuation layers. This architecture establishes a cyber-physical agricultural system in which continuous feedback between monitoring, analytics, and automated control enhances water-use efficiency, input optimization, and overall farm productivity.

**Table 1.** Layered Technical Framework for IoT-Based Precision Agriculture Systems.

| Layer | Layer Name | Core Components | Main Functions | Technical Contribution to System Performance |
|---|---|---|---|---|
| 1 | Sensing Layer (Perception Layer) | Soil moisture sensors, nutrient sensors, temperature & humidity sensors, optical/multispectral sensors, UAV-mounted cameras, environmental monitoring devices | Real-time acquisition of spatial and temporal agricultural data | Enables continuous environmental monitoring and accurate field-level data collection |
| 2 | Communication Layer (Network Layer) | LPWAN, LoRaWAN, ZigBee, NB-IoT, cellular networks, satellite links, IoT gateways | Secure transmission and aggregation of sensor data to processing units | Ensures reliable connectivity, scalability, and low-latency data transfer |
| 3 | Data Processing Layer (Edge–Cloud Layer) | Edge computing nodes, cloud platforms, data storage systems, Complex Event Processing (CEP) engines | Data filtering, preprocessing, storage, anomaly detection, integration of multi-source datasets | Reduces latency, improves data management efficiency, and enables large-scale analytics |
| 4 | Intelligence & Decision-Making Layer | AI/ML algorithms, predictive irrigation models, neural networks, deep reinforcement learning models | Data-driven decision generation for irrigation, fertilization, pest control, and yield prediction | Enhances decision accuracy, optimizes resource allocation, and improves productivity |
| 5 | Actuation & Control Layer | Automated irrigation valves, variable-rate applicators, smart sprayers, autonomous tractors, agricultural robots | Execution of control commands in the field and implementation of optimized actions | Completes cyber-physical feedback loop and enables automated precision farming |

## 11. Applications of the Internet of Things in Smart Agriculture

With the rapid expansion of the Internet of Things (IoT) network, nearly every aspect of life—including health and fitness, home automation, vehicle trackers, and smart cities—has been impacted. Naturally, agriculture is no exception. Over the past decades, agriculture has undergone numerous technological transformations and has become increasingly industrialized and technology-driven. By employing various smart agricultural devices, farmers have gained better control over livestock management and crop growth.

The growing demand for food, both in quantity and quality, necessitates the adoption of innovative solutions in agriculture [33]. IoT is a rapidly growing network of technologies capable of offering numerous solutions for optimizing the agricultural industry. Additionally, IoT plays a role in smaller-scale applications such as greenhouse cultivation or even indoor potted plants. However, in countries with large cultivated lands, IoT can save billions in water management, maximize crop yield, and reduce labor costs [34]. Agriculture encompasses multiple sectors:

- Animal feed production, closely linked to livestock farming.
- Oilseed crop cultivation, which holds high economic importance.
- Fruit production, which historically contributes to national exports.

IoT is relevant not only to farming but also to forestry and greenhouse management. Essentially, wherever agricultural production or horticulture exists, IoT can introduce new capabilities and efficiencies. The core role of IoT in agriculture is to increase productivity and simplify agricultural operations. Other applications of IoT in agriculture include [35]:

- Management and tracking of agricultural transport vehicles, including tractors.
- Unmanned tractors with remote-control capabilities.
- Use of drones for surveying agricultural fields.
- Pesticide spraying using drones.
- Soil analysis for fertilizer and moisture content.
- Monitoring meteorological conditions.
- Storage monitoring, such as water and fuel tanks.
- Collection, storage, and analysis of data from sensors.

## 12. Smart Irrigation Systems in Agriculture

IoT is an emerging concept in agriculture. With the creation of smart farms, IoT has gained significant popularity in the agricultural sector. IoT helps farmers improve the quality, quantity, efficiency, and protection of agricultural production [36]. Combining IoT with Artificial Intelligence (AI) can lead to transformative improvements in traditional agriculture. These advancements include management and control of internal processes in smart agricultural environments, including harvesting and storage of crops; use of AI for data analysis and rapid decision-making for subsequent actions; optimized use of data collected from smart agricultural sensors; improved efficiency in the use of resources (soil, water, fertilizers, pesticides, etc.); monitoring and ensuring the safety of farm workers; weather forecasting and proactive crop protection; use of drones to improve crop health; remote management via mobile devices; increased profitability and cost-effective production; reduction of waste and cost savings; application of unmanned aerial vehicles (drones); production of high-quality, healthy crops; integrated pest management; deployment of expert agricultural systems; implementation of smart and precision agriculture; environmental protection; reduction of production costs; ensuring food safety; automation of agricultural operations; and use of robotics in farming. These applications collectively illustrate how IoT and AI are revolutionizing agriculture, making it more efficient, sustainable, and profitable while minimizing environmental impact.

