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IoT and sensor networks for smart agriculture: Technologies, applications, and future directions

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Abstract

The growing need to produce food under the pressures of the climate and scarcity of resources and the growing population has stimulated the adoption of digital technologies in agriculture. Internet of Things (IoT) and wireless sensor networks (WSNs) are released as the important facilitators of smart agriculture enabling real-time monitoring, precise farming, and automated decision making. This survey integrates the latest developments in IoT-based and sensor based agricultural systems, focusing on the system architectures, hardware, communication protocols and applications. The applications referenced are precision irrigation, crop health management, automation of greenhouses, livestock management, and optimization of the post-harvest supply chain. There are the emerging trends of Artificial Intelligence-powered IoT (AIoT), edge and fog computing, unmanned aerial vehicle (UAV)-based monitoring, blockchain-powered traceability and energy-efficient sensing technologies, which are critically discussed. Moreover, the impact of big data analytics and machine learning on the conversion of sensor-based data into meaningful results via decision support systems is mentioned. Nonetheless, despite the major advancements, large-scale implementation is held back by some issues such as sensor and energy limitations, inadequate rural coverage, data confidentiality, and the inability to integrate systems of heterogeneous components. The possible solutions and future research directions are addressed and concern the creation of scalable architectures, standardization framework, and supportive policy interventions. On the whole, the review gives an in-depth and systematic description of IoT-based smart agriculture that can be vital to researchers, practitioners, and policy makers as one of the ways to have a sustainable, intelligent agricultural system.

Keywords: Internet of things (IoT), smart agriculture, wireless sensor networks, precision farming, big data analytics, machine learning, decision support systems, sustainable agriculture

Introduction

In recent decades, agriculture has undergone significant transformation driven by rapid advancements in digital technologies. Traditional farming practices, though effective at small scales, face increasing challenges from climate variability, water scarcity, soil degradation, declining arable land, and rising food demand. These pressures necessitate sustainable and efficient solutions, leading to the emergence of smart agriculture based on the integration of the Internet of Things (IoT) and sensor-based technologies.

IoT enables real-time monitoring, data-driven decision-making, and automation in farming operations. Precision agriculture, a key application, optimizes inputs such as water, fertilizers, and pesticides, improving productivity while reducing environmental impacts. Soil-based NPK sensors are particularly important for assessing soil fertility and enabling precise nutrient management (Kumar *et al.*, 2025) ^[8]. IoT systems typically consist of interconnected devices that monitor parameters such as soil moisture, temperature, humidity, and crop health, supported by cloud computing and data analytics for predictive decision-making. Wireless sensor networks (WSNs) further enhance these capabilities by providing distributed, real-time environmental monitoring through sensor nodes with sensing, processing, and communication functions (Jawad *et al.*, 2017) ^[5]. These systems support precision farming by enabling optimized irrigation, nutrient management, and early detection of pests and diseases, thereby improving sustainability.

Unlike conventional farming methods that rely on uniform input application and manual practices, smart agriculture integrates IoT, artificial intelligence (AI), and data analytics to improve efficiency and scalability (Dhanaraju *et al.*, 2022) ^[2]. AI-based systems further enhance predictive capabilities for crop yield, disease detection, and resource management (Kahar *et al.*, 2024) ^[6]. IoT applications also extend to aquaculture and greenhouse management, optimizing environmental conditions and resource use (Liu *et al.*, 2025) ^[9]. Despite these benefits, challenges such as high costs, energy constraints, data security, interoperability issues, and limited technical expertise persist. This review provides an overview of IoT and WSN applications in agriculture, highlighting advancements, challenges, and future research directions for sustainable and intelligent farming systems.

2. Fundamentals of IoT in Agriculture

Agriculture has traditionally relied on manual observation, empirical knowledge, and experience-driven decision-making to manage crops and livestock. While such approaches have sustained agricultural production for centuries, they are increasingly inadequate in addressing the complexities of modern agriculture. Rapid population growth, climate variability, declining natural resources, and the need for higher productivity have necessitated the adoption of advanced technological solutions. In this context, the Internet of Things (IoT) has emerged as a transformative technology that enables data-driven and automated agricultural practices. IoT in agriculture refers to a network of interconnected physical devices embedded with sensors, actuators, communication modules, and processing units that continuously monitor environmental and operational parameters. These devices collect real-time data related to soil conditions, weather parameters, crop health, and livestock status, which are subsequently transmitted to cloud or edge computing platforms for storage, analysis, and decision-making. The integration of IoT technologies allows farmers to gain actionable insights, optimize resource utilization, and enhance productivity while minimizing environmental impacts.

Furthermore, the incorporation of artificial intelligence (AI) and machine learning (ML) techniques into IoT systems facilitates predictive analytics, anomaly detection, and automation of agricultural operations (Kahar *et al.*, 2024; Jawad *et al.*, 2017; Navarro *et al.*, 2020; Alahmad *et al.*, 2023) ^[6, 1, 11, 5].

2.1 Architecture of Agricultural IoT Systems

IoT-based agricultural systems are generally structured into a multi-layered architecture that ensures efficient data acquisition, transmission, processing, and application. The most widely adopted framework consists of three primary layers: the perception layer, network layer, and application layer. Each layer plays a critical role in enabling seamless integration of sensing, communication, and intelligent decision-making processes. The perception layer, also known as the sensing layer, forms the physical interface between the agricultural environment and the digital system. It comprises a wide range of sensors deployed across the field to capture real-time data on soil moisture, temperature, humidity, light intensity, pH levels, and crop health indicators. Advanced sensing technologies, such as capacitive soil moisture sensors, multispectral and hyperspectral imaging sensors, and biosensors for pathogen detection, have significantly enhanced the accuracy and reliability of data collection. The network layer is responsible for transmitting the collected data from sensor nodes to centralized processing systems. This layer utilizes various wireless communication protocols, including ZigBee, LoRaWAN, NB-IoT, Wi-Fi, and cellular networks, depending on the application requirements, transmission range, and power constraints. Low-power wide-area network (LPWAN) technologies, particularly LoRaWAN and NB-IoT, are widely preferred in agricultural applications due to their ability to support long-range communication with minimal energy consumption. The application layer represents the intelligence of the IoT system, where data is processed, analyzed, and transformed into actionable insights. This layer incorporates cloud computing platforms, edge computing devices, and AI-based analytics tools to perform tasks such as predictive modeling, anomaly detection, and decision support.

