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Digital Agriculture and IoT-Based Farming Systems: A Comprehensive Review

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ABSTRACT

Digital agriculture and Internet of Things (IoT)-based farming systems represent a paradigm shift in modern agricultural practices, offering data-driven solutions to address global food security challenges. This comprehensive review examines the current state, key technologies, applications, and future prospects of digital agriculture with a focus on IoT-enabled smart farming systems. The integration of IoT sensors, artificial intelligence (AI), unmanned aerial vehicles (UAVs), big data analytics, blockchain technology, and cloud computing has transformed traditional farming into precision-oriented, resource-efficient operations. IoT-based systems enable real-time monitoring of soil moisture, crop health, weather conditions, and livestock welfare, facilitating informed decision-making and automated farm management. Studies have demonstrated that IoT-enabled precision agriculture can increase crop yields by up to 25%, reduce water consumption by 30%, and significantly lower input costs (Charania & Li, 2020). However, widespread adoption faces challenges including high initial investment costs, limited rural connectivity, data privacy concerns, digital literacy gaps, and interoperability issues. This review synthesizes findings from recent literature to provide a holistic understanding of how digital technologies are reshaping the agricultural landscape, particularly in developing countries, and identifies future research directions for sustainable smart farming.

Keywords: *Digital Agriculture; Internet of Things (IoT); Precision Farming; Smart Agriculture; Sustainable Crop Management.*

INTRODUCTION

Agriculture has been the backbone of human civilization for millennia, providing sustenance and economic stability to communities worldwide. However, the agricultural sector faces unprecedented challenges in the twenty-first century, driven by rapid population growth, climate change, resource depletion, and evolving consumer demands (Lipper et al., 2014).

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The United Nations Food and Agriculture Organization (FAO) estimates that global food production must increase by 60% by 2050 to sustain a projected world population of 9.7 billion people. Traditional farming methods, while effective for generations, are increasingly insufficient to meet these rising demands due to limitations in productivity, efficiency, and sustainability (Bogoviz et al., 2023). Digital agriculture, also referred to as Agriculture 4.0, represents the convergence of advanced digital technologies with agricultural practices to optimize farming operations, enhance productivity, and promote environmental sustainability (Maffezzoli et al., 2024). At its core, digital agriculture leverages the Internet of Things (IoT), artificial intelligence (AI), big data analytics, cloud computing, unmanned aerial vehicles (UAVs), blockchain technology, robotics, and Geographic Information Systems (GIS) to create interconnected, data-driven farming ecosystems (Javaid et al., 2022). The IoT serves as the foundational technology that connects physical devices, sensors, and machinery across the farm, enabling seamless data collection, transmission, and analysis in real time (Zhai et al., 2020).

The evolution of precision agriculture can be traced through distinct phases. Agriculture 3.0 introduced GPS technology, remote sensing, and GIS to gather data on soil conditions, crop health, and weather patterns (Latino et al., 2022). Agriculture 4.0, described as the digital revolution in agriculture, brought sophisticated IoT sensor networks, AI-powered analytics, drone-based monitoring, and variable rate technology (VRT) to the field (Zambon et al., 2019). More recently, Agriculture 5.0 has emerged with a human-centric approach, combining technology with human ingenuity and sustainable practices through advanced IoT, robotics, and collaborative human-machine systems (Islam et al., 2024; & Hurst & Spiegal, 2023).

Despite these technological advancements, significant barriers to adoption persist, particularly in low- and middle-income countries (LMICs). Over 150 million smallholder farmers in developing countries lack access to digital agricultural services, and the growth rate of digital agricultural solutions has slowed from 33% during 2012-2018 to just 9% during 2018-2022 (World Bank, 2025). This review paper aims to provide a comprehensive examination of digital agriculture and IoT-based farming systems, exploring their technological foundations, practical applications, benefits, challenges, and future directions.

2. Key Technologies in Digital Agriculture

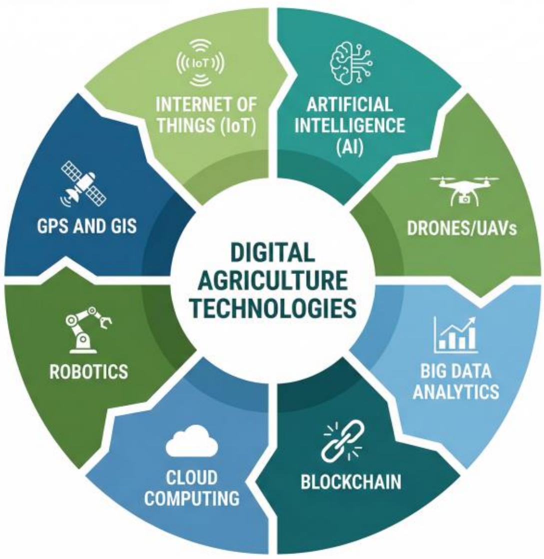

Figure1. Key Technologies Driving Digital Agriculture

2.1 Internet of Things (IoT) in Agriculture

The Internet of Things (IoT) serves as the foundation of smart agricultural technology, integrating all facets of intelligent systems across various agricultural practices (Abioye et al., 2023). IoT in agriculture involves deploying interconnected sensors, actuators, and devices throughout the farming environment to collect, transmit, and analyze real-time data on soil conditions, weather patterns, crop health, and livestock welfare. Key IoT communication solutions include wireless sensor networks (WSNs), Radio-Frequency Identification (RFID), Low Power Wide Area Networks (LoRaWAN), Zigbee, Bluetooth, and cellular networks that support interconnectivity among devices (Juwono et al., 2023; & Ku et al., 2023).

Smart sensors play a crucial role in precision agriculture by detecting environmental changes and transmitting information to central processors (Ullo & Sinha, 2021). These sensors are equipped with microprocessors that enable local data processing, autonomous decision-making, and direct communication with other devices via various wireless protocols (Yin et al., 2021). Soil sensors provide critical data on moisture levels, pH, temperature, nutrient content, and electrical conductivity, guiding decisions related to irrigation, fertilization, and planting (Roper et al., 2021). Plant health monitoring employs sensors including leaf sensors, chlorophyll fluorescence sensors, Normalized Difference Vegetation Index (NDVI) sensors, and hyperspectral sensors to assess crop condition (Li et al., 2021). Countries such as those in Europe, Australia, and the USA have embraced smart farming, alongside individual nations like Italy, Brazil, Ireland, and India (Frontiers, 2025).

2.2 Artificial Intelligence and Machine Learning

Artificial intelligence (AI) and machine learning (ML) are integral to transforming raw agricultural data into actionable insights. AI-powered predictive models analyze complex relationships between environmental variables, soil conditions, crop genetics, and historical performance to forecast crop yields with accuracy rates exceeding 90% (Omdena, 2025). Hybrid machine learning models, such as Random Forest Regressors and LightGBM, process massive datasets from satellite imagery, weather stations, soil sensor networks, and historical crop performance databases to generate precise predictions (Altalak et al., 2022).

Deep learning techniques, particularly convolutional neural networks (CNNs), have demonstrated remarkable capabilities in image-based crop disease detection and pest identification using UAV-collected imagery (Mukherjee et al., 2019). AI also powers decision support systems (DSS) that process data from multiple sources to provide farmers with optimized recommendations for irrigation scheduling, fertilizer application rates, pest management strategies, and harvest timing (Rahman et al., 2023). Explainable AI techniques