## 13. Key Equipment and Technologies in Precision and Smart Agriculture

Over the past few decades, agriculture has evolved from small- and medium-scale operations into an industrial and commercial activity. This transformation allows large companies to operate in agriculture much like other industries. Consequently, all agricultural activities can be automated, planned, and managed through IoT-based solutions. It is projected that from 2017 to 2022, the global smart agriculture market will grow at an annual rate of 19.3%, reaching USD 23.14 billion by 2022 [37].

The key drivers for this growth include increasing demand for higher crop yields, expanded use of information and communication technologies in agriculture, and rapid global climate changes. Market providers offer a variety of solutions, most of which rely on sensors and efficient communication for a wide range of applications. The main technologies and equipment currently available for smart and precision agriculture are discussed below.

### 13.1. Acoustic Sensors

Acoustic sensors provide unique solutions for farm management, including soil cultivation, weed removal, and fruit harvesting. Their main advantages are low cost and rapid response, especially compared to portable equipment. These sensors work by measuring changes in noise levels during interaction with other materials, such as soil particles. Acoustic sensors are commonly used for pest monitoring and classification of seed types based on sound absorption spectra [38].

### 13.2. Optical Sensors

Optical sensors utilize light reflection to measure soil organic matter, moisture, color, mineral content, and clay composition. They assess soil characteristics based on reflected light across different parts of the electromagnetic spectrum. Changes in reflection indicate variations in soil density and other parameters. Fluorescence-based optical sensors can monitor plant growth, particularly fruit maturity. When combined with microwave scattering, optical sensors can also describe canopy structures of crops like olive trees [39].

### 13.3. Ultrasonic Sensors

Ultrasonic sensors are cost-effective, versatile, and easy to use, with adjustable sampling rates. Common applications include tank monitoring, spray distance measurement (e.g., controlling boom height and width for uniform coverage), object detection, and canopy monitoring. When combined with cameras, ultrasonic sensors can track weed coverage. Plant height is determined using ultrasonic sensors, while cameras assess the extent of crop and weed coverage [40].

### 13.4. Electro-Optical Sensors

Electro-optical sensors differentiate between plant types and are used to identify weeds, unwanted plants, and herbicide targets, especially in wide-row crops. When combined with GPS, these sensors can map weed distribution and density. They can also distinguish vegetation from soil based on spectral reflectance [41].

### 13.5. Airflow Sensors

Airflow sensors measure soil air permeability, moisture content, and soil structure to identify different soil types. Measurements can be performed in fixed or mobile positions. The output determines the pressure required to inject a specified amount of air at a given soil depth. This method evaluates soil properties such as compaction, structure, and moisture, producing a unique soil signature [42].

### 13.6. Electrochemical Sensors

Electrochemical sensors assess soil characteristics such as nutrient content, including pH. They provide a faster, less expensive alternative to conventional chemical soil analyses. Macro- and micronutrients, salinity, and soil pH can all be measured using these sensors [43].

### 13.7. Electromagnetic Sensors

Electromagnetic sensors measure soil electrical conductivity and transient electromagnetic responses. They are used to detect electrical responses and adjust variable-rate applications in real-time. These sensors employ electrical circuits to measure particle conductivity or charge accumulation through contact or non-contact methods. Residual nitrates and organic matter in soil can also be measured using electromagnetic sensors [44].

### 13.8. Mechanical Sensors

Mechanical sensors evaluate soil mechanical resistance (compaction). They penetrate the soil or extract a sample, with pressure measured using load cells or pressure gauges. The applied force correlates to soil resistance against the tool's front edge [45].