Table 1: Comprehensive Architecture of IoT Systems in Agriculture

Layer	Core Functions	Technologies & Components	Innovative Features	Agricultural Applications	References
Perception Layer	Real-time sensing and data acquisition	Soil moisture, NPK, pH, temperature & humidity sensors, drones, biosensors	High-resolution sensing, multispectral imaging, real-time diagnostics	Soil monitoring, crop health, disease detection	Kumar <i>et al.</i> , 2024 ^[22] ; Zhang <i>et al.</i> , 2024 ^[28] ; Duguma & Bai, 2024 ^[30]
Network Layer	Data transmission and connectivity	ZigBee, LoRaWAN, NB-IoT, Wi-Fi, 4G/5G, satellite	Low-power, long-range, energy-efficient communication	Remote monitoring, alerts, smart irrigation	Khan <i>et al.</i> , 2024 ^[29] ; Nawaz & Babar, 2025 ^[31] ; Cisse <i>et al.</i> , 2024 ^[24]
Application Layer	Data processing and decision-making	Cloud, edge computing, AI/ML, big data, dashboards	Predictive analytics, automation, DSS, digital twins	Precision irrigation, yield prediction, livestock monitoring	Kumar <i>et al.</i> , 2024 ^[22] ; Zhang <i>et al.</i> , 2024 ^[28] ; Khan <i>et al.</i> , 2024 ^[29]
Integration Layer	Interoperability and data integration	APIs, IoT platforms, middleware, blockchain	Secure sharing, traceability, smart contracts	Supply chain tracking, farm-to-market traceability	Li <i>et al.</i> , 2021 ^[26] ; Al-Najadi <i>et al.</i> , 2025 ^[27] ; Seetaram <i>et al.</i> , 2024 ^[25]
Control Layer	Automated actuation and control	Actuators, valves, drones, robotics	Autonomous control, adaptive systems	Smart irrigation, fertilization, greenhouse automation	Li <i>et al.</i> , 2021 ^[26] ; Al-Najadi <i>et al.</i> , 2025 ^[27] ; Olugbemi & Ola, 2022 ^[22]

2.2 Components of IoT Systems in Agriculture

An IoT-based agricultural system comprises several interconnected components that work collectively to enable

efficient monitoring, analysis, and control of farming operations. At the core of the system are sensors and actuators, which serve as the primary interface between the physical environment and

the digital system. Sensors are responsible for measuring environmental parameters such as soil moisture, temperature, humidity, nutrient levels, and crop health, while actuators execute control actions, such as opening irrigation valves, applying fertilizers, or regulating greenhouse conditions. Microcontrollers and gateways act as intermediate processing units that collect data from sensors, perform preliminary processing, and transmit the information to cloud or edge platforms. These devices are often equipped with embedded systems capable of handling data aggregation, filtering, and communication tasks. Gateways also play a crucial role in bridging short-range communication protocols (e.g., ZigBee) with long-range networks (e.g., cellular or cloud-based systems). The communication modules enable seamless data transfer between different components of the IoT system. Depending on the application requirements, various wireless communication technologies are employed, including ZigBee for short-range communication, LoRaWAN for long-range low-power transmission, and NB-IoT for wide-area connectivity. The selection of communication technology is influenced by factors such as coverage area, energy efficiency, data rate, and cost. Another critical component is the data storage and cloud computing infrastructure, which facilitates the handling of large volumes of agricultural data. Cloud platforms provide scalable storage, advanced analytics, and remote accessibility, while edge computing enables real-time processing at the device level, reducing latency and bandwidth requirements. Finally, decision support systems (DSS) utilize advanced algorithms, including AI and machine learning models, to analyze collected data and generate actionable recommendations. These systems assist farmers in making informed decisions related to irrigation scheduling, nutrient management, pest control, and crop harvesting. By integrating predictive analytics and automation, DSS significantly enhances the efficiency and sustainability of agricultural practices. The adoption of IoT systems offers several advantages, including real-time monitoring and control, reduced resource wastage, improved productivity, enhanced yield predictability, and support for sustainable farming practices. These benefits collectively contribute to the development of resilient and efficient agricultural systems.

2.3 Applications of IoT in Agriculture

The application of IoT in agriculture spans a wide range of domains, transforming conventional farming into a highly efficient and technology-driven system. One of the most prominent applications is precision agriculture, which involves the use of sensor data and analytics to optimize the application of inputs such as water, fertilizers, and pesticides. By considering spatial and temporal variability within fields, precision agriculture enhances resource efficiency and crop productivity. Another important application is climate-smart agriculture, where IoT systems are used to monitor microclimatic conditions and predict weather-related risks. These systems enable farmers to take proactive measures against adverse climatic events such as droughts, floods, and temperature extremes, thereby improving resilience to climate change. IoT technologies are also widely used in livestock monitoring, where wearable sensors and tracking devices are employed to monitor animal health, behavior, and location. This enables early detection of diseases, improves animal welfare, and enhances productivity in livestock farming systems. In the domain of post-harvest management, IoT systems play a crucial role in reducing losses by monitoring storage conditions such as temperature, humidity, and gas composition. Smart

storage systems ensure optimal conditions for preserving agricultural produce, thereby extending shelf life and reducing spoilage. Furthermore, greenhouse automation represents a significant advancement in controlled environment agriculture. IoT-enabled systems continuously monitor and regulate environmental parameters such as temperature, humidity, light intensity, and CO₂ levels to maintain optimal growing conditions. Automated control systems adjust these parameters in real time, ensuring consistent crop growth and higher yields. Overall, the integration of IoT technologies across these applications demonstrates their transformative potential in enhancing agricultural productivity, sustainability, and resilience. As technological advancements continue, IoT is expected to play an increasingly vital role in addressing global food security challenges and promoting smart farming practices.

3. Sensor Networks in Agriculture

Wireless Sensor Networks (WSNs) constitute a fundamental component of IoT-based agricultural systems, enabling continuous, real-time, and spatially distributed monitoring of environmental and crop-related parameters. These networks consist of interconnected sensor nodes deployed across agricultural fields to collect high-resolution data on soil conditions, microclimate variations, crop health, and livestock status. By facilitating data-driven decision-making, WSNs play a crucial role in advancing precision agriculture, optimizing resource utilization, and improving overall farm productivity. The integration of WSNs into agricultural systems allows for automated data acquisition and transmission through energy-efficient wireless communication protocols. These sensor nodes, often equipped with low-power microcontrollers and radio communication modules, can operate in harsh environmental conditions and remote locations. The data collected by WSNs is transmitted to centralized systems or cloud platforms for processing and analysis, enabling farmers to respond proactively to changing field conditions. As a result, WSNs significantly enhance the efficiency, sustainability, and resilience of modern agricultural practices.

