Archives of Current Research International

Volume 25, Issue 4, Page 85-105, 2025; Article no.ACRI.132153
ISSN: 2454-7077

Exploring the Role of IoT in Transforming Agriculture: Current Applications and Future Prospects

Maddali Anusha [a++*], Amitabh Soni [b++], Rashmi Mohapatra [c#], Vimal Kumar [d++], M. R. Bhanusree [e++], Damayanti Giri [f†] and Shubham Gupta [g++]

[a] *Department of Agricultural Engineering, Vignan's Foundation For Science Technology and Research Vadlamudi, Guntur, Andhra Pradesh, India.*
[b] *Department of Agricultural Engineering, Vignan's Foundation for Science, Technology and Research, Vadlamudi, Guntur, Andhra Pradesh, India.*
[c] *School of Comparative Indic Studies and Tribal Science, Kalinga Institute of Social Sciences (KISS), Deemed to be University, Bhubaneswar, Odisha – 751024, India.*
[d] *School of Agricultural sciences, IIMT University, Meerut, India.*
[e] *Department of Horticulture, Agricultural College, Palem, PJTAU, Telangana, India.*
[f] *Department of Botany, School of Comparative Indic Studies and Tribal Science, Kalinga Institute of Social Sciences (KISS), Deemed to be University, Bhubaneswar - 751 024, India.*
[g] *School of Agricultural Sciences and Engine, IFTM University, India.*

Author's contribution

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

Article Information

DOI: https://doi.org/10.9734/acri/2025/v25i41139

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: https://pr.sdiarticle5.com/review-history/132153

Review Article

Received: 04/01/2025
Accepted: 07/03/2025
Published: 24/03/2025

[++] *Assistant Professor;*
[#] *Associate Professor (Botany), Dean;*
[†] *Research Scholar;*
**Corresponding author: Email: maddalianusha33@gmail.com;*

Cite as: *Anusha, Maddali, Amitabh Soni, Rashmi Mohapatra, Vimal Kumar, M. R. Bhanusree, Damayanti Giri, and Shubham Gupta. 2025. "Exploring the Role of IoT in Transforming Agriculture: Current Applications and Future Prospects". Archives of Current Research International 25 (4):85-105. https://doi.org/10.9734/acri/2025/v25i41139.*

ABSTRACT

The Internet of Things (IoT) has revolutionized modern agriculture by integrating smart technologies that enhance efficiency, sustainability, and productivity across various farming sectors. IoT applications in precision agriculture, livestock management, water resource optimization, post-harvest logistics, and supply chain management enable real-time monitoring, automated decision-making, and predictive analytics. Research indicates that IoT-based agricultural systems can increase crop yields by 25%, reduce irrigation water consumption by 50%, and lower post-harvest losses by 30%. IoT-driven precision farming utilizes smart sensors, AI-driven analytics, and automated systems to optimize soil moisture management, pest control, and nutrient application, ensuring resource-efficient production. In livestock management, IoT-enabled wearables and automated feeding systems improve animal health monitoring, enhance milk yield, and reduce disease-related losses. Water conservation through IoT-based smart irrigation and hydroponic systems has shown a 40% improvement in water-use efficiency, mitigating the impact of climate change. Post-harvest management and supply chain integration with IoT technologies have reduced food spoilage through real-time temperature monitoring, smart packaging, and blockchain-enabled traceability. Despite these advancements, challenges such as high implementation costs, cybersecurity risks, infrastructure limitations, and the need for skilled labour hinder widespread adoption. Studies indicate that nearly 45% of rural farms lack access to stable internet connectivity, restricting the deployment of IoT-based agricultural solutions. Overcoming these barriers through policy reforms, financial incentives, and digital literacy programs will accelerate IoT adoption and drive agricultural transformation. The future of IoT in agriculture lies in further integration with artificial intelligence, robotics, and blockchain for enhanced automation, food security, and climate resilience. As technology advances, IoT-driven smart farming will play a pivotal role in achieving global agricultural sustainability, ensuring higher productivity with reduced environmental impact.

Keywords: IoT-agriculture; precision-farming; smart-irrigation; livestock-management; supply-chain; post-harvest.

1. INTRODUCTION

The global agricultural sector is undergoing a rapid transformation driven by advancements in digital technologies, with the Internet of Things (IoT) emerging as a game-changer in modern farming (Thilakarathne et al., 2025). The increasing global population and the growing demand for food have necessitated the adoption of data-driven solutions to optimize resource utilization and enhance productivity. IoT technology enables real-time data collection, intelligent decision-making, and automation, thereby revolutionizing traditional agricultural practices. The integration of smart sensors, wireless communication networks, cloud computing, and artificial intelligence (AI) has paved the way for precision agriculture, a data-intensive approach aimed at maximizing crop yields while minimizing environmental impacts. Various reports suggest that by 2050, food production must increase by nearly 70% to meet the nutritional demands of the global population. Digital technologies, including IoT, play a crucial role in achieving this target while ensuring sustainability and resilience against climate change. Researchers have proposed different IoT-based technologies in the agriculture field that are increasing production with less workforce effort. Researchers have also worked on different IoT-based agriculture projects to improve the quality and increase agricultural productivity.Carnegie Melon University has worked on a plant nursery by using wireless sensor technology (Farooq et al., 2020; Gulaiya et al., 2024; Shafique et al., 2019).

1.1 Agriculture in the Digital Age

The agricultural sector has historically relied on conventional practices that often lead to inefficiencies in resource allocation, pest and disease management, and supply chain logistics (Sjah et al., 2020). The emergence of digital agriculture, characterized by the convergence of information and communication technologies (ICTs), remote sensing, automation, and data analytics, has revolutionized farming methodologies. IoT serves as a fundamental pillar of digital agriculture, enabling seamless connectivity between physical devices and digital platforms. Studies indicate that smart farming solutions powered by IoT can enhance agricultural efficiency by 20-30%, significantly reducing water and fertilizer wastage. Precision farming techniques utilizing IoT-based sensors help in monitoring soil moisture, temperature, humidity, and nutrient levels, leading to improved decision-making and higher yields (Ikram et al., 2022). According to a report, the global IoT in agriculture market is expected to reach USD 30.8 billion by 2026, growing at a CAGR of 10.1% due to increasing technological adoption and government initiatives promoting smart farming.

1.2 Importance of Precision Agriculture and Technological Interventions

Precision agriculture has gained significant traction as a data-driven approach aimed at optimizing agricultural inputs, improving crop health, and ensuring environmental sustainability. IoT technologies facilitate precision farming by enabling remote monitoring, automated irrigation, GPS-based machinery, and predictive analytics for disease detection. Research highlights that precision agriculture can reduce fertilizer application by 40%, decrease water consumption by 50%, and increase crop yields by 25%. The role of IoT in precision agriculture extends beyond the farm, encompassing supply chain optimization, logistics, and food traceability. The deployment of IoT-powered solutions such as smart greenhouses, automated drones, and AI-based decision support systems has demonstrated remarkable improvements in agricultural output. A study by found that IoT-based smart farming applications reduced operational costs by up to 30%, enhancing overall farm profitability. Governments and private enterprises worldwide are investing heavily in IoT-driven precision agriculture to ensure food security and reduce environmental degradation (Babar et al., 2024).

1.3 Concept of Internet of Things (IoT)

The Internet of Things (IoT) is a network of interconnected devices embedded with sensors, software, and communication technologies that facilitate data exchange and automation without human intervention. IoT in agriculture involves the deployment of smart sensors, GPS modules, drones, and cloud computing platforms to monitor and control farming operations in real time. The fundamental components of IoT-based agriculture include data acquisition (sensors for soil, weather, and crop monitoring), data transmission (wireless networks such as LPWAN, 5G, and satellite connectivity), data processing (cloud computing and AI-driven analytics), and automation (actuators for precision application of inputs). Reports indicate that IoT applications in agriculture can improve water use efficiency by 40%, enhance pest management strategies, and optimize fertilizer application through data-driven recommendations. The implementation of IoT enables farmers to make informed decisions, minimize production losses, and achieve higher profitability while reducing dependency on manual labour (Dhanaraju et al., 2022).

1.4 Evolution of IoT Applications in Agricultural Systems

The evolution of IoT in agriculture has been driven by technological advancements, increasing adoption of smart devices, and growing concerns regarding food security and sustainability. The early phases of agricultural IoT focused on remote sensing and automated irrigation systems, primarily leveraging GPS and satellite imagery. The integration of AI, machine learning (ML), and big data analytics with IoT has expanded its applications across the entire agricultural value chain (Misra et al., 2020). According to one report, IoT-enabled precision agriculture has increased global agricultural productivity by 15-20% over the past decade. The development of low-power wide area networks (LPWAN) has facilitated the implementation of cost-effective and energy-efficient IoT solutions in rural areas. Recent advances include the use of blockchain-integrated IoT systems to ensure food traceability, robotic automation for crop harvesting, and AI-driven predictive analytics for yield forecasting. Research suggests that IoT-based smart agriculture platforms have reduced post-harvest losses by up to 35% through real-time monitoring of storage conditions and supply chain logistics.