### 13.9. Eddy Flux Sensors

Eddy flux sensors measure the exchange of $CO_2$, water vapor, methane, and other gases, as well as energy between the soil surface and the atmosphere. This method provides precise measurements of surface energy flux and gas exchanges in various ecosystems, with critical applications in agriculture. Their high accuracy and ability to monitor large areas make them preferred over enclosed chambers [46].

### 13.10. Light Tracking and Adjustment Sensors

Light-tracking sensors (e.g., LiDAR) are widely used in applications such as land mapping, soil type identification, 3D farm modeling, erosion monitoring, and yield prediction. When combined with GPS, LiDAR can produce 3D maps of orchards or crop fields. Additionally, this technology is commonly used for estimating biomass of various crops and trees [47].

## 14. IoT Roadmap

The Internet of Things (IoT) is not a technology of the future—it exists today and is driving major transformations in modern cities and everyday human life worldwide. IoT interacts with devices, assets, information, knowledge, services, and businesses. Today, using the Internet and modern technology is considered essential in many domains.

IoT applications are widespread, including urban and residential areas, agriculture and fisheries, water supply networks, industrial water management, and wastewater treatment facilities. In the water industry, key applications of IoT include [48]:

- Monitoring water leaks and losses in facilities.
- Smart water consumption management.
- Remote system control.
- Sensor analysis and management.
- Maintenance management.
- Water and wastewater quality monitoring.
- Smart energy management.
- Smart metering.

With the global population expected to reach 10 billion by 2050, water resources will become increasingly critical. In arid and semi-arid regions such as Iran, water resource management is particularly valuable. Approximately 50% of Iran's water resources are underground, with less than 5% flowing on the surface. While surface water can be replenished through subsequent rainfall, groundwater cannot. Recent innovations in IoT have created opportunities to manage water resources more effectively and promote water conservation. Consequently, IoT and its applications play a pivotal role in daily life and smart agriculture.

## 15. Level of IoT Adoption in Agriculture

IoT is a rapidly expanding technology, increasingly adopted by many countries [49]. The distribution of published articles across countries illustrates where IoT has been applied in agriculture, particularly for irrigation (**Figure 2**).

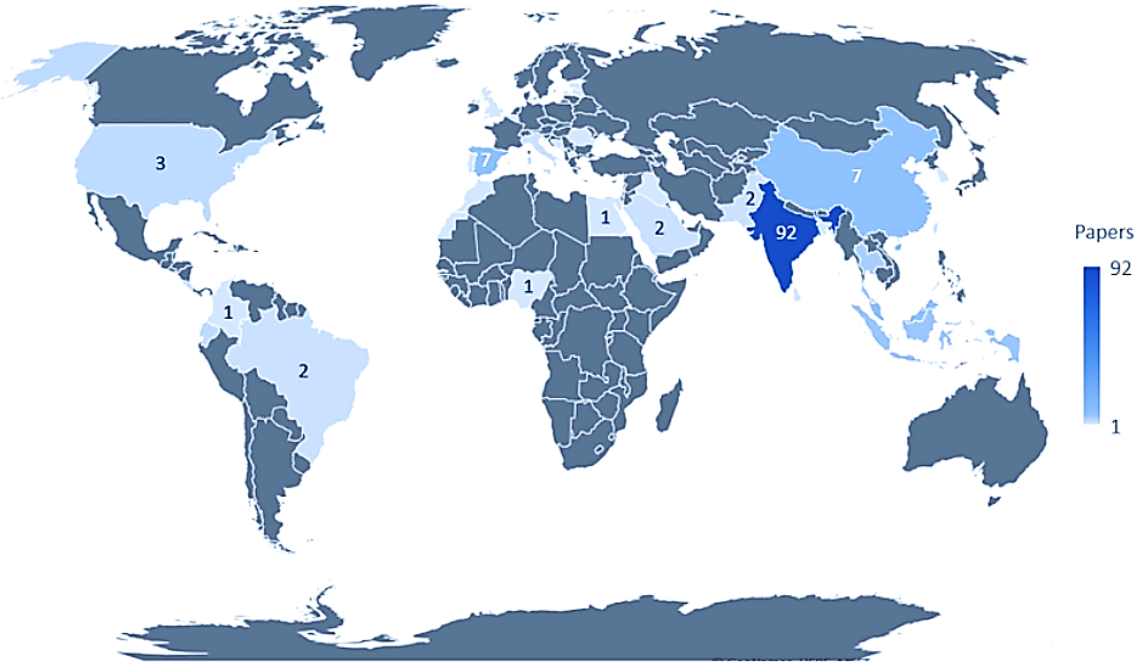

**Figure 2.** Geographical distribution of published articles on the use of the Internet of Things for irrigation worldwide.