3.1 Types of Sensors in Agriculture

A wide variety of sensors are employed in agricultural WSNs to monitor physical, chemical, and biological parameters critical for precision farming. These sensors form the backbone of data acquisition systems and directly influence the accuracy and reliability of IoT-based agricultural solutions. Recent advancements in sensor technologies, including nanotechnology and spectroscopy, have significantly improved sensing precision, sensitivity, and real-time monitoring capabilities (Sahu & Victor, 2025) ^[15]. Modern smart agriculture systems increasingly rely on integrated sensing platforms capable of multi-parameter detection, enabling comprehensive field-level insights and improved decision-making (Musa *et al.*, 2023) ^[16]. Early developments in agricultural sensing primarily focused on environmental monitoring; however, recent innovations have expanded capabilities to include biochemical sensing, pathogen detection, and crop phenotyping (Ruiz-Garcia *et al.*, 2009) ^[19]. Advanced sensing techniques such as hyperspectral imaging and optical sensing enable non-destructive crop health assessment and early stress detection (S & Baulkani, 2022) ^[17]. Similarly, nanomaterial-based biosensors have enhanced the ability to detect plant pathogens at early stages with high sensitivity (Rahaman & Azharuddin, 2022) ^[18]. The integration of intelligent sensing with data analytics further supports precision agriculture practices and improves farm-level decision-making

(Pandiyaraju *et al.*, 2023) ^[20]. In addition, wearable and embedded sensing technologies have significantly improved livestock monitoring systems by enabling continuous tracking and predictive health analysis (Yinjun, 2024) ^[21].

3.2 Sensor Network Topologies and Communication Protocols

The efficiency and reliability of WSNs in agriculture largely depend on the network topology and communication protocols employed. Network topology determines how sensor nodes are interconnected and how data is transmitted within the system. The selection of an appropriate topology is influenced by factors such as farm size, terrain, energy constraints, and required data reliability. In a star topology, all sensor nodes communicate directly with a central gateway or base station. This configuration is simple to implement and requires minimal coordination among nodes; however, it is limited by communication range and lacks redundancy. Failure of the central node can disrupt the entire network. In contrast, a mesh topology allows sensor nodes to communicate with multiple neighboring nodes, creating a decentralized and self-healing network. This topology enhances reliability and coverage, as

data can be rerouted through alternative paths in case of node failure. Mesh networks are particularly suitable for large and heterogeneous agricultural environments. A hybrid topology, which combines elements of both star and mesh configurations, offers a balance between simplicity and reliability. In addition to topology, communication protocols play a critical role in determining the performance of WSNs. ZigBee is commonly used for short-range, low-power communication in small-scale farms and greenhouse environments. LoRaWAN has gained significant popularity due to its long-range communication capabilities and low energy consumption, making it ideal for large and remote agricultural fields. NB-IoT, a cellular-based technology, provides wide-area connectivity with low bandwidth requirements and is suitable for large-scale deployments. Meanwhile, Wi-Fi and Bluetooth are primarily used in localized environments, such as greenhouses and farm buildings, where high data rates are required. The choice of communication technology involves trade-offs between range, power consumption, data rate, and cost. Therefore, selecting an appropriate combination of topology and communication protocol is essential for designing efficient and scalable agricultural WSNs.

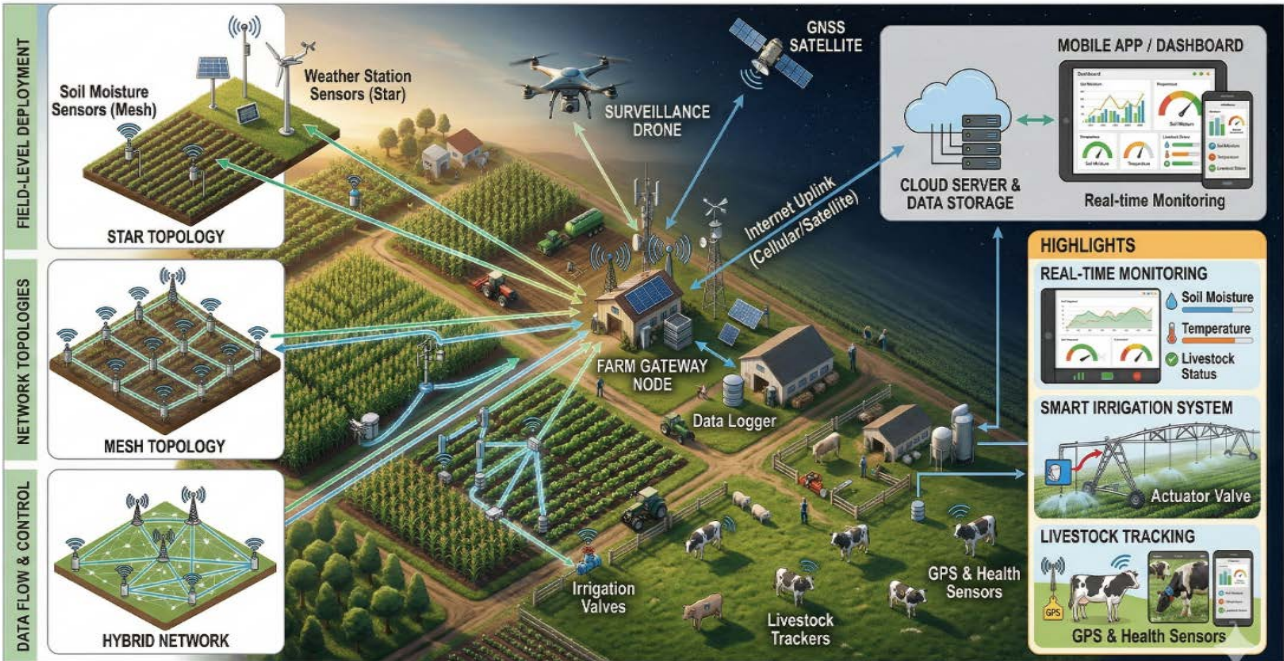


Fig 1: Wireless Sensor Network (WSN) Framework for IoT-Based Smart Agriculture

Table 2: Advanced Sensor Technologies in Smart Agriculture

Sensor Type	Parameter Measured	Underlying Technology	Innovative Features	Agricultural Applications	References
Soil Moisture Sensor	Volumetric water content	Capacitive, TDR, FDR	High precision, low power, real-time sensing	Smart irrigation, drought management	Kumar <i>et al.</i> , 2025 ^[8] ; Dhanaraju <i>et al.</i> , 2022 ^[2]
Soil pH Sensor	Soil acidity/alkalinity	Electrochemical probes, ion-selective electrodes	Continuous monitoring, IoT integration	Fertilizer optimization, soil health	Alahmad <i>et al.</i> , 2023 ^[1] ; Iluno & Nwaogwugwu, 2025 ^[4]
Soil Nutrient Sensor	N, P, K levels	Ion-selective, optical sensing	Real-time nutrient profiling	Precision fertilization, yield optimization	Kumar <i>et al.</i> , 2025 ^[8] ; Alahmad <i>et al.</i> , 2023 ^[1]
Temperature & Humidity Sensor	Climatic conditions	Thermistors, capacitive sensors	Compact, real-time tracking	Climate monitoring, greenhouse automation	Navarro <i>et al.</i> , 2020 ^[11] ; Liu <i>et al.</i> , 2025 ^[9]
Light Sensor (PAR)	Photosynthetically active radiation	Photodiodes, quantum sensors	Accurate measurement, calibration	Crop growth monitoring	Liu <i>et al.</i> , 2025 ^[9] ; Alahmad <i>et al.</i> , 2023 ^[1]
Crop Health Sensor	Chlorophyll, reflectance	Multispectral, hyperspectral imaging	Early stress detection, non-invasive	Disease detection, nutrient deficiency	Liu <i>et al.</i> , 2025 ^[9] ; Navarro <i>et al.</i> , 2020 ^[11]
Biosensors	Pathogens, toxins	Nanocomposites, enzymatic sensors	High sensitivity, rapid response	Disease monitoring, food safety	Frontiers in Plant Science, 2025; Iluno &