1.5 Objectives and Scope of the Review

The primary objective of this review is to provide a comprehensive analysis of the advancements and applications of IoT technology in agriculture, emphasizing its role in enhancing productivity, sustainability, and resource efficiency (Kumar et al., 2024). The review aims to explore various IoT-driven innovations, their impact on different agricultural practices, and the challenges associated with large-scale adoption. Key aspects covered in this review include IoT-enabled precision farming, smart irrigation systems, livestock monitoring, post-harvest management, and future trends in digital agriculture. The scope extends to assessing the integration of IoT with emerging technologies such as AI, blockchain, and 5G for developing next-generation agricultural solutions. By examining recent research findings, industry reports, and case studies, this review seeks to highlight the transformative potential of IoT in modern agriculture and its implications for global food security.

2. FUNDAMENTALS OF IOT IN AGRICULTURE

The fundamental integration of the Internet of Things (IoT) in agriculture has revolutionized traditional farming practices by enhancing productivity, optimizing resource use, and ensuring sustainability (Raj et al., 2021). The ability to interconnect devices, sensors, and cloud computing platforms has facilitated real-time data collection, predictive analytics, and automation, allowing farmers to make informed decisions. The global IoT in agriculture market is projected to reach USD 30.8 billion by 2026, with an estimated compound annual growth rate (CAGR) of 10.1%, driven by the increasing demand for smart farming solutions. Studies indicate that IoT-based smart farming can increase water-use efficiency by 50%, improve fertilizer application precision by 30%, and enhance crop yields by up to 25%. The fundamentals of IoT in agriculture involve understanding its core components, architecture, role in precision monitoring, connectivity protocols, and integration with artificial intelligence and machine learning for advanced decision-making.

2.1 Concept of IoT and its Components

The Internet of Things (IoT) is a system of interrelated computing devices, mechanical and digital machines, equipped with sensors and software that facilitate seamless data exchange (Liu et al., 2017). In agriculture, IoT applications encompass smart farming technologies, automated irrigation, real-time pest and disease monitoring, and precision livestock management. IoT functions through interconnected components, including sensors for data collection, actuators for automation, communication networks for data transfer, and cloud computing platforms for data processing. Sensors deployed in smart farming measure soil moisture, temperature, pH levels, and crop health, ensuring precision-based agricultural interventions. Research demonstrates that smart soil moisture sensors have improved irrigation efficiency by 40%, reducing water wastage and enhancing productivity. Actuators play a crucial role in automating agricultural operations, such as adjusting irrigation schedules based on real-time data, thereby increasing water-use efficiency and crop yield. The rapid growth of cloud computing has further strengthened IoT applications, allowing large-scale data analysis and predictive modelling to improve farm management. The adoption of IoT in agriculture has been accelerated by the integration of artificial intelligence and machine learning, enabling predictive analytics for yield estimation, disease forecasting, and optimized input applications (Shaikh et al., 2022).

2.2 Basic Architecture of IoT Systems in Agriculture

The architecture of IoT in agriculture is structured into multiple layers that facilitate data collection, transmission, processing, and application. The perception layer comprises IoT sensors that gather critical data on soil health, climate conditions, and crop growth. This layer plays a pivotal role in precision agriculture, enabling automated monitoring of agricultural parameters, leading to a 35% reduction in crop losses through early detection of diseases. The network layer ensures seamless connectivity between sensors and cloud-based data centers, employing technologies such as LoRaWAN, Zigbee, and NB-IoT for long-range, low-power communication (Maurya et al., 2023). IoT-driven connectivity has allowed for real-time data transmission, enabling farmers to receive automated alerts and recommendations for optimal agricultural practices. The processing layer integrates big data analytics, AI-driven models, and machine learning algorithms to analyze incoming sensor data and provide actionable insights. Predictive analytics powered by IoT has improved pest outbreak detection, reducing pesticide application by 40%, thus promoting eco-friendly farming practices. The application layer consists of user interfaces such as smart farming dashboards and mobile applications that allow farmers to visualize real-time farm data and make informed decisions. The combination of these layers enables precision farming, real-time monitoring, and resource optimization, improving productivity and sustainability in modern agriculture (Monteiro et al., 2021).

2.3 Role of Sensors, Actuators and Communication Networks

IoT-based smart agriculture heavily relies on sensors, actuators, and advanced communication networks to facilitate real-time monitoring and automation (Table 1). Sensors play a crucial role in precision farming by collecting data on soil conditions, crop health, weather patterns, and livestock activity (Table 2). These include soil moisture sensors, which optimize irrigation management, and nutrient sensors that ensure balanced fertilization, reducing nutrient leaching and environmental pollution. Studies show that IoT-based pest monitoring systems have decreased pesticide application by 30% while maintaining crop protection efficiency. Actuators complement sensors by executing automated responses based on real-time data, such as activating irrigation systems when soil moisture levels drop below the threshold or adjusting greenhouse ventilation based on humidity readings. The automation of agricultural operations through IoT-driven actuators has demonstrated a 40% improvement in water-use efficiency, significantly enhancing resource conservation (Kumar et al., 2024). Communication networks form the backbone of IoT applications in agriculture, ensuring seamless data transmission between field sensors and cloud-based analytics platforms. Technologies such as LPWAN (Low Power Wide Area Network), 5G, and satellite-based IoT solutions have revolutionized connectivity in agriculture, enabling real-time data exchange over large geographical areas. Research indicates that 5G-powered IoT farms have increased agricultural efficiency by 25%, addressing the challenges of delayed decision-making and limited connectivity in rural areas. The integration of IoT with advanced communication networks has facilitated the deployment of precision agriculture solutions, allowing farmers to monitor farm conditions remotely and optimize resource allocation based on real-time data.

2.4 Connectivity Protocols and Cloud Computing in IoT

The effectiveness of IoT in agriculture depends on reliable connectivity protocols and cloud computing infrastructure (Mekala et al., 2017). Wireless technologies such as Zigbee, LoRaWAN, and NB-IoT provide low-power, long-range connectivity, enabling remote monitoring of agricultural parameters. Studies indicate that LoRaWAN-enabled IoT networks have improved farm productivity by 30%, reducing input wastage and enhancing resource efficiency. Cloud computing serves as the central processing hub for IoT-generated data, providing storage, analytics, and AI-driven insights for precision farming. Cloud-based IoT platforms support big data analytics, enabling farmers to receive automated recommendations for irrigation scheduling, pest management, and fertilization strategies. Research highlights that AI-powered cloud computing solutions in agriculture have increased yield forecasting accuracy by 20%, reducing production uncertainties and optimizing farm output. The integration of blockchain with IoT has further strengthened agricultural supply chain management, ensuring transparency, traceability, and security in data transactions. Reports indicate that blockchain-integrated IoT solutions have reduced food fraud incidents by 30%, improving consumer trust and market efficiency. The continued advancements in connectivity protocols and cloud computing infrastructure are driving the expansion of IoT in agriculture, enabling precision-driven, data-centric farming practices (Obaid et al., 2014).

2.5 Integration with Artificial Intelligence and Machine Learning

The fusion of IoT with artificial intelligence (AI) and machine learning (ML) has transformed agriculture into a predictive and automated ecosystem. AI-driven IoT applications utilize real-time data to develop predictive models for crop yield estimation, pest outbreak forecasting, and soil fertility management. Machine learning algorithms analyze historical and real-time sensor data, allowing farmers to optimize input applications and minimize environmental impact. Research suggests that AI-integrated IoT systems have increased agricultural efficiency by 20-30%, reducing reliance on chemical inputs and enhancing sustainability. The deployment of autonomous farming technologies, such as drone-based crop monitoring and robotic harvesting systems, has further improved agricultural productivity. AI-powered drones equipped with IoT sensors provide real-time aerial imaging and crop health assessments, increasing farm surveillance efficiency by 40%. Robotic harvesting systems have demonstrated a 40% reduction in labour costs while improving harvest precision and quality (Kootstra et al., 2021). The integration of AI and ML with IoT is shaping the future of agriculture, providing data-driven solutions for climate resilience, resource

Table 1. Role of Sensors, Actuators, and Communication Networks in the Role of IoT in Transforming Agriculture

Component	Description	Applications in Agriculture	Benefits
Sensors	Devices that detect and measure various environmental and biological parameters.	Soil moisture sensors, temperature sensors, pH sensors, humidity sensors, nutrient sensors, and light sensors.	Real-time monitoring, data collection, precision agriculture, disease prediction, yield forecasting.
Actuators	Mechanical or electronic devices that receive signals and perform physical actions.	Automated irrigation systems, fertilizer dispensers, pest control devices, and greenhouse climate controllers.	Automated control of irrigation, spraying, and fertigation; reduced labor costs, enhanced efficiency.
Communication Networks	Systems that transmit data from sensors and actuators to central servers or cloud systems.	Wireless Sensor Networks (WSN), Low-Power Wide-Area Networks (LPWAN), Bluetooth, Zigbee, 5G.	Seamless data transfer, real-time monitoring, connectivity over long distances, enhanced decision-making.
Role of IoT	Integration of sensors, actuators, and networks for smart agriculture solutions.	Smart farming, precision agriculture, livestock monitoring, supply chain optimization.	Increased productivity, resource optimization, reduced environmental impact, enhanced decision-making.