- Countries that have implemented IoT for irrigation largely rely on agriculture as a key economic sector.
- India leads with the highest number of publications (92 articles, 57.5% of total).

- China and Spain each have 7 articles.
- Costa Rica, Ecuador, Indonesia, Thailand, and the USA have between 3 and 6 articles each.
- Other countries have 1–2 articles.

These statistics reflect data up to mid-2019 [50].

Interestingly, among the five countries with the largest agricultural areas (China, USA, Australia, Brazil, Kazakhstan), only one ranks among the top five in IoT-based water management research. India, despite having the highest number of publications on IoT irrigation systems, ranks seventh in terms of agricultural land area. Among the top six countries by publications, three—India, China, and Spain—face high to moderate water scarcity (**Figure 2**).

Some countries with less water scarcity also use IoT in agriculture but have fewer publications (e.g., the USA). This does not mean these countries are not reducing water use; efforts may be undertaken primarily by private enterprises, with results patented rather than published. Overall, most IoT agricultural publications originate from developing countries.

The figure illustrates the adoption of this technology and indicates increasing interest in IoT for agriculture in recent years. The lower number of articles for 2019 is due to incomplete data collection, as not all studies for that year had been published [51].

## 16. Applications of the Internet of Things

A key objective of the Internet of Things (IoT) is to create intelligent environments such as smart agriculture, smart homes, smart healthcare systems, smart transportation, and so on, by leveraging various sensing technologies, devices, and communication protocols. Generally, the application of IoT in agriculture and irrigation provides three major advantages, enabling significant progress in the automation and intelligent management of systems. These advantages are intelligent sensing and monitoring, smart analysis and planning, and subsequent intelligent control, management, and operation.

## 17. IoT-Based Smart Agriculture

The advantages and applications of the Internet of Things are summarized in **Table 2**. These include reducing farmers' irrigation-related challenges, enabling smart irrigation, optimizing the use of rainfall and minimizing water wastage, reducing costs associated with irrigation and agriculture, increasing crop yield, saving energy (up to 35%), resources, and labor, eliminating manual supervision for soil moisture measurement and detection, timely irrigation to prevent crop losses, ensuring adequate water supply for plant survival during critical periods, preventing premature irrigation, adjusting water delivery height to reduce surface evaporation and plant damage, remote monitoring, wireless technology integration, using insulation sheets in water distribution pipes to prevent heating, among others. These are key benefits of integrating IoT with intelligent systems, highlighting the need for modern society to adopt this technology in agriculture and daily life [52]. Based on these points, smart management enabled by IoT in agriculture and irrigation can be categorized as follows:

1. Intelligent management of agricultural inputs: smart irrigation, smart soil quality control, smart seed management, and smart fertilization.
2. Management of damaging factors: smart weed and pest control.

**Table 2.** Advantages and Applications of IoT in Agriculture.

| **Advantages** | **Applications** |
|---|---|
| Increased efficiency in water, soil, fertilizers, and pesticides | Intelligent management of agricultural inputs (water, soil, seeds, fertilizers, and pesticides) |
| Reduced production costs | Intelligent management of damaging factors (pests, plant diseases, and weeds) |
| Increased profitability | Intelligent management of climatic conditions |
| Improved quantity, quality, and safety of agricultural products | Intelligent management of agricultural equipment and machinery |
| Sustainable development | Smart control of crop growth |
| Food security | Smart livestock management |
| Environmental protection | Intelligent management of product sales and marketing |

The Internet of Things (IoT) has created a major revolution across various industries and business sectors worldwide. The advancement of this technology has also impacted the production of different agricultural products and livestock management. IoT technology enables farmers to connect various agricultural tools and equipment to the Internet and intelligently control cultivation conditions, significantly increasing crop yields while reducing losses. Smart agriculture has been developed using wireless sensor network technology [53]. These sensors are cost-effective, capable of detecting environmental conditions using simple devices, and can be applied for various purposes within the farm.