					Nwaogwugwu, 2025 ^[4]
Livestock Sensors	Activity, temperature, location	RFID, GPS, wearables	Real-time tracking, AI detection	Animal health monitoring	Navarro <i>et al.</i> , 2020 ^[11] ; Kahar <i>et al.</i> , 2024
Gas Sensors	CO ₂ , NH ₃ , methane	Semiconductor, electrochemical	Environmental monitoring	Greenhouse, livestock management	Liu <i>et al.</i> , 2025 ^[9] ; Dhanaraju <i>et al.</i> , 2022 ^[2]
Water Quality Sensors	pH, turbidity, DO	Optical, electrochemical	Real-time alerts	Irrigation, aquaculture	Liu <i>et al.</i> , 2025 ^[9] ; Kumar <i>et al.</i> , 2025 ^[8]

3.3 Applications of Sensor Networks in Agriculture

Sensor networks have enabled a wide range of applications in agriculture by providing continuous and accurate data for decision-making. One of the most significant applications is in smart irrigation systems, where soil moisture sensors, weather data, and evapotranspiration models are integrated to optimize water usage. Such systems can reduce water consumption by up to 30-40% while maintaining or improving crop yield, thereby contributing to sustainable water management. Another critical application is disease detection and crop health monitoring. Advanced optical sensors, multispectral imaging systems, and biosensors can identify early signs of plant stress, nutrient deficiencies, and pathogen infections. Early detection allows for timely intervention, reducing crop losses and minimizing the use of chemical pesticides. Environmental monitoring is also a key application of WSNs, where sensors continuously measure parameters such as temperature, humidity, solar radiation, and wind speed. This information is used to optimize microclimatic conditions, particularly in controlled environments such as greenhouses, thereby enhancing crop growth and productivity. In precision fertilization, nutrient sensors provide real-time information on soil nutrient levels, enabling site-specific fertilizer application. This approach reduces fertilizer wastage, lowers production costs, and minimizes environmental pollution caused by nutrient runoff. Furthermore, WSNs play a vital role in livestock health management, where wearable sensors track animal behavior, feeding patterns, movement, and physiological

parameters such as body temperature. The integration of these data with AI-based analytics enables predictive healthcare, early disease detection, and improved animal welfare, ultimately enhancing productivity in livestock farming systems. Overall, the application of sensor networks in agriculture demonstrates their transformative impact on modern farming practices. By enabling real-time monitoring, predictive analytics, and automated control, WSNs contribute significantly to the development of efficient, sustainable, and intelligent agricultural systems.

4. IoT-Enabled Agricultural Applications

The convergence of Internet of Things (IoT) technologies and wireless sensor networks (WSNs) has significantly transformed modern agricultural practices by enabling real-time monitoring, intelligent analytics, and automated control of farming operations. These systems facilitate continuous data acquisition from diverse agricultural environments and support data-driven decision-making processes. By integrating sensing technologies, communication networks, and advanced analytics, IoT-based agricultural systems enhance resource utilization efficiency, reduce operational costs, and improve crop productivity and sustainability. Recent studies emphasize that IoT-driven smart agriculture plays a crucial role in addressing global food security challenges while ensuring environmental sustainability (Kumar *et al.*, 2024; Olugbemi & Ola, 2022; Cisse *et al.*, 2024) ^[22, 24, 23].

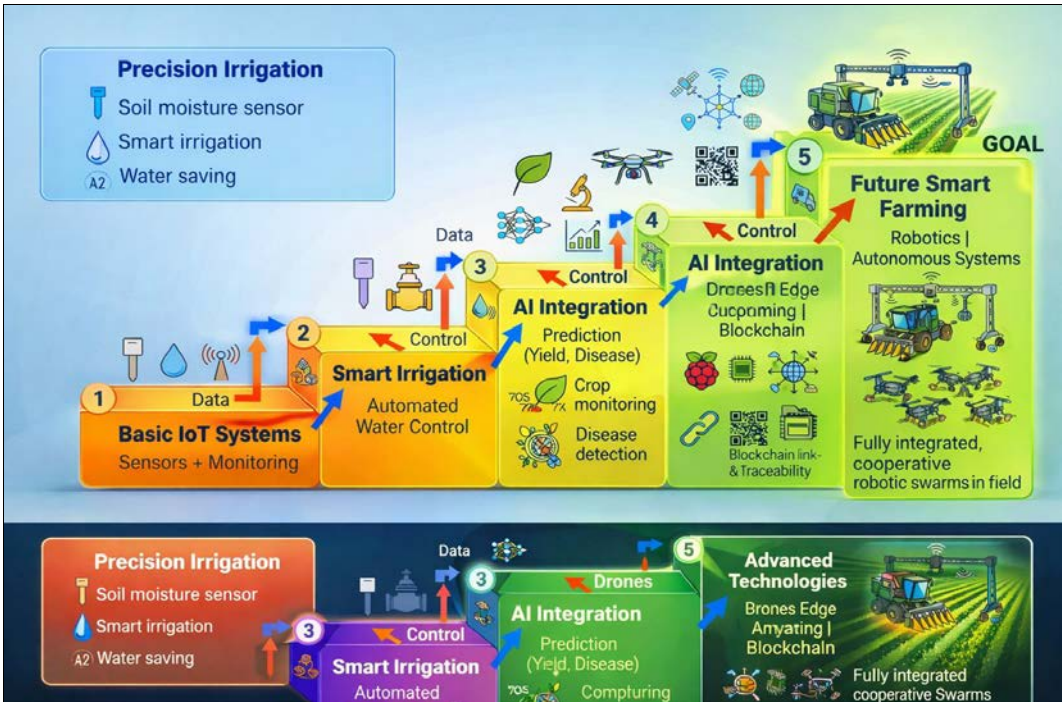


Fig 2: Evolution of Smart Farming Technologies from Conventional to IoT-Enabled Agriculture

4.1 Precision Irrigation Systems

Water scarcity remains a major constraint in agricultural production, particularly in developing countries such as India,

where irrigation accounts for a significant proportion of freshwater consumption. Conventional irrigation practices are often inefficient, leading to excessive water use, nutrient

leaching, and soil degradation. IoT-based precision irrigation systems have emerged as an effective solution to these challenges by enabling real-time monitoring and automated control of irrigation processes. These systems integrate soil moisture sensors, temperature sensors, and weather forecasting data with artificial intelligence (AI)-based decision support systems to determine optimal irrigation schedules. Data collected from the field is transmitted via low-power communication technologies such as LoRaWAN, ZigBee, and NB-IoT to cloud or edge platforms, where it is analyzed to generate actionable insights. Automated actuators, including pumps and valves, are then used to deliver precise amounts of water based on crop requirements. The implementation of precision irrigation technologies has demonstrated significant improvements in water-use efficiency, with reported reductions in water consumption of up to 30-40%. Additionally, these systems contribute to enhanced crop yield, reduced nutrient losses, and improved soil health, thereby supporting sustainable agricultural practices (Kumar *et al.*, 2024; Cisse *et al.*, 2024) ^[22, 24].