(Source: Kumar et al., 2024)

Table 2. Sensor Types and Their Applications (Dhanaraju et al., 2022)

Sensors	Applications	Working Procedure
Acoustic sensors	Pest monitoring and detection, classifying seed varieties, fruit harvesting.	Measuring variations in noise level when interacting with other materials, such as soil particles.
Airflow sensors	Measuring soil air permeability, moisture, and structure in static or mobile modes.	Based on various soil properties, producing unique identifying signatures.
Eddy covariance-based sensors	Quantifying exchanges of CO_2, water vapor, methane, or other gases; measuring surface atmosphere and trace gas fluxes.	Measuring continuous flux over large areas.
Electrochemical sensors	Analyzing soil nutrient levels and pH.	Measuring nutrients in soil, salinity, and pH using sensors.
Electromagnetic sensors	Recording electrical conductivity, electromagnetic responses, residual nitrates, and organic matter in soil.	Electrical circuits measure soil particles' ability to conduct or accumulate electrical charge.
Field Programmable Gate Array (FPGA) based sensors	Measuring real-time plant transpiration, irrigation, and humidity.	Programmable silicon chips and logic blocks are integrated with programmable interconnected digital circuits.
Light Detection and Ranging	Land mapping, soil type determination, farm 3D modeling,	Emitting pulsed light waves that bounce off objects; the

Sensors	Applications	Working Procedure
(LIDAR)	erosion monitoring, soil loss, and yield forecasting.	return time of each pulse is used for assessment.
Mass flow sensors	Yield monitoring based on the amount of grain flow through a combine harvester.	Sensing mass flow using modules like grain moisture sensors, data storage devices, and internal software.
Mechanical sensors	Measuring soil compaction or mechanical resistance.	Recording force assessed by strain gauges or load cells.
Optical sensors	Monitoring soil organic substances, moisture, color, minerals, composition, clay content, fruit maturation, etc.	Using light reflectance phenomena to measure changes in wave reflections.
Optoelectronic sensors	Differentiating plant types to detect weeds in wide-row crops.	Differentiation based on reflection spectra.
Soft Water Level-Based (SWLB) sensors	Characterizing hydrological behaviors in catchments (water level, flow, time-step acquisitions).	Measuring rainfall, stream flow, and other water presence parameters.
Telematics sensors	Assessing location, travel routes, and operational activities of machines and farm systems.	Facilitating telecommunication between places, especially inaccessible points.
Ultrasonic ranging sensors	Tank monitoring, spray distance measurement, uniform spray coverage, object detection, monitoring crop canopy, weed detection.	Using transducers to send and receive ultrasonic pulses to relay information about object proximity.
Remote sensing	Crop assessment, yield modeling, forecasting, land cover mapping, degradation monitoring, plant and pest identification.	Using satellite-based systems to collect, process, and disseminate environmental data from fixed and mobile platforms.

conservation, and yield optimization. The widespread adoption of IoT in agriculture is driving a paradigm shift toward smart farming, improving efficiency, sustainability, and profitability. The combination of IoT with AI, cloud computing, and advanced communication networks is enabling precision-driven farming solutions, optimizing resource use, and enhancing productivity. As technological advancements continue to evolve, IoT-powered smart agriculture is poised to address global food security challenges and ensure sustainable agricultural practices in the digital age.

3. IoT-ENABLED PRECISION AGRICULTURE

The integration of the Internet of Things (IoT) into precision agriculture has revolutionized traditional farming methods by enabling real-time monitoring, data-driven decision-making, and automation (Sharma et al., 2024). With increasing challenges in global food production, including climate change, resource scarcity, and the need for higher efficiency, IoT technologies provide a solution that optimizes agricultural inputs while minimizing environmental impact. The global precision agriculture market, driven by IoT innovations, is projected to reach USD 20.84 billion by 2027, growing at a compound annual growth rate (CAGR) of 12.6%. Research suggests that IoT-based precision agriculture enhances crop yields by up to 25%, reduces water consumption by 50%, and lowers fertilizer application by 30%. These advancements have positioned IoT as a key enabler of sustainable and intelligent farming, ensuring increased productivity while maintaining ecological balance.

3.1 Smart Farming and Data-Driven Decision Making

Smart farming is an advanced agricultural approach that integrates IoT devices, artificial intelligence (AI), and big data analytics to create intelligent farm management systems. The ability to collect, analyze, and utilize vast amounts of data in real-time allows farmers to optimize irrigation schedules, control pest infestations, and monitor soil health with unprecedented accuracy (Patil et al., 2023). IoT-powered decision-support systems have demonstrated a 40% improvement in resource efficiency, leading to cost reductions and increased farm profitability. Smart farming is based on interconnected sensors and automation technologies that enable precise control over farming operations, reducing human intervention while improving output quality. Data analytics plays a central role in IoT-driven agriculture, helping farmers process historical and real-time information to predict trends and mitigate risks. AI-powered analytics tools analyze patterns in weather, soil conditions, and crop health, offering actionable insights that minimize losses. Research indicates that AI-driven predictive models improve yield forecasting accuracy by 20-30%, allowing for better planning and resource allocation. Automation, another key component of smart farming, reduces dependency on manual labor, enhances operational efficiency, and ensures consistent crop management. Robotic systems, automated tractors, and drone-assisted farming are increasingly being integrated with IoT networks to streamline agricultural processes, reducing labor costs by up to 50% (Khan et al., 2024).

3.2 Real-Time Monitoring of Soil and Crop Health

The ability to monitor soil and crop health in real-time has transformed agricultural productivity and sustainability. IoT-based sensors continuously collect and analyze soil parameters, including moisture content, temperature, pH levels, and nutrient availability, allowing farmers to apply precise input quantities as required. Studies indicate that IoT-driven soil monitoring systems have reduced irrigation needs by 40% and improved fertilizer efficiency by 35%. This technology ensures optimal soil conditions, preventing issues such as over-fertilization, soil degradation, and water stress, which are critical concerns in modern agriculture. Remote sensing technologies, including satellite imagery and drone surveillance, further enhance crop health monitoring by providing detailed, real-time insights into plant growth and disease detection. Hyperspectral and multispectral imaging systems detect early signs of pest infestations and nutrient deficiencies, enabling timely intervention. Research highlights that drone-assisted IoT monitoring has reduced pesticide usage by 40%, leading to more sustainable and eco-friendly farming practices. Advanced AI algorithms analyze sensor data to predict potential threats to crop health, supporting farmers in making preemptive decisions that prevent yield losses (Mohyuddin et al., 2024). These technologies ensure improved agricultural resilience by mitigating risks associated with unpredictable weather conditions and plant diseases.

3.3 Automated Irrigation and Water Management Systems

Water scarcity remains a significant challenge for global agriculture, and IoT-enabled automated irrigation systems offer a sustainable solution by optimizing water use. These systems employ real-time soil moisture sensors, weather data integration, and AI-driven analytics to determine precise irrigation needs, preventing both overwatering and drought stress. Studies indicate that IoT-enabled smart irrigation has reduced water wastage by 50% while increasing water-use efficiency in farming operations. Precision irrigation relies on smart sensors that continuously monitor soil conditions and water availability, adjusting irrigation schedules accordingly (Abioye et al., 2020). Cloud-based platforms process real-time data and send automated commands to irrigation controllers, ensuring efficient water distribution. Research suggests that precision irrigation reduces irrigation costs by 35% while enhancing crop resilience to climate variability. IoT-based drip and sprinkler irrigation systems further optimize water application, reducing evaporation losses and improving soil moisture retention. These technologies have been instrumental in enhancing crop water productivity, with studies showing a 30% increase in yield per unit of water applied.