By utilizing these sensors and other wireless tools, farmers can access information regarding different stages of planting, crop growth, and harvesting, soil moisture, nutritional status and soil composition, plant diseases and pests, and more. Based on the data collected by these systems, farmers can take timely actions and implement appropriate measurement and management strategies [54]. The applications of IoT are summarized in **Table 3**.

**Table 3.** Applications of the Internet of Things in Agriculture, Environment, Water, Livestock, and Greenhouses.

| Sector | Applications |
|---|---|
| Agriculture | Farm management, plant irrigation control systems, crop monitoring, pest and disease management, weather prediction, and more |
| Environment | Monitoring and controlling pollution in urban areas, monitoring critical incidents in remote areas such as forest fires, landslides, avalanches, earthquakes in seismic zones, etc. |
| Water | Monitoring and controlling water in natural and built environments, water quality monitoring (e.g., presence of chemicals and pollutants) in rivers or water distribution infrastructure, detection of leaks in pipes or reservoirs, river, dam, and reservoir water level control, flood and drought detection. |
| Livestock | Tracking domestic animals through identification systems, monitoring vaccination status, preventing the spread of diseases, collecting accurate data on animal numbers and production, etc. |
| Greenhouse | Controlling soil temperature and moisture, monitoring greenhouse ambient temperature using wireless sensors, monitoring nutrient movement, and other parameters |

## 18. The Internet of Things: A Key Tool for Smart Agriculture

Today, due to technological advancements and the growing global population, traditional agricultural methods can no longer meet increasing demands. To produce higher-quality crops at lower costs, solutions such as the Internet of Things (IoT) in smart agriculture and precision irrigation have emerged. Innovative ideas and technological progress help the agricultural sector increase production and optimize resource allocation. In the late 19th and 20th centuries, mechanical innovations such as tractors and other machinery were introduced, while nowadays, IoT is employed to produce more agricultural products with lower costs and more efficient resource utilization. IoT can play roles ranging from the deployment of comprehensive smart solutions in agriculture to the development of specific market-ready sensors [55].

Applications of IoT in agriculture include monitoring agricultural vehicles, livestock management, warehouse supervision, and other uses. Livestock-specific sensors alert shepherds when animals leave the herd, enabling timely return, while soil sensors can detect irregular conditions such as excessive soil acidity, allowing farmers to produce higher-quality crops. Unmanned tractors, which are remotely controlled, significantly reduce labor costs, and sensors measuring soil moisture, temperature, and mineral composition enable improved monitoring of agricultural conditions.

In the coming years, the use of such technologies, along with other smart agricultural innovations, is expected to rise significantly. Deploying IoT devices in agriculture could lead to an annual growth rate of 20% in agricultural outputs. Specific applications of IoT in smart and precision agriculture include soil monitoring systems, wireless sensor monitoring, smart machinery, and drone-based information management platforms. For example, CropX produces hardware and software solutions that measure soil moisture, temperature, and electrical conductivity, alerting farmers about optimal irrigation requirements. TempuTech provides wireless sensor systems for grain elevators and silos, helping farmers mitigate hazards such as fire and dust using GE equipment. CLAAS, a leading agricultural engineering manufacturer, allows farmers to operate machinery in Autopilot mode, improving crop flow, minimizing losses, and automating operations. Finally, PrecisionHawk has developed autonomous UAVs that collect high-quality data via sensors for mapping and imaging farmland; drones can detect weather conditions using AI and determine optimal flight paths based on factors such as wind speed and atmospheric pressure [56].

## 19. Results

This section presents an integrated analytical discussion of the reviewed findings by directly linking quantitative performance outcomes with technological architecture, sustainability implications, and practical implementation feasibility. Rather than separating results from interpretation, the analysis synthesizes reported performance indicators—such as water-use efficiency, yield improvement, and input optimization—within a broader technical and sustainability-oriented framework.

The study highlights the significant impacts of IoT-based smart agriculture and precision farming systems on crop productivity, resource optimization, and sustainability. The integration of various sensors—such as soil moisture, temperature, nutrient, airflow, and optical sensors—enabled continuous monitoring of environmental parameters, providing real-time insights for efficient farm management [57]. Data collected from wireless sensor networks (WSNs) and IoT-enabled devices allowed automated irrigation, fertilization, and pest control based on field-specific requirements, reducing input waste and operational costs [58].