4.2 Crop Health Monitoring and Disease Management

Crop health monitoring is a critical component of modern

agriculture, as diseases, pests, and nutrient deficiencies can significantly impact crop yield and quality. Traditional methods of disease detection rely on manual inspection, which is often inefficient and prone to delays. IoT-enabled crop monitoring systems provide continuous and automated assessment of plant health through advanced sensing technologies. These systems utilize optical sensors, including multispectral and hyperspectral imaging devices, to analyze plant reflectance characteristics and detect early signs of stress. Biosensors, particularly those based on nanotechnology, enable the detection of pathogens at early stages, while environmental sensors monitor climatic conditions such as temperature and humidity that influence disease development. The integration of these sensing technologies with AI and machine learning algorithms enables predictive disease modeling and early warning systems. As a result, farmers can implement timely interventions, such as targeted pesticide application and precision fertilization, thereby reducing crop losses and minimizing environmental impacts. These technologies play a vital role in advancing precision agriculture and improving overall farm productivity (Olugbemi & Ola, 2022; Cisse *et al.*, 2024) ^[24, 23].

Table 4.3: IoT-Based Greenhouse Automation Framework

Control Domain	Sensors and Devices	Data Processing Techniques	Automation Mechanisms	Innovative Features	Agricultural Impact
Temperature Regulation	Thermistors, infrared sensors	AI-based climate modeling	Fans, heaters, ventilation systems	Predictive climate control	Stable crop growth
Humidity Control	Capacitive humidity sensors	Real-time analytics	Fogging and misting systems	Adaptive humidity control	Reduced plant stress
Light Management	PAR sensors, photodiodes	Smart lighting algorithms	LED grow lights, shading systems	Dynamic light optimization	Enhanced photosynthesis
CO ₂ Optimization	Gas sensors	Controlled enrichment models	CO ₂ injection systems	Precision gas regulation	Increased productivity
Soil Moisture Management	Soil moisture sensors	Closed-loop feedback systems	Automated irrigation systems	Smart irrigation integration	Water conservation
Integrated Control Systems	IoT platforms, edge devices	AI and ML models	Centralized control dashboards	Autonomous greenhouse systems	Reduced labor and energy costs
(Seetaram <i>et al.</i> , 2024 ^[25] ; Li <i>et al.</i> , 2021 ^[26] ; Al-Najadi <i>et al.</i> , 2025) ^[27] .					

4.3 Livestock Monitoring and Management

Livestock farming is an essential component of agricultural systems, requiring continuous monitoring of animal health, behavior, and environmental conditions. Traditional livestock management practices are labor-intensive and lack real-time monitoring capabilities, which can result in delayed disease detection and reduced productivity. IoT-based livestock monitoring systems address these challenges by integrating wearable sensors, GPS tracking technologies, and wireless communication networks. These systems enable continuous tracking of physiological parameters such as body temperature, heart rate, and activity levels, as well as behavioral patterns related to feeding and movement. Data collected from these sensors is analyzed using AI and machine learning algorithms to detect anomalies, predict diseases, and optimize livestock management practices. GPS-enabled devices also facilitate real-time location tracking, which is particularly useful for grazing management and theft prevention. In the Indian agricultural context, IoT-based dairy management systems have been increasingly adopted in regions such as Punjab and Haryana, where wearable sensors are used to monitor milk-producing cattle. These technologies have demonstrated improvements in milk yield, reproductive

efficiency, and overall animal health, while reducing veterinary costs (Kumar *et al.*, 2024) ^[22].

4.4 Supply Chain and Post-Harvest Management

Post-harvest losses remain a significant challenge in agricultural systems, particularly in developing countries, where inadequate storage and inefficient supply chain infrastructure lead to substantial economic losses. IoT technologies provide effective solutions by enabling real-time monitoring and control of storage and transportation conditions. IoT-based systems utilize sensors to monitor temperature, humidity, moisture content, and gas composition (such as ethylene) throughout the supply chain. These systems generate real-time alerts when environmental conditions deviate from optimal thresholds, enabling timely corrective actions. Additionally, the integration of IoT with blockchain technology enhances traceability, transparency, and accountability in agricultural supply chains. The adoption of IoT-enabled post-harvest management systems has been shown to reduce losses by 20-30%, improve product quality, and ensure compliance with food safety standards. These advancements significantly enhance supply chain efficiency and market competitiveness (Olugbemi & Ola, 2022; Cisse *et al.*, 2024) ^[24, 23].