3.4 Climate and Weather Forecasting through IoT

Climate unpredictability poses a major risk to agricultural productivity, making real-time weather monitoring and forecasting essential for precision farming (Selvam et al., 2023). IoT-based weather stations collect meteorological data, including temperature, humidity, rainfall, wind speed, and solar radiation, allowing farmers to make informed decisions regarding planting, irrigation, and harvesting. AI-driven climate prediction models analyze historical and real-time data, offering accurate forecasts that reduce yield losses due to extreme weather events. Research suggests that IoT-enabled weather forecasting has improved agricultural planning efficiency by 25% and reduced climate-related crop failures by 30%. Microclimate monitoring is another advantage of IoT in precision agriculture, allowing farmers to track localized weather variations that influence crop growth. Greenhouse farmers, in particular, benefit from IoT-based climate control systems that automatically adjust temperature, humidity, and ventilation settings, optimizing conditions for plant development. AI-enhanced IoT models have demonstrated a 20% improvement in microclimate prediction accuracy, leading to increased productivity in controlled-environment agriculture. By integrating real-time weather data with precision farming techniques, IoT systems ensure that farmers can respond proactively to climatic changes, reducing losses and improving sustainability (Getahun et al., 2024).

3.5 Variable Rate Technology (VRT) and Site-Specific Farming

Variable Rate Technology (VRT) is a core component of precision agriculture that allows for site-specific application of inputs such as fertilizers, pesticides, and irrigation water based on real-time field conditions. IoT-powered VRT systems utilize GPS, remote sensing, and AI-driven analytics to create detailed field maps, identifying variability in soil fertility, moisture levels, and crop health. Research suggests that VRT adoption has reduced fertilizer application by 30% and improved nutrient-use efficiency by 40%. Precision fertilization through IoT-enabled VRT ensures that fertilizers are applied only where needed, reducing runoff and environmental pollution. AI-integrated VRT systems analyze soil nutrient data and plant health indicators, delivering customized fertilization plans that optimize yield potential while minimizing excess application. Research highlights that precision fertilization has increased nitrogen-use efficiency by 25%, promoting sustainable soil management (Raghuram et al., 2022). IoT-driven pest and disease monitoring systems further enhance site-specific farming by detecting early signs of infestations and optimizing pesticide application. AI-powered image recognition tools identify pest populations and recommend precise pesticide dosages, reducing chemical dependency while maintaining effective pest control. Studies indicate that IoT-based pest monitoring has decreased pesticide use by 40%, contributing to environmentally sustainable farming practices. The combination of VRT and site-specific management has not only improved resource efficiency but also enhanced crop quality and farm profitability, making IoT an indispensable tool in modern precision agriculture (Saleem et al., 2023). IoT-enabled precision agriculture is reshaping the agricultural landscape by integrating real-time monitoring, automation, and AI-driven decision support systems. The ability to optimize resource utilization, reduce environmental impact, and enhance productivity ensures that IoT remains at the forefront of agricultural innovation. As technological advancements continue, IoT-driven precision farming is expected to play a critical role in addressing global food security challenges and ensuring sustainable and resilient agricultural practices.

4. IoT IN CROP PRODUCTION AND MANAGEMENT

The application of the Internet of Things (IoT) in crop production and management has redefined agricultural practices, allowing farmers to enhance productivity while minimizing resource wastage (Table 3) (Duguma et al., 2024). IoT-driven technologies provide real-time monitoring, predictive analytics, and automation, leading to optimized crop management. The integration of IoT with artificial intelligence (AI), machine learning (ML), remote sensing, and blockchain has enabled precision agriculture by facilitating data-driven decision-making. Research suggests that IoT-based farming techniques can increase crop productivity by up to 25%, reduce irrigation water usage by 50%, and lower fertilizer application by 30%. The global IoT market in agriculture is projected to expand significantly, reaching an estimated value of USD 30.8 billion by 2026, growing at a compound annual growth rate (CAGR) of 10.1%. The use of IoT in crop management covers various aspects, including soil moisture and nutrient monitoring, automated pest and disease detection, drone-based crop surveillance, smart greenhouse systems, and blockchain integration for supply chain transparency. These innovations contribute to improved efficiency, sustainability, and profitability in modern agricultural practices.

4.1 Soil Moisture and Nutrient Sensing for Optimal Crop Growth

Soil health is a fundamental factor in ensuring sustainable agricultural productivity, and IoT-driven soil moisture and nutrient sensing systems have revolutionized soil management practices (Shahab et al., 2025). The use of IoT-based sensors allows continuous monitoring of soil parameters, including moisture levels, pH, temperature, and nutrient concentrations, enabling precise irrigation and fertilization strategies. Studies indicate that real-time soil monitoring has reduced irrigation water requirements by 40% and improved fertilizer efficiency by 35%, leading to better crop yields and reduced environmental degradation. The integration of AI-driven predictive analytics enables farmers to determine soil deficiencies in advance and apply site-specific nutrient management strategies to enhance crop growth. These systems have also been instrumental in preventing over-fertilization and nutrient runoff, reducing the negative environmental impact associated with excessive chemical use. AI-enhanced data analytics further optimize soil management by identifying trends in soil nutrient availability, assisting in long-term soil fertility conservation. The adoption of IoT-enabled soil sensors has significantly improved agronomic efficiency, ensuring better crop establishment and higher productivity through data-driven decision-making (Alahmad et al., 2023).

4.2 IoT-Based Pest and Disease Detection Systems

Pest and disease outbreaks are among the leading causes of agricultural losses, affecting nearly 40% of global crop production annually. IoT-based pest and disease detection systems provide an advanced approach to mitigating these challenges by integrating real-time monitoring, AI-powered analytics, and automated alerts. Smart sensors and imaging technologies detect early signs of pest infestations and plant diseases, allowing farmers to take immediate action before the damage spreads. Studies have shown that IoT-assisted pest monitoring reduces pesticide application by 40%, minimizing chemical residues on crops while maintaining effective pest control (Sharma et al., 2024). The use of AI-driven image recognition enables the identification of plant stress symptoms, distinguishing between nutrient deficiencies, fungal infections, and insect damage with high accuracy. Hyperspectral imaging and remote sensing technologies further enhance disease detection by identifying anomalies in crop physiology at an early stage. These advanced monitoring systems optimize pest management strategies, reducing over-reliance on chemical pesticides while improving overall farm productivity. The adoption of IoT in disease surveillance has proven to be a game-changer in precision farming, allowing for timely interventions that protect crops while ensuring environmental sustainability.

4.3 Remote Sensing and Unmanned Aerial Vehicles (UAVs) for Crop Monitoring

Remote sensing and unmanned aerial vehicles (UAVs) have transformed the way farmers monitor and manage crops, providing high-resolution imagery and real-time field assessment (Roslim et al., 2021). The integration of IoT-based drones with multispectral and hyperspectral imaging cameras enables detailed crop health analysis, identifying stress factors such as nutrient deficiencies, drought conditions, and pest infestations. Research suggests that UAV-assisted crop monitoring has improved scouting efficiency by 40% and reduced overall crop losses by 20% through early detection of agronomic issues. AI-powered drone analytics process aerial imagery to assess plant vigor, chlorophyll content, and soil variability, providing valuable insights that enhance decision-making in precision farming. IoT-integrated UAVs also facilitate precision spraying of fertilizers and pesticides, reducing chemical wastage and ensuring targeted application based on crop health data. The application of UAVs in large-scale farming operations has significantly improved the efficiency of farm monitoring while minimizing the labour-intensive process of field scouting. Remote sensing data collected through satellite and drone-based platforms further enhances yield prediction accuracy, allowing farmers to optimize resource allocation and improve overall farm productivity (Adinarayana et al., 2024). These technologies have played a crucial role in reducing production uncertainties, and ensuring a more resilient and efficient agricultural system.

4.4 Smart Greenhouses and Controlled Environment Agriculture

The adoption of IoT in smart greenhouses has facilitated controlled-environment agriculture, allowing farmers to optimize crop-growing conditions with minimal manual intervention. Automated greenhouse systems equipped with IoT sensors regulate temperature, humidity, CO_2 concentration, and light intensity, ensuring ideal conditions for plant growth. Studies indicate that IoT-powered greenhouse management has increased crop yields by 30% while reducing energy consumption by 25%, leading to improved resource efficiency. These smart greenhouses integrate AI-driven climate control, adjusting environmental parameters in response to real-time sensor data. AI-based predictive models assess plant growth requirements and automate irrigation and nutrient delivery, preventing resource wastage and improving overall crop health. The implementation of hydroponic and aeroponic systems within IoT-controlled greenhouses has further enhanced water-use efficiency by 50%, making these solutions particularly valuable in water-scarce regions (Nair et al., 2025). The ability to monitor and adjust growing conditions remotely through cloud-based platforms ensures that greenhouse operations remain optimized for productivity. Smart greenhouses have also contributed to increased production of high-value crops by enabling year-round cultivation, independent of seasonal and climatic limitations. The continued evolution of IoT-driven greenhouse farming has improved agricultural sustainability, reducing dependency on chemical inputs and optimizing energy-efficient crop production.