Application of smart irrigation systems demonstrated up to 35% reduction in water consumption while maintaining or improving crop yield [59]. These findings are consistent with recent studies demonstrating that optimized irrigation management, soil moisture monitoring, and precision irrigation strategies can substantially improve water productivity and maintain crop yield under water-limited conditions [60]. Furthermore, field-scale investigations on silage maize have confirmed the effectiveness of advanced irrigation scheduling in enhancing water-use efficiency and irrigation performance [61]. Similarly, UAV-based monitoring platforms and AI-driven data analysis enabled precise mapping of crop conditions, early detection of plant stress, and timely intervention, leading to improved quantitative and qualitative performance of crops [62].

The results also indicate that IoT implementation facilitates optimized management of fertilizers and pesticides, which contributes to environmental protection and sustainable agricultural practices [63]. Farmers using IoT-driven systems reported enhanced decision-making capability, operational efficiency, and economic benefits, confirming that technological adoption positively correlates with increased productivity and cost reduction [64]. Recent developments in smart irrigation technologies further support these findings, as IoT-based irrigation platforms enable real-time monitoring, automated decision-making, and efficient resource allocation, resulting in improved irrigation management and reduced operational costs [65]. In addition, artificial intelligence has emerged as a powerful tool for forecasting water demand, optimizing resource distribution, and mitigating water scarcity challenges in agricultural systems [66]. Overall, the integration of IoT with precision agriculture has transformed conventional farming into a data-driven, automated, and sustainable process, with measurable improvements in resource utilization, crop yield, and environmental impact. While these findings provide qualitative evidence of the benefits of IoT adoption, a more detailed examination of reported performance indicators offers additional insight into the magnitude of these improvements.

To further evaluate the reported results, performance indicators across reviewed studies were analyzed in terms of water-use efficiency, yield enhancement, input reduction, and operational cost savings. Most IoT-based irrigation systems demonstrated measurable improvements in water productivity, while AI-assisted monitoring systems improved decision accuracy and reduced response time to environmental stress. These performance metrics confirm that IoT-enabled systems provide quantifiable agronomic and economic advantages rather than purely conceptual benefits.

To strengthen the analytical depth of this review, recent empirical and experimental studies demonstrate that IoT-enabled systems significantly enhance water-use efficiency and crop productivity compared to traditional agricultural practices. For instance, an IoT-driven smart irrigation system integrating real-time monitoring, cloud computing, and embedded sensors achieved up to 47% reduction in water consumption and a 43% increase in lettuce yield under controlled agricultural conditions [67]. In another recent implementation, an IoT-based smart agriculture platform achieved approximately 30% reduction in water usage while maintaining optimal irrigation levels; this was realized through predictive irrigation scheduling and continuous soil and environmental monitoring, highlighting the potential of automated IoT irrigation systems to conserve scarce water resources in arid settings [68]. Although water management remains one of the most extensively studied applications of IoT in agriculture, the benefits of these technologies extend beyond irrigation-related outcomes.

Beyond irrigation efficiency, precision agriculture research also reports notable improvements in broader agricultural performance indicators. The implementation of IoT-based multi-sensor systems for soil nutrient and climate monitoring enables site-specific management strategies, improving decision-making accuracy and enhancing sustainability outcomes [69,70]. Additionally, comprehensive reviews of IoT-enabled precision agriculture frameworks indicate that the integration of intelligent sensing, machine learning algorithms, and automated control mechanisms can substantially improve crop monitoring accuracy, resource allocation efficiency, and overall farm productivity [71,72]. The cumulative evidence from these studies suggests that the advantages of IoT adoption are not limited to specific crops or production systems but are observable across diverse agricultural contexts.