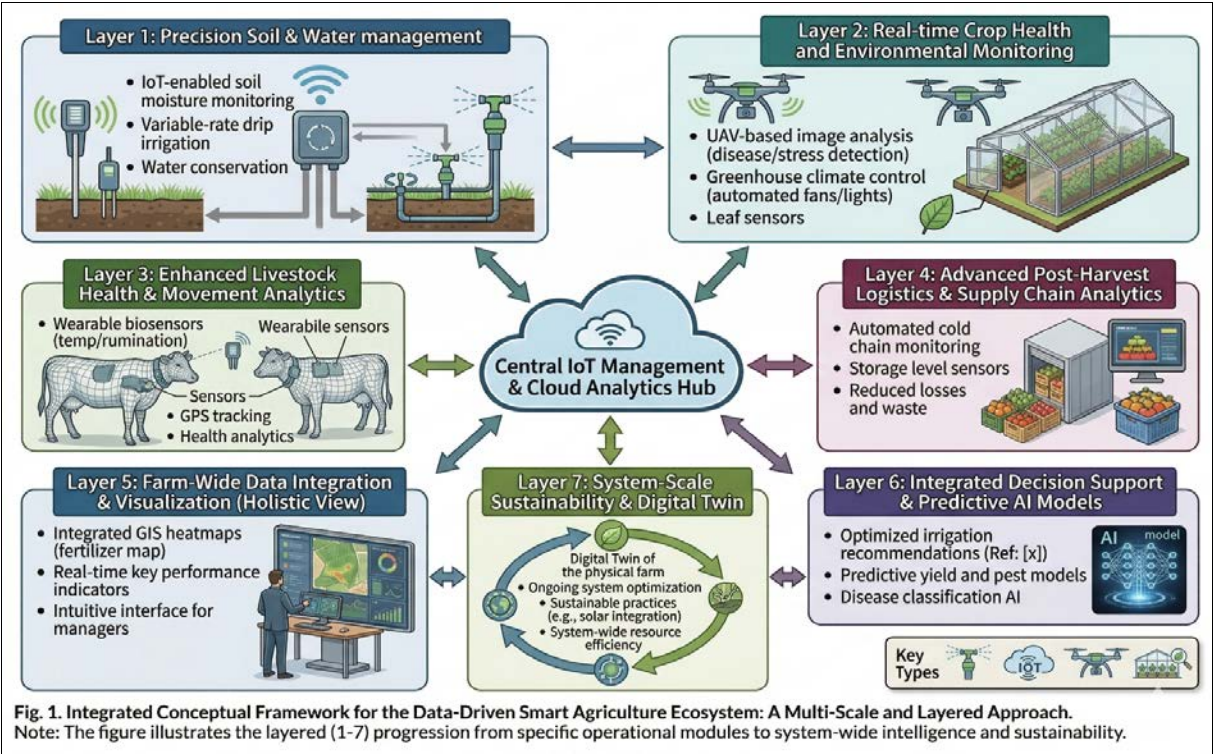


Fig 3: IOT based smart Agriculture system

Table 4.5: Integrated IoT Framework for Supply Chain and Post-Harvest Management

Stage	Sensors and Technologies	Monitored Parameters	Data Processing & Integration	System Functionality	Outcome/Impact	References
Storage	Temperature, humidity, CO ₂ sensors	Storage environment conditions	Cloud-based analytics	Smart storage systems	Reduced spoilage	Seetaram <i>et al.</i> , 2024 ^[25]
Transportation	GPS, temperature sensors	Location, temperature tracking	IoT-enabled logistics platforms	Real-time monitoring	Cold chain optimization	Li <i>et al.</i> , 2021 ^[26]
Ripening Control	Ethylene gas sensors	Ripening stages	AI-based prediction models	Smart packaging systems	Reduced wastage	Al-Najadi <i>et al.</i> , 2025 ^[27]
Quality Assurance	pH, moisture sensors	Product quality indicators	DSS and cloud platforms	Automated quality control	Improved product safety	Seetaram <i>et al.</i> , 2024 ^[25]
Traceability	IoT + blockchain	End-to-end tracking	Distributed ledger systems	Transparent supply chain	Enhanced trust and export quality	Li <i>et al.</i> , 2021 ^[26]
Market Integration	IoT platforms, mobile apps	Demand and supply data	Big data analytics	Smart market linkage	Better price realization	Al-Najadi <i>et al.</i> , 2025 ^[27]

5. Recent Trends in IoT and Sensor Networks in Agriculture
The rapid advancement of Internet of Things (IoT) technologies and wireless sensor networks (WSNs) has significantly accelerated the transformation of modern agriculture into a data-driven and intelligent system. Recent innovations in artificial intelligence (AI), edge computing, low-power embedded systems, and advanced communication protocols have enabled efficient monitoring, automation, and optimization of agricultural operations. These developments allow farmers to continuously monitor environmental and crop conditions, predict potential risks, and implement timely interventions.

Consequently, IoT-enabled agriculture is emerging as a key solution to address global challenges such as food security, climate variability, and resource scarcity (Kumar *et al.*, 2024; Zhang *et al.*, 2024) ^[28, 22].accelerated the adoption of smart farming technologies by promoting digital infrastructure and providing financial support to farmers. Empirical studies indicate that IoT-enabled agricultural systems in India can reduce input costs by 20-40% and increase crop yields by 15-30%, demonstrating their transformative potential (Kumar *et al.*, 2024) ^[22].

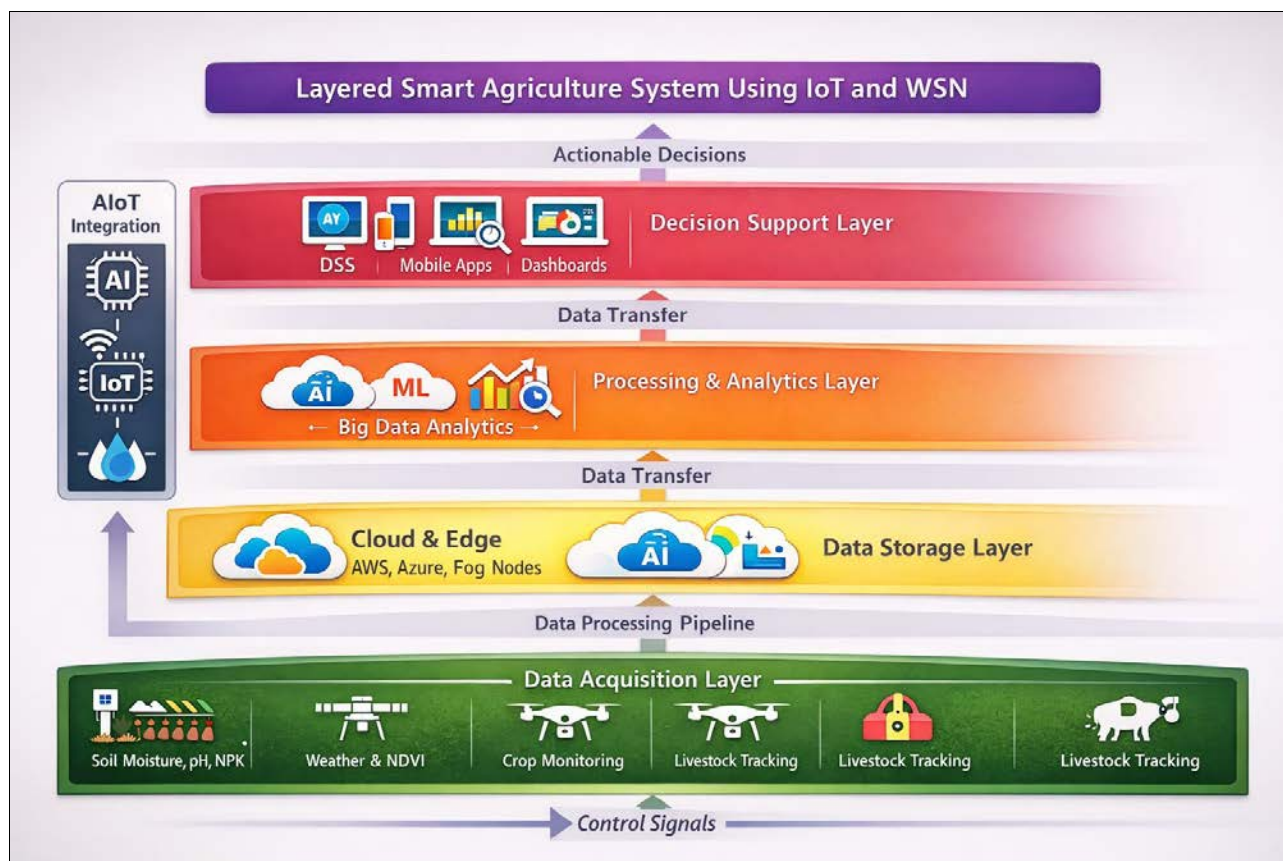


Fig 4: Layered Architecture of IoT and Wireless Sensor Network-Based Smart Agriculture System