4.5 Integration of Blockchain for Traceability in Crop Supply Chains

Blockchain technology, when combined with IoT, has transformed supply chain transparency and traceability in agriculture. IoT-enabled sensors track agricultural products throughout the supply chain, recording real-time data on production, harvesting, transportation, and storage conditions. Blockchain secures this data in a decentralized ledger, ensuring that it remains immutable and transparent. Research suggests that blockchain-integrated IoT solutions have reduced food fraud by 30% and improved supply chain efficiency by 25%, enhancing trust and accountability in agricultural trade. Real-time monitoring of perishable crops during transportation has ensured compliance with food safety standards, reducing post-harvest losses by 20% (Onwude et al., 2020). Blockchain-enabled smart contracts facilitate automated transactions between farmers, distributors, and retailers, minimizing delays and enhancing financial transparency in the agricultural marketplace. The integration of IoT and blockchain has also provided consumers with access to verifiable data regarding the origin and quality of their food products, fostering greater consumer confidence. By eliminating supply chain inefficiencies and reducing losses due to poor handling and storage conditions, blockchain-IoT integration has strengthened food security while promoting fair trade practices in agriculture. The integration of IoT into crop production and management has significantly improved efficiency, sustainability, and traceability in modern agriculture. The ability to monitor soil health, detect pests and diseases early, utilize UAV-based crop surveillance, optimize greenhouse environments, and enhance supply chain transparency through blockchain has reshaped the agricultural

Table 3. IoT in Crop Production and Management (Adinarayana et al., 2024, Onwude et al., 2020)

Aspect	Description	Technologies Involved	Benefits
Soil Monitoring	Real-time monitoring of soil parameters such as moisture, temperature, pH, and nutrient levels.	Soil moisture sensors, pH sensors, nutrient sensors, IoT platforms.	Enhanced soil health management, optimized irrigation and fertilization, improved crop yield.
Precision Irrigation	Automated irrigation systems based on soil moisture levels and environmental conditions.	Smart irrigation controllers, wireless sensors, actuators, IoT-enabled sprinklers.	Water conservation, reduced operational costs, improved water-use efficiency.
Pest and Disease Detection	Early detection of pests and diseases through remote monitoring and predictive analytics.	Image sensors, AI algorithms, IoT platforms, drone surveillance systems.	Reduced crop losses, timely interventions, better pest and disease management.
Climate Monitoring	Monitoring and forecasting weather conditions affecting crop growth.	Weather stations, temperature and humidity sensors, IoT communication networks.	Improved decision-making for planting, harvesting, and crop protection.
Crop Growth Monitoring	Continuous tracking of plant health, growth patterns, and stress factors.	Multi-spectral cameras, smart farming platforms, machine learning algorithms.	Enhanced crop productivity, precision farming, efficient resource allocation.
Supply Chain Management	Real-time monitoring of produce during storage, packaging, and transportation.	RFID tags, GPS tracking, IoT cloud platforms, smart logistics.	Improved traceability, reduced post-harvest losses, better quality management.
Data Analytics and Decision Support	Analyzing collected data to enhance farm management practices.	Big data analytics, cloud computing, AI-based decision support systems.	Improved productivity, resource optimization, predictive maintenance.
Farm Machinery Automation	Automated machinery for planting, harvesting, and post-harvest operations.	Autonomous tractors, robotic weeders, IoT-enabled machines.	Reduced labor dependency, increased operational efficiency, precision farming.
Smart Greenhouses	Controlled environment agriculture through IoT-enabled systems.	Climate sensors, smart actuators, automated ventilation, and lighting systems.	Enhanced crop quality, resource efficiency, year-round production.

landscape. These advancements have ensured data-driven precision farming, reducing wastage and improving crop quality while addressing the growing demand for sustainable food production. As IoT technologies continue to evolve, their role in agriculture is expected to expand further, contributing to increased food security and climate-resilient farming practices (Sarma et al., 2024).

5. IoT IN LIVESTOCK MANAGEMENT

The application of the Internet of Things (IoT) in livestock management has transformed traditional animal husbandry into an automated, data-driven system that improves productivity, and animal health, and ensures resource efficiency. IoT-driven livestock management involves the integration of smart sensors, artificial intelligence (AI), and cloud-based platforms to monitor animal behaviour, optimize feeding, automate milking, and detect diseases in real time. Research suggests that IoT-based livestock monitoring systems can reduce animal mortality rates by 30%, improve milk production by 20%, and increase overall farm efficiency by 25%. The global IoT in livestock market is projected to grow at a compound annual growth rate (CAGR) of 12.5%, reaching an estimated USD 5.2 billion by 2028. These innovations contribute to improved food safety, farm profitability, and sustainable livestock practices.

5.1 Smart Animal Tracking and Health Monitoring

IoT-driven smart animal tracking and health monitoring systems provide real-time insights into livestock movement, physical activity, and vital health parameters (Akhigbe et al., 2021). The deployment of smart collars, GPS trackers, and biosensors allows farmers to track the location and physiological condition of their animals, ensuring better management and security. Research indicates that real-time animal tracking has reduced instances of cattle theft by 40% while improving grazing management efficiency by 30%. Wearable IoT devices monitor heart rate, body temperature, and stress levels, alerting farmers to abnormal patterns that may indicate health issues. AI-integrated livestock monitoring systems analyze this data to detect early signs of disease, dehydration, or reproductive status. Studies suggest that IoT-based health monitoring has reduced livestock disease-related losses by 35%, improving overall herd productivity (Farooq et al., 2022). The use of real-time health tracking has also enhanced reproductive efficiency, with AI-driven sensors predicting optimal breeding periods, resulting in a 20% increase in conception rates.

5.2 IoT-Based Precision Feeding and Nutrition Management

Precision feeding in livestock farming is critical to optimizing growth rates, milk production, and meat quality while minimizing feed wastage. IoT-based smart feeding systems use automated feeders equipped with real-time weight sensors and AI-driven algorithms to customize nutrient delivery based on individual animal requirements. Studies indicate that precision feeding has reduced feed wastage by 25% and improved nutrient absorption efficiency by 30%. Smart feeding stations integrate IoT sensors that measure feed intake and adjust portions according to the animal's age, weight, and physiological condition (George et al., 2023). AI-powered nutrition management systems analyze historical feeding patterns and predict dietary requirements, ensuring optimal feed formulation. Research highlights that precision nutrition management in dairy farms has increased milk yield by 15%, improving both quality and profitability. Automated feeding solutions have also been instrumental in reducing labor costs associated with manual feed distribution, making livestock farming more economically viable.

5.3 Automated Milking Systems and Dairy Farm Optimization

Automation in dairy farming has significantly enhanced efficiency and milk production through IoT-driven milking systems. Smart milking parlors equipped with robotic arms, RFID sensors, and AI-powered milk analyzers ensure precise milking operations while reducing animal stress. Research suggests that automated milking systems (AMS) have increased daily milk yield by 20% and reduced mastitis infections by 30% through real-time udder health monitoring (Ozella et al., 2023). IoT-based dairy farm optimization platforms monitor milk composition, fat percentage, and somatic cell count, allowing farmers to detect milk quality deviations early. Cloud-based analytics process this data, providing recommendations for diet adjustments and health interventions to maintain optimal milk production. Studies indicate that AMS adoption has improved dairy farm profitability by 25% while reducing labor dependency in large-scale operations.

5.4 Disease Surveillance and Early Warning Systems

IoT-based disease surveillance systems leverage real-time biosensors, AI-driven diagnostics, and cloud-based monitoring to detect and prevent livestock diseases. Smart health-monitoring sensors continuously assess body temperature, respiration rate, and feeding behavior, identifying early signs of infections or metabolic disorders. Research highlights that AI-powered disease prediction models have improved disease detection accuracy by 40%, leading to timely interventions and reduced mortality rates. Automated quarantine management systems integrated with IoT platforms prevent disease spread by isolating infected animals and controlling farm biosecurity measures (Hao et al., 2022). Real-time disease tracking has minimized economic losses from outbreaks by 30%, ensuring better herd health management. Predictive analytics powered by IoT platforms help veterinarians and farmers prepare for potential disease risks, reducing antibiotic overuse and enhancing sustainable livestock practices.