Moreover, IoT adoption in agricultural systems has been associated with measurable gains in resource optimization and productivity across diverse farming contexts. Reports suggest that data-driven irrigation and nutrient management strategies supported by IoT and AI technologies can result in 25–50% water savings and 10–20% productivity improvements, depending on environmental and operational conditions [73,74]. Similar trends have been reported in recent agricultural studies, where optimized irrigation scheduling and nonlinear crop growth modeling significantly enhanced crop yield and water productivity under different irrigation regimes [75]. Moreover, national-scale analyses indicate that improving irrigation management practices remains one of the most effective approaches for increasing agricultural water productivity, particularly in water-scarce regions [76]. These improvements are largely attributed to real-time sensing infrastructures and adaptive control systems that reduce inefficiencies inherent in conventional farming methods [77].

Collectively, these findings confirm that integrating IoT technologies into precision farming not only advances sustainability objectives but also delivers quantifiable performance enhancements. Importantly, the consistency of reported outcomes across different geographical regions, crop types, and technological configurations reinforces the robustness and generalizability of these benefits. Through continuous monitoring, predictive analytics, and automated feedback loops, IoT-enabled systems empower farmers to make informed, data-driven decisions that improve both environmental stewardship and agricultural productivity [78–81].

## 20. Discussion

The findings of this study align closely with previous research, demonstrating that IoT and precision agriculture provide substantial benefits across multiple domains of farm management. For instance, Tzounis et al. [82] and Boursianis et al. [83] emphasize that sensor-based monitoring and UAV-assisted imaging enhance real-time decision-making and enable proactive management of crop stress and irrigation. Similarly, Ayaz et al. [84] highlight how smart sensors reduce manual supervision and optimize input usage, corroborating our findings on water and fertilizer efficiency. Comparative studies also show variations in adoption and impact across different countries. García et al. [85] report that India leads in IoT-based irrigation publications, while countries with larger agricultural land, such as China and the USA, show lower publication rates but substantial private-sector innovations. This suggests that while IoT adoption is widespread, contextual factors such as water scarcity, technological infrastructure, and socio-economic conditions influence implementation effectiveness.

In terms of technology, integration of AI with IoT, as highlighted by Geetha Lekshmy et al. [86] and Revathi and Poonguzhali [87], enables predictive analytics and dynamic resource allocation, surpassing traditional precision agriculture systems in responsiveness and accuracy. Similarly, UAVs and drones provide additional layers of monitoring and data collection, improving crop yield predictions and early detection of environmental stressors [88].

This study confirms that smart agriculture not only enhances productivity but also promotes sustainability through optimized input usage, environmental protection, and cost reduction. These observations are strongly supported by recent experimental studies showing that precise irrigation management, soil moisture-based scheduling, and deficit irrigation strategies improve both yield and water productivity while reducing water consumption [89–91]. Similarly, crop response analyses and crop coefficient determination under advanced irrigation systems have demonstrated the potential of precision water management to enhance resource-use efficiency and sustainability [92]. However, challenges remain regarding large-scale adoption, standardization of workflows, and initial investment costs, consistent with observations by Dlodlo and Kalezhi [93] and Shi et al. [94]. Addressing these barriers, particularly in developing countries, is critical for widespread implementation and for realizing the full potential of IoT-based agricultural technologies.

The integration of IoT, AI, and advanced sensor technologies in precision agriculture represents a paradigm shift in farming practices. Compared to conventional methods, these systems offer improved efficiency, environmental sustainability, and economic benefits, establishing a clear pathway for future smart farming initiatives globally. While the agronomic, environmental, and economic benefits of IoT-based smart agriculture are increasingly evident, the practical realization of these benefits depends on the technical and operational feasibility of large-scale implementation. Therefore, evaluating feasibility factors is essential for understanding the long-term sustainability and scalability of these technologies.

Although IoT-based smart agriculture systems demonstrate significant potential in improving productivity and sustainability, their large-scale implementation depends on several technical feasibility factors. A structured evaluation of feasibility must consider infrastructure readiness, economic viability, scalability, data management capacity, and system interoperability.

From a technical infrastructure perspective, reliable internet connectivity, stable power supply, and access to cloud or edge computing platforms are essential prerequisites. In many rural and developing regions, limited broadband coverage and unstable electricity networks may restrict full deployment of IoT architectures. Therefore, hybrid systems incorporating low-power wide-area networks (LPWAN), edge computing, and solar-powered sensor nodes are recommended to enhance feasibility. Economic feasibility represents another critical dimension. While initial investment costs for sensors, UAVs, gateways, and data platforms may be relatively high, long-term operational savings—particularly in water, fertilizer, pesticide use, and labor—can offset these costs. Studies reporting up to 35% water savings and measurable yield improvements indicate that return on investment (ROI) can be achieved within a reasonable time horizon, especially in water-scarce regions. Recent investigations into smart irrigation and AI-assisted water management further suggest that the economic feasibility of IoT adoption increases substantially in regions facing water scarcity, where efficient allocation of water resources directly contributes to both agricultural productivity and long-term sustainability [95–99].