Table 5.1: Emerging Trends in IoT and Sensor Networks in Agriculture

Trend	Core Technologies	Applications in Agriculture	Technical Advantages	Agricultural Impact
AI-Integrated IoT (AIoT)	Machine learning algorithms, deep learning models, IoT platforms, data analytics frameworks	Crop yield prediction, pest and disease detection, irrigation optimization, nutrient management	Enables predictive and prescriptive analytics, improves pattern recognition, supports real-time intelligent decision-making	Enhances productivity, reduces input wastage, improves crop quality and farm efficiency
Edge and Fog Computing	Edge devices, fog nodes, embedded processors, distributed computing architectures	Real-time irrigation control, greenhouse automation, livestock monitoring, anomaly detection	Reduces latency, minimizes bandwidth usage, enables local data processing, improves system responsiveness	Facilitates faster decision-making, enhances reliability in low-connectivity areas, reduces dependence on cloud infrastructure
Low-Power and Energy-Efficient Sensors	Energy-efficient microcontrollers, capacitive sensors, energy harvesting systems (solar, RF), sleep-mode protocols	Soil moisture monitoring, environmental sensing, long-term field deployment, remote farm monitoring	Low energy consumption, extended operational lifetime, reduced maintenance requirements	Enables scalable deployment in remote/off-grid areas, reduces operational costs, supports sustainable farming practices
UAV and Drone-Based Monitoring	Unmanned aerial vehicles, multispectral imaging sensors, GPS, remote sensing technologies	Crop health assessment, stress detection, irrigation mapping, precision spraying	High spatial resolution, rapid data acquisition, large-area coverage, non-invasive monitoring	Enables early detection of crop stress and diseases, reduces chemical usage, improves yield and resource efficiency
Blockchain-Enabled IoT Systems	Distributed ledger technology, smart contracts, cryptographic protocols, IoT integration platforms	Supply chain traceability, product authentication, logistics management, quality assurance	Ensures data immutability, enhances transparency, improves trust among stakeholders, automates transactions	Reduces fraud, improves food safety, enhances market access and traceability in agricultural supply chains
Biosensors and Nanotechnology	Nanocomposite sensors, electrochemical biosensors, optical biosensors, molecular detection systems	Pathogen detection, nutrient deficiency monitoring, soil health analysis, plant stress detection	High sensitivity and selectivity, rapid response time, real-time detection capabilities	Enables early intervention, reduces crop losses, minimizes pesticide usage, improves crop health monitoring
Hybrid Communication Networks	LoRaWAN, ZigBee, NB-IoT, Wi-Fi, cellular networks (4G/5G), mesh networking	Farm-wide connectivity, sensor data transmission, remote monitoring, integrated IoT systems	Improved network reliability, extended coverage, efficient data transmission, reduced packet loss	Ensures consistent data flow, enhances system performance, supports large-scale agricultural

				deployments
Smart Irrigation Systems	Soil moisture sensors, weather forecasting systems, automated valves, AI-based decision models	Precision irrigation, water resource management, automated irrigation scheduling	Feedback-based control, optimized water usage, real-time monitoring, reduced human intervention	Saves water (30-40%), improves crop yield, prevents over-irrigation and nutrient leaching
Robotics and Autonomous Systems	Autonomous tractors, robotic harvesters, computer vision, AI-based navigation systems	Planting, weeding, spraying, harvesting, precision farming operations	High precision, reduced human error, automation of repetitive tasks, increased operational efficiency	Reduces labor dependency, lowers operational costs, enhances productivity and precision agriculture practices
Cloud-Based Decision Support Systems (DSS)	Cloud computing, big data analytics, AI/ML models, dashboards, mobile applications	Crop planning, irrigation scheduling, pest management, yield forecasting	Scalable data storage, advanced analytics, remote accessibility, real-time insights	Enables data-driven decision-making, improves farm management, reduces risks and uncertainties
Predictive Maintenance Systems	IoT sensors, vibration analysis, thermal sensors, AI-based fault detection models	Monitoring farm machinery, tractors, irrigation systems, equipment health	Early fault detection, reduced downtime, optimized maintenance scheduling	Increases equipment lifespan, reduces repair costs, ensures continuous farm operations

6. Data Analytics and Decision Support in Smart Agriculture

The rapid adoption of Internet of Things (IoT) technologies in agriculture has resulted in the generation of massive volumes of heterogeneous data from sensors monitoring soil properties, crop conditions, environmental parameters, livestock health, and post-harvest systems. However, raw data alone does not provide actionable insights unless it is processed, analyzed, and interpreted effectively. The integration of big data analytics, machine learning (ML), and cloud computing has significantly improved the ability of agricultural systems to respond dynamically to changing environmental and operational conditions (Wolfert *et al.*, 2017; Liakos *et al.*, 2018) ^[32, 33].

6.1 Big Data in Agriculture

Modern agricultural systems equipped with IoT devices generate large-scale and diverse datasets characterized by high volume, variety, velocity, and veracity. These datasets include soil moisture levels, pH values, nutrient concentrations, temperature, humidity, crop growth indicators, livestock health metrics, and storage conditions. The sheer volume of data generated daily from sensor networks presents challenges in terms of storage, processing, and analysis. Additionally, the variety of data sources, including structured sensor data, unstructured images, and textual information, requires advanced data integration techniques. Real-time data streams further increase complexity, as timely processing is essential for decision-making in critical operations such as irrigation and disease control. In countries such as India, large-scale farms and agri-tech platforms increasingly rely on cloud-based infrastructures to aggregate and analyze agricultural data across regions, enabling both farm-level and regional decision-making. The application of big data

analytics in agriculture has been recognized as a key driver for improving efficiency and sustainability in modern farming systems (Wolfert *et al.*, 2017) ^[32].

6.2 Machine Learning Models

ML techniques such as Random Forest, SVM, neural networks, and clustering support yield prediction, disease detection, and irrigation optimization (Liakos *et al.*, 2018; Kamilaris & Prenafeta-Boldú, 2018) ^[33, 34].

6.3 Decision Support Systems (DSS)

DSS integrate sensor data and analytics to provide recommendations for irrigation, fertilization, and pest management (Rose *et al.*, 2016) ^[35].

6.4 Data Visualization and Interaction

Dashboards, heat maps, and time-series tools enable intuitive data interpretation and real-time monitoring (Wolfert *et al.*, 2017) ^[32].

6.5 Predictive Analytics

Predictive models forecast crop yield, pest outbreaks, and irrigation needs, reducing uncertainty (Kamilaris & Prenafeta-Boldú, 2018) ^[34].