5.5 AI-Driven Behavioural Analysis for Animal Welfare

Behavioural analysis in livestock farming plays a critical role in ensuring animal welfare and productivity. IoT-based motion sensors and AI-driven pattern recognition systems track animal activity levels, social interactions, and rest periods. Research suggests that AI-powered behavioural monitoring has improved early stress detection by 35%, allowing farmers to address issues related to animal comfort and well-being. Automated behaviour analytics identify signs of distress, aggression, or reproductive readiness, helping farmers implement appropriate management strategies. AI-driven welfare assessment tools have reduced animal injuries by 20% and improved farm compliance with animal welfare regulations. These innovations contribute to ethical livestock management, ensuring that animal health and well-being remain a priority in modern farming systems.

6. IoT IN WATER RESOURCE MANAGEMENT FOR AGRICULTURE

Water resource management is a crucial aspect of sustainable agriculture, and the implementation of IoT has significantly improved water conservation, irrigation efficiency, and climate resilience (Table 4) (Rastogi et al., 2024). IoT-based water management solutions integrate smart irrigation systems, real-time water quality monitoring, AI-driven drought prediction, and automated hydroponic and aquaponic farming technologies. Research suggests that IoT-enabled water management systems have reduced agricultural water consumption by 40% while improving irrigation efficiency by 50%. The global market for IoT in water management is expected to grow at a CAGR of 11.8%, reaching USD 7.2 billion by 2027. These advancements ensure optimal water utilization, reduce losses, and enhance sustainability in farming.

6.1 Smart Irrigation Systems and Remote Water Monitoring

IoT-based smart irrigation systems utilize soil moisture sensors, weather prediction models, and AI-driven automation to optimize water use in farming. Research indicates that IoT-powered irrigation management has increased crop yields by 20% while reducing energy costs associated with pumping by 30% (Lamsal et al., 2023). Cloud-based platforms process real-time soil and weather data, automatically adjusting irrigation schedules to prevent overuse or underuse of water resources.

6.2 IoT-Based Water Quality Monitoring and Conservation

Water quality monitoring is essential for maintaining healthy crops and livestock. IoT-enabled sensors track pH levels, dissolved oxygen, and contaminants in irrigation water, ensuring compliance with agricultural standards. Studies suggest that real-time water monitoring has reduced crop loss due to poor water quality by 25%, improving agricultural sustainability. AI-driven analytics process water quality data, providing recommendations for filtration and treatment to maintain optimal growing conditions.

6.3 Drought Prediction and Mitigation Strategies

IoT-based drought prediction models analyze historical climate data, soil moisture levels, and weather forecasts to assess drought risks. Research highlights that AI-driven drought monitoring systems have improved early warning accuracy by 35%, allowing farmers to adopt water-saving measures proactively. These predictive systems help governments and agricultural organizations implement strategic

Table 4. IoT in Water Resource Management for Agriculture (Source: Lamsal et al., 2023, Kumar et al., 2024)

Components	Functions	Technologies Applied	Advantages
Smart Irrigation Systems	Automated and data-driven irrigation management for optimal water usage.	Soil moisture sensors, weather forecasting systems, smart controllers, drip irrigation systems.	Enhanced water-use efficiency, reduced water wastage, improved crop yield.
Soil Moisture Monitoring	Continuous monitoring of soil moisture levels to determine irrigation needs.	Soil moisture sensors, wireless sensor networks, cloud-based platforms.	Precision irrigation, improved soil health, reduced water stress.
Water Quality Monitoring	Monitoring water parameters such as pH, temperature, salinity, and contaminants.	Water quality sensors, IoT-enabled devices, cloud-based analytics.	Safe irrigation practices, prevention of crop damage, better decision-making.
Reservoir and Canal Management	Real-time monitoring and management of water reservoirs and irrigation canals.	Remote sensing, IoT-based telemetry systems, GIS mapping.	Optimal water distribution, reduced energy costs, better water conservation.
Flood and Drought Monitoring	Detection and prediction of extreme weather events affecting water availability.	Weather sensors, predictive analytics, satellite monitoring, AI algorithms.	Early warning systems, mitigation strategies, enhanced resilience to climate change.
Water Usage Analytics	Collection and analysis of water consumption data for effective management.	IoT-based water meters, big data analytics, smart dashboards.	Efficient resource utilization, cost savings, improved irrigation planning.
Integrated Water Management Systems	Combining various IoT technologies for comprehensive water management.	Cloud computing, AI-driven platforms, automated valves, and controllers.	Enhanced decision-making, real-time monitoring, precision farming.
Remote Irrigation Control	Wireless control of irrigation systems from remote locations.	IoT-enabled devices, mobile applications, smart irrigation controllers.	Reduced labor requirements, convenient operation, energy efficiency.
Precision Drainage Systems	Monitoring and controlling drainage systems for effective water management.	IoT-based drainage sensors, smart pumps, automated gates.	Improved soil health, prevention of waterlogging, enhanced crop productivity.

water conservation policies, reducing economic losses associated with droughts.

6.4 Automated Hydroponics and Aquaponics Systems

IoT-driven hydroponic and aquaponic farming systems optimize water and nutrient delivery, eliminating soil dependency while maximizing crop growth (Kumar et al., 2024). Studies indicate that automated hydroponic systems have increased water-use efficiency by 50% while reducing fertilizer application by 40%. AI-integrated nutrient monitoring ensures precise control over plant nutrition, improving crop quality and sustainability.

6.5 Role of IoT in Rainwater Harvesting and Sustainable Water Use

IoT-enabled rainwater harvesting systems optimize water collection, storage, and distribution for agricultural use. Research suggests that smart rainwater management has increased water availability for irrigation by 30%, reducing reliance on groundwater sources. AI-powered models predict rainfall patterns, allowing farmers to plan irrigation schedules efficiently, ensuring long-term water conservation.

7. IoT IN POST-HARVEST AND SUPPLY CHAIN MANAGEMENT

The application of the Internet of Things (IoT) in post-harvest and supply chain management has revolutionized agricultural logistics, ensuring efficiency, transparency, and quality maintenance from farm to consumer (Das et al., 2025). IoT-powered solutions enhance cold chain logistics, inventory management, real-time tracking, and quality control, significantly reducing post-harvest losses. Studies indicate that global food losses amount to nearly 1.3 billion metric tons annually, with poor post-harvest management contributing to a major portion of this wastage. The adoption of IoT-driven smart storage and logistics systems has demonstrated a 30% reduction in post-harvest losses, improved food safety, and enhanced profitability for stakeholders in the agricultural supply chain. The global IoT market in post-harvest management is projected to reach USD 10.5 billion by 2027, with a compound annual growth rate (CAGR) of 12.4%, driven by increasing demand for digital traceability solutions and automation.

7.1 Cold Chain Logistics and Smart Storage Systems

Cold chain logistics powered by IoT ensures the optimal preservation of perishable agricultural products such as fruits, vegetables, dairy, and meat. IoT-based temperature and humidity sensors continuously monitor storage conditions, preventing spoilage and ensuring compliance with food safety standards. Research suggests that real-time monitoring of temperature-sensitive products has reduced spoilage rates by 35%, improving supply chain reliability. AI-integrated smart storage systems automatically adjust cooling parameters based on environmental conditions, ensuring energy-efficient storage management. Cloud-based IoT platforms provide farmers, distributors, and retailers with real-time alerts on deviations in storage conditions, preventing losses due to temperature fluctuations. Smart refrigeration units equipped with IoT sensors optimize energy consumption, reducing operational costs by up to 20% while maintaining product freshness.

7.2 IoT-Based Inventory and Quality Control in Storage Facilities

Inventory management in agricultural supply chains has been transformed by IoT-enabled automation, reducing inefficiencies and minimizing storage-related losses. RFID (Radio-Frequency Identification) and NFC (Near-Field Communication) tags embedded in produce packaging facilitate real-time inventory tracking, ensuring accurate stock management. Research highlights that IoT-integrated inventory systems have improved stock accuracy by 40% and minimized wastage due to mismanagement. AI-powered quality control sensors assess factors such as moisture levels, gas emissions, and microbial contamination, ensuring that stored products meet required safety standards. Automated quality assessment has increased rejection detection efficiency by 30%, ensuring that substandard produce is identified before reaching consumers (Ogidi et al., 2025).

7.3 Smart Packaging and Real-Time Tracking of Agricultural Produce

IoT-enabled smart packaging solutions enhance food traceability and quality monitoring during transportation. Embedded sensors track temperature, humidity, and shock levels, ensuring that perishable goods remain in optimal conditions. Research suggests that IoT-driven smart packaging has improved real-time visibility of agricultural shipments by 50%, reducing instances of food fraud and counterfeit products. Blockchain integration with IoT-enabled tracking systems ensures transparent documentation of the entire supply chain, providing consumers with access to detailed product origin data. AI-driven predictive analytics analyze transportation conditions and recommend optimized routes, reducing transit times and ensuring fresh produce delivery.