Scalability and interoperability also determine technical viability. IoT-based systems must support integration of heterogeneous devices, multi-vendor platforms, and evolving communication protocols. The absence of standardized workflows, particularly for UAV data processing and decision-support integration, remains a barrier to seamless expansion.

Data management capacity is another feasibility constraint. Large-scale deployment generates high-volume, high-velocity agricultural data streams. Without efficient data filtering, edge analytics, and secure storage frameworks, systems may face latency, bottlenecks, or cybersecurity risks. Therefore, the integration of AI-driven data compression, complex event processing (CEP), and secure communication protocols is necessary to ensure operational robustness.

Finally, social and institutional readiness affects implementation feasibility. Farmer training, technical literacy, government support policies, and access to financing mechanisms significantly influence adoption rates. In developing countries, pilot-scale implementations combined with subsidy programs and public–private partnerships can facilitate gradual large-scale deployment.

Overall, technical feasibility of IoT-based precision agriculture is achievable, provided that infrastructure, economic, data, and institutional factors are systematically addressed. When these enabling conditions are satisfied, smart agriculture systems transition from experimental solutions to scalable and sustainable agricultural management frameworks. Taken together, the evidence indicates that successful deployment of IoT-enabled precision agriculture requires not only technological innovation but also supportive infrastructure, effective governance, and stakeholder engagement.

## 21. Conclusions

This study developed an integrative and performance-oriented analytical review of IoT-based precision agriculture systems by systematically linking technological architecture to quantified agronomic, environmental, and economic outcomes. Unlike prior reviews that primarily emphasized conceptual frameworks or isolated technological components, this research synthesized recent empirical findings (2022–2026) within a unified layered IoT architecture and evaluated measurable performance indicators. The main findings of this study demonstrate that IoT-enabled smart irrigation and precision farming systems consistently improve water-use efficiency (25–50%), enhance crop productivity (10–20% depending on environmental conditions), and reduce input waste through data-driven monitoring and automated control. The proposed five-layer technical architecture (sensing, communication, data processing, intelligence, and actuation) clarifies how cyber-physical integration enables real-time decision-making and continuous feedback loops in agricultural systems. The analysis confirms that IoT-based agriculture is no longer purely conceptual but represents a technically viable and performance-validated approach to sustainable intensification. Despite these contributions, this study has several limitations. First, as a structured analytical review, the findings depend on previously published empirical studies rather than primary field experimentation. Second, reported performance improvements vary across climatic, economic, and infrastructural contexts, limiting direct generalization. Third, heterogeneity in evaluation methodologies across studies makes standardized cross-comparison challenging. Finally, economic feasibility assessments remain partly context-dependent, particularly for smallholder farming systems in developing regions.

Future research should therefore focus on developing standardized performance evaluation frameworks for IoT-based agricultural systems, conducting large-scale longitudinal field experiments across diverse agro-climatic regions, and integrating advanced AI-driven predictive models with edge computing architectures to reduce latency and improve scalability. Additionally, comprehensive cost–benefit and return-on-investment analyses are required to support policy-level decision-making. Research on interoperability standards, cybersecurity resilience, and farmer-centered adoption models will further facilitate large-scale implementation. Overall, this study concludes that IoT-enabled precision agriculture provides a scalable pathway toward sustainable agricultural transformation when supported by adequate infrastructure, economic planning, and institutional readiness. By bridging technological architecture with measurable agronomic performance and implementation feasibility, this research contributes a structured roadmap for transitioning from pilot-scale smart farming initiatives to resilient, data-driven agricultural systems capable of addressing future water scarcity and food security challenges.

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## Conflicts of Interest

The author declares no conflict of interest.

## AI Use Statement

The author declares that no artificial intelligence (AI) tools were used in the preparation of this manuscript.

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