6.6 Integrated Systems:

The integration of IoT, ML, and cloud computing supports end-to-end agricultural optimization, including post-harvest quality assessment (Kahar *et al.*, 2025; Wolfert *et al.*, 2017) ^[32, 6].

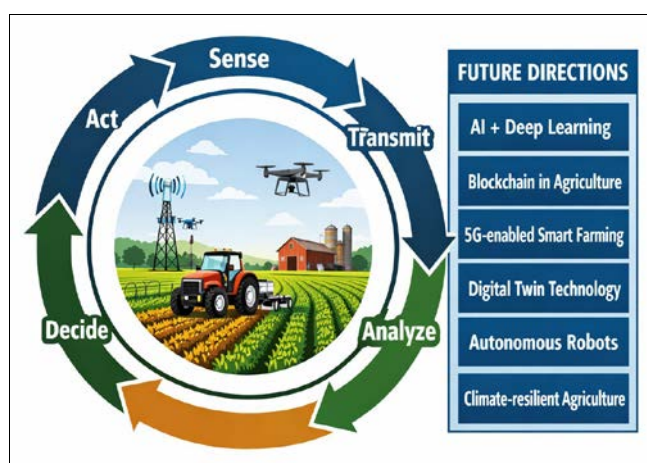
Table 6.1: Integrated Data Analytics Framework for Smart Agriculture

Component	Technologies Used	Type of Data Generated	Analytical Methods Employed	Key Applications in Agriculture	Impact on Agricultural Systems	References
Data Acquisition Layer	IoT sensors, UAVs, satellite imaging, RFID sensors	Soil, crop, weather, livestock data	Real-time sensing, remote sensing	Field monitoring, crop tracking, livestock health	Accurate data collection, supports precision farming	Alahmad <i>et al.</i> , 2023 ^[1] ; Liu <i>et al.</i> , 2025 ^[9]
Data Transmission Layer	WSN, LoRaWAN, ZigBee, NB-IoT, 4G/5G	Sensor streams, telemetry, geospatial data	Communication protocols, routing	Remote monitoring, real-time alerts	Reliable data transfer, scalability	Jawad <i>et al.</i> , 2017 ^[5] ; Navarro <i>et al.</i> , 2020 ^[11]
Data Storage Layer	Cloud (AWS, Azure), edge/fog, databases	Structured/unstructured datasets	Data warehousing, indexing	Data management, historical analysis	Scalable storage, supports big data	Navarro <i>et al.</i> , 2020 ^[11] ; Kumar <i>et al.</i> , 2025 ^[8]
Data Processing & Analytics Layer	ML, DL, AI, big data frameworks	Integrated real-time datasets	Prediction, classification, clustering	Yield prediction, disease detection	Improved accuracy, predictive insights	Liakos <i>et al.</i> , 2018 ^[33] ; Kahar <i>et al.</i> , 2024 ^[6]
Decision Support	DSS, mobile apps,	Insights, alerts,	Optimization, AI	Irrigation,	Better decision-	Rose <i>et al.</i> , 2016

Layer	dashboards	recommendations	models	fertilization, pest control	making, efficiency	[35]; Kahar <i>et al.</i> , 2024 [6]
Data Visualization Layer	Dashboards, GIS, heat maps	Trends, maps, indicators	Visualization, UI tools	Monitoring, stress detection	Easy interpretation, quick decisions	Wolfert <i>et al.</i> , 2017 [32]
Integration & System Layer	IoT + AI + cloud, APIs, middleware	Multi-source data	Data fusion, interoperability	Smart farming systems	Holistic management, sustainability	Alahmad <i>et al.</i> , 2023 [1]; Liu <i>et al.</i> , 2025 [9]

6.7 Challenges in Agricultural Data Analytics

Despite the significant potential of data-driven agriculture, several challenges limit the effective utilization of IoT-generated data. Agricultural datasets are often characterized by high volume, heterogeneity, and real-time streaming requirements, which complicate data storage, integration, and processing. Ensuring data quality and reliability remains a critical concern, as sensor inaccuracies, calibration drift, and environmental interference can lead to erroneous inputs and unreliable analytical outcomes. Additionally, limited computational infrastructure and connectivity constraints in rural regions restrict the deployment of advanced analytics frameworks, particularly those dependent on cloud-based processing. Data privacy and security also pose significant risks, as sensitive farm-level information requires robust protection mechanisms to prevent unauthorized access and misuse (Rahu *et al.*, 2022; Alahmad *et al.*, 2023) [12, 1].



7. Challenges and Limitations of IoT in Agriculture

The implementation of IoT-based agricultural systems faces a range of technical, economic, social, and regulatory challenges that hinder large-scale adoption. Technically, issues such as sensor inaccuracies, power constraints, and unreliable network connectivity in remote areas affect system performance and data continuity. Economically, high initial investment costs, recurring maintenance expenses, and uncertain return on investment discourage adoption, particularly among smallholder farmers. Social barriers, including limited digital literacy, skill gaps, and resistance to technological change, further slow implementation. Moreover, environmental conditions such as extreme weather and harsh field environments can damage IoT devices, while the absence of standardized protocols and supportive policy frameworks results in fragmented deployment. Addressing these challenges requires integrated strategies, including the development of energy-efficient and robust sensors, expansion of rural connectivity, farmer training programs, financial support mechanisms, and the establishment of standardized regulations to ensure secure and interoperable IoT ecosystems in agriculture (Dhanaraju *et al.*, 2022; Kahar *et al.*, 2024; Rahu *et al.*, 2022) [12, 6, 2].

8. Conclusion

The last ten years have witnessed the development of Internet of Things (IoT) technology and sensor networks in the agricultural industry as a theoretical construct to a working implementation. The combination of low-cost sensors, wireless communication, cloud-based computing, and data analytics has made it possible to monitor precise, automated control of applications in areas of irrigation management, crop health management, greenhouse automation, livestock surveillance, and supply chain management. These practices have shown great efficiency of the resources, such as less water consumption, improved application of fertilizers, less demand of labor, and healthy crop growth. Empirical evidence, especially in India and other locations, reports increment of yield of 10-30% and reduction in costs of 15-40%, and also enhanced environmental sustainability due to precise interventions. The integration of multi-sensor data also allows the pests, nutrient deficiency and water stress to be detected early. Nevertheless, its use is still limited due to barriers like low rural connectivity, expensive installation, standardisation, interoperability and issues related to the privacy of data. Also, a lack of digital literacy of farmers limits the use of decision support systems, even with the continued interest by ICAR and agricultural institutions. The hybrid connectivity models, new solutions, in which LPWAN can be used to complement 5G, semantic data frameworks to support interoperability, and new technologies, including blockchain to support supply chain visibility, edge computing to support real-time analytics, and federated learning to support privacy-preserving data processing, are emerging solutions. All in all, smart and interconnected systems that connect sensing, analytics, and communication technologies are the future of agriculture. It will involve collaborations, standardization, and favorable policies that would facilitate sustainable, climate-resilient, and high-productivity agricultural systems.

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