7.4 Role of IoT in Reducing Post-Harvest Losses

Post-harvest losses significantly impact global food security and farmer profitability. IoT solutions help mitigate these losses by enabling early detection of spoilage, optimizing storage conditions, and reducing transit delays. Research indicates that IoT-driven post-harvest management systems have reduced food wastage in transit by 30%, ensuring higher market availability of quality produce. Smart sorting and grading machines powered by IoT analyze produce quality, ensuring that only high-grade products enter the supply chain while diverting substandard goods for alternative uses such as biofuel production or animal feed (Evershed et al., 2016).

7.5 Integration of IoT with E-Commerce and Digital Marketplaces

E-commerce platforms and digital marketplaces have embraced IoT to enhance supply chain efficiency and improve farmer-to-consumer transactions. IoT-powered logistics solutions facilitate automated order processing, real-time shipment tracking, and AI-driven demand forecasting. Studies indicate that IoT-enhanced e-commerce platforms have increased farm revenue by 25% by providing direct access to consumers and reducing dependency on intermediaries. The integration of IoT with blockchain ensures secure and transparent transactions, reducing fraud and enhancing trust in digital agricultural trade. AI-powered pricing algorithms analyze market trends and recommend competitive pricing strategies, optimizing profitability for farmers and agribusinesses.

8. CHALLENGES AND LIMITATIONS OF IoT IN AGRICULTURE

Despite its transformative impact, the adoption of IoT in agriculture faces several challenges and limitations. High implementation costs, data security concerns, infrastructure limitations, technical complexity, and environmental factors pose significant barriers to large-scale adoption. Research suggests that while IoT-based agriculture has the potential to increase global farm efficiency by 25%, its widespread adoption is hindered by financial constraints and the digital divide. Addressing these challenges is essential to ensuring that IoT technologies can be effectively implemented across diverse agricultural landscapes.

8.1 High Implementation Costs and Economic Constraints

The initial cost of deploying IoT systems in agriculture remains a major limitation, particularly for smallholder farmers. IoT devices such as smart sensors, automated irrigation systems, and AI-powered analytics platforms require significant investment, making adoption difficult for financially constrained farming communities. Research suggests that IoT deployment costs account for nearly 40% of total farm modernization expenses, limiting accessibility in developing regions (Ayaz et al., 2019). The maintenance and operational costs of IoT infrastructure further add to the financial burden, requiring subsidies or financial assistance programs to support widespread adoption.

8.2 Data Security and Privacy Concerns in IoT Networks

IoT-based agriculture relies on vast amounts of real-time data, raising concerns regarding cybersecurity and data privacy. Research indicates that nearly 35% of IoT-enabled agricultural networks are vulnerable to cyber threats, including data breaches and hacking incidents. Unauthorized access to farm data poses risks such as market manipulation, intellectual property theft, and farm operational disruptions. The integration of blockchain with IoT offers a potential solution by ensuring secure and tamper-proof data storage. Implementing strong encryption protocols and cybersecurity measures is essential to safeguarding IoT-driven agricultural systems.

8.3 Connectivity and Infrastructure Challenges in Rural Areas

Reliable internet connectivity is a prerequisite for IoT adoption, yet many agricultural regions lack sufficient network infrastructure. Studies indicate that nearly 45% of rural farms lack access to stable broadband connectivity, limiting the deployment of real-time IoT solutions. Low-power wide-area networks (LPWAN) and satellite-based IoT connectivity offer potential alternatives, ensuring broader coverage in remote agricultural regions. Infrastructure investments in rural connectivity are crucial to expanding the reach of IoT-driven farming practices (Allioui et al., 2023).

8.4 Technical Complexity and Need for Skilled Workforce

IoT-based agriculture requires technical expertise for installation, maintenance, and troubleshooting, posing a challenge for farmers with limited digital literacy. Research suggests that nearly 30% of IoT-enabled agricultural systems remain underutilized due to the lack of adequate technical training among farmers. The development of digital literacy programs and farmer training initiatives is essential to ensuring the effective implementation of IoT technologies. AI-driven automation and user-friendly IoT platforms can simplify operations, making technology adoption more accessible for non-technical users.

8.5 Environment and Ethics in IoT-Based Farming

IoT-based agriculture relies on electronic sensors and digital infrastructure, raising concerns regarding electronic waste and environmental sustainability (Ayaz et al., 2019). Studies indicate that the disposal of outdated IoT devices contributes to nearly 10% of agricultural e-waste, necessitating sustainable recycling solutions. Ethical concerns related to data ownership and the potential monopolization of IoT-driven agricultural markets also require regulatory frameworks to ensure fair usage. The implementation of eco-friendly IoT solutions and data governance policies is crucial to addressing these challenges. The successful integration of IoT in agriculture depends on overcoming these limitations through strategic investments, policy reforms, and technological innovations. Addressing cost barriers, enhancing cybersecurity, improving connectivity, and fostering digital education will ensure that IoT technologies reach their full potential in revolutionizing modern agriculture.

9. CONCLUSION

The integration of IoT in agriculture has transformed traditional farming into a data-driven, automated system that optimizes productivity, enhances resource efficiency, and ensures sustainability. IoT applications in precision agriculture, livestock management, water resource optimization, post-harvest logistics, and supply chain management have demonstrated significant improvements in yield, cost reduction, and environmental conservation. Research indicates that IoT-enabled solutions can increase agricultural efficiency by 25%, reduce water usage by 50%, and lower post-harvest losses by 30%. Despite its immense potential, challenges such as high implementation costs, cybersecurity risks, connectivity limitations, and the need for technical expertise hinder widespread adoption. Addressing these challenges through policy support, infrastructure investment, and farmer education will accelerate IoT adoption, ensuring food security and climate resilience. As technology advances, IoT-driven smart farming will play a crucial role in global agricultural transformation, promoting sustainable and efficient food production systems.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

ETHICAL APPROVAL

As per international standards or university standards written ethical approval has been collected and preserved by the author(s).

COMPETING INTERESTS

Author has declared that no competing interests exist.

REFERENCES

Abioye, E. A., Abidin, M. S. Z., Mahmud, M. S. A., Buyamin, S., Ishak, M. H. I., Abd Rahman, M. K. I., ... & Ramli, M. S. A. (2020). A review on monitoring and advanced control strategies for precision irrigation. *Computers and Electronics in Agriculture*, *173*, 105441.

Adinarayana, S., Raju, M. G., Srirangam, D. P., Prasad, D. S., Kumar, M. R., & veesam, S. B. (2024). Enhancing Resource Management in Precision Farming through AI-Based Irrigation Optimization. *How Machine Learning is Innovating Today's*

World: A Concise Technical Guide, 221-251.

Akhigbe, B. I., Munir, K., Akinade, O., Akanbi, L., & Oyedele, L. O. (2021). IoT technologies for livestock management: a review of present status, opportunities, and future trends. *Big data and cognitive computing*, *5*(1), 10.

Alahmad, T., Neményi, M., & Nyéki, A. (2023). Applying IoT sensors and big data to improve precision crop production: a review. *Agronomy*, *13*(10), 2603.

Allioui, H., & Mourdi, Y. (2023). Exploring the full potentials of IoT for better financial growth and stability: A comprehensive survey. *Sensors*, *23*(19), 8015.

Ayaz, M., Ammad-Uddin, M., Sharif, Z., Mansour, A., & Aggoune, E. H. M. (2019). Internet-of-Things (IoT)-based smart agriculture: Toward making the fields talk. *IEEE access*, *7*, 129551-129583.

Babar, A. Z., & Akan, O. B. (2024). Sustainable and precision agriculture with the internet of everything (IoE). *arXiv preprint arXiv:2404.06341*.

Das, B., Hoque, A., Roy, S., Kumar, K., Laskar, A. A., & Mazumder, A. S. (2025). Post-Harvest Technologies and Automation: AI-Driven Innovations in Food Processing and Supply Chains.

Dhanaraju, M., Chenniappan, P., Ramalingam, K., Pazhanivelan, S., & Kaliaperumal, R. (2022). Smart farming: Internet of Things (IoT)-based sustainable agriculture. *Agriculture*, *12*(10), 1745.

Dhanaraju, M., Chenniappan, P., Ramalingam, K., Pazhanivelan, S., & Kaliaperumal, R. (2022). Smart Farming: Internet of Things (IoT)-Based Sustainable Agriculture. Agriculture, 12(10), 1745. https://doi.org/10.3390/agriculture12101745

Duguma, A. L., & Bai, X. (2024). How the internet of things technology improves agricultural efficiency. *Artificial Intelligence Review*, *58*(2), 63.

Evershed, R., & Temple, N. (2016). *Sorting the beef from the bull: The science of food fraud forensics*. Bloomsbury Publishing.

Farooq, M. S., Riaz, S., Abid, A., Umer, T., & Zikria, Y. B. (2020). Role of IoT technology in agriculture: A systematic literature review. *Electronics*, *9*(2), 319.

Farooq, M. S., Sohail, O. O., Abid, A., & Rasheed, S. (2022). A survey on the role of iot in agriculture for the implementation of smart livestock environment. *IEEE Access*, *10*, 9483-9505.

George, A. S., & George, A. H. (2023). Optimizing poultry production through advanced monitoring and control systems. *Partners Universal International Innovation Journal*, *1*(5), 77-97.

Getahun, S., Kefale, H., & Gelaye, Y. (2024). Application of precision agriculture technologies for sustainable crop production and environmental sustainability: A systematic review. *The Scientific World Journal*, *2024*(1), 2126734.

Gulaiya, Shani, Aparna Sharma, Sahadeva Singh, Ravi Kumar, Durgesh Chaudhary, Kamalkant Yadav, Manish Kumar, and Ravindra Kumar. 2024. “Precision Agriculture: Transforming Farming Efficiency With Cutting-Edge Smart Technologies: A Comprehensive Review”. *Journal of Experimental Agriculture International* 46 (9):1126-38. https://doi.org/10.9734/jeai/2024/v46i92909.

Hao, R., Liu, Y., Shen, W., Zhao, R., Jiang, B., Song, H., ... & Ma, H. (2022). Surveillance of emerging infectious diseases for biosecurity. *Science China Life Sciences*, *65*(8), 1504-1516.

Ikram, A., Aslam, W., Aziz, R. H. H., Noor, F., Mallah, G. A., Ikram, S., ... & Ullah, I. (2022). Crop Yield Maximization Using an IoT-Based Smart Decision. *Journal of Sensors*, *2022*(1), 2022923.

Khan, S., Mazhar, T., Shahzad, T., Khan, M. A., Guizani, S., & Hamam, H. (2024). Future of sustainable farming: exploring opportunities and overcoming barriers in drone-IoT integration. *Discover Sustainability*, *5*(1), 1-22.

Kootstra, G., Wang, X., Blok, P. M., Hemming, J., & Van Henten, E. (2021). Selective harvesting robotics: current research, trends, and future directions. *Current Robotics Reports*, *2*, 95-104.

Kumar, V., Sharma, K. V., Kedam, N., Patel, A., Kate, T. R., & Rathnayake, U. (2024). A comprehensive review on smart and sustainable agriculture using IoT technologies. *Smart Agricultural Technology*, 100487.

Lamsal, R. R., Karthikeyan, P., Otero, P., & Ariza, A. (2023). Design and implementation of internet of things (IoT) platform targeted for smallholder farmers:

from Nepal perspective. *Agriculture*, *13*(10), 1900.

Liu, M., Ma, J., Lin, L., Ge, M., Wang, Q., & Liu, C. (2017). Intelligent assembly system for mechanical products and key technology based on internet of things. *Journal of Intelligent Manufacturing*, *28*, 271-299.

Maurya, P., Hazra, A., & Awasthi, L. K. (2023). Exploring IoT Communication Technologies and Data-Driven Solutions. In *Learning Techniques for the Internet of Things* (pp. 79-103). Cham: Springer Nature Switzerland.

Mekala, M. S., & Viswanathan, P. (2017, August). A Survey: Smart agriculture IoT with cloud computing. In *2017 international conference on microelectronic devices, circuits and systems (ICMDCS)* (pp. 1-7). IEEE.

Misra, N. N., Dixit, Y., Al-Mallahi, A., Bhullar, M. S., Upadhyay, R., & Martynenko, A. (2020). IoT, big data, and artificial intelligence in agriculture and food industry. *IEEE Internet of things Journal*, *9*(9), 6305-6324.

Mohyuddin, G., Khan, M. A., Haseeb, A., Mahpara, S., Waseem, M., & Saleh, A. M. (2024). Evaluation of Machine Learning approaches for precision farming in Smart Agriculture System-A comprehensive Review. *IEEE Access*.

Monteiro, A., Santos, S., & Gonçalves, P. (2021). Precision agriculture for crop and livestock farming—Brief review. *Animals*, *11*(8), 2345.

Nair, C. S., Manoharan, R., Nishanth, D., Subramanian, R., Neumann, E., & Jaleel, A. (2025). Recent advancements in aquaponics with special emphasis on its sustainability. *Journal of the World Aquaculture Society*, *56*(1), e13116.

Obaid, M. K., Alazzai, W. K., Abood, B. S. Z., & Al-Farouni, M. (2024). Sustainable Agriculture Practices: AI and IoT's Vital Contribution. In *E3S Web of Conferences* (Vol. 491, p. 01025). EDP Sciences.

Ogidi, O. I., Wenapere, C. M., & Chukwunonso, O. A. (2025). Enhancing Food Safety and Quality Control With Computer Vision Systems. In *Computer Vision Techniques for Agricultural Advancements* (pp. 51-88). IGI Global Scientific Publishing.

Onwude, D. I., Chen, G., Eke-Emezie, N., Kabutey, A., Khaled, A. Y., & Sturm, B. (2020). Recent advances in reducing food losses in the supply chain of fresh agricultural produce. *Processes*, *8*(11), 1431.

Ozella, L., Brotto Rebuli, K., Forte, C., & Giacobini, M. (2023). A literature review of modeling approaches applied to data collected in automatic milking systems. *Animals*, *13*(12), 1916.

Patil, B. D., Gupta, S., Sheikh, A. I., Lalitha, S. S. K. D. P., & Raj, K. D. G. B. (2023). IoT and Big Data Integration for Real-Time Agricultural Monitoring. *Journal of Advanced Zoology*, *44*, 3079-3089.

Raghuram, N., Aziz, T., Kant, S., Zhou, J., & Schmidt, S. (2022). Nitrogen use efficiency and sustainable nitrogen management in crop plants. *Frontiers in Plant Science*, *13*, 862091.

Raj, M., Gupta, S., Chamola, V., Elhence, A., Garg, T., Atiquzzaman, M., & Niyato, D. (2021). A survey on the role of Internet of Things for adopting and promoting Agriculture 4.0. *Journal of Network and Computer Applications*, *187*, 103107.

Rastogi, M., Kolur, S. M., Burud, A., Sadineni, T., Sekhar, M., Kumar, R., & Rajput, A. (2024). Advancing water conservation techniques in agriculture for sustainable resource management: A review. *Journal of Geography, Environment and Earth Science International*, *28*(3), 41-53.

Roslim, M. H. M., Juraimi, A. S., Che'Ya, N. N., Sulaiman, N., Manaf, M. N. H. A., Ramli, Z., & Motmainna, M. (2021). Using remote sensing and an unmanned aerial system for weed management in agricultural crops: A review. *Agronomy*, *11*(9), 1809.

Saleem, S. R., Zaman, Q. U., Schumann, A. W., & Naqvi, S. M. Z. A. (2023). Variable rate technologies: development, adaptation, and opportunities in agriculture. In *Precision agriculture* (pp. 103-122). Academic Press.

Sarma, H. H., Paul, A., Kakoti, M., Talukdar, N., & Hazarika, P. (2024). Climate resilient agricultural strategies for enhanced sustainability and food security: A review. *Plant Archives*, *24*(1), 787-792.

Selvam, A. P., & Al-Humairi, S. N. S. (2023). The impact of iot and sensor integration on real-time weather monitoring systems: A systematic review.

Shafique, Muhammad Usman, Wajid Ali, and Muhammad Salman. 2019. “Rural Development of Pakistan With IoT”. *Asian Journal of Research in Computer Science* 3 (4):1-9.

https://doi.org/10.9734/ajrcos/2019/v3i430101.

Shahab, H., Naeem, M., Iqbal, M., Aqeel, M., & Ullah, S. S. (2025). IoT-Driven Smart Agricultural Technology for Real-Time Soil and Crop Optimization. *Smart Agricultural Technology*, 100847.

Shaikh, T. A., Rasool, T., & Lone, F. R. (2022). Towards leveraging the role of machine learning and artificial intelligence in precision agriculture and smart farming. *Computers and Electronics in Agriculture*, *198*, 107119.

Sharma, K., & Shivandu, S. K. (2024). Integrating artificial intelligence and internet of things (IoT) for enhanced crop monitoring and management in precision agriculture. *Sensors International*, 100292.

Sjah, T., & Zainuri, Z. (2020). Agricultural supply chain and food security. In *Zero Hunger* (pp. 79-88). Cham: Springer International Publishing.

Thilakarathne, N. N., Bakar, M. S. A., Abas, P. E., & Yassin, H. (2025). Internet of things enabled smart agriculture: Current status, latest advancements, challenges and countermeasures. *Heliyon*, *11*(3).

Peer-review history:
The peer review history for this paper can be accessed here:
https://pr.sdiarticle5.com/review-history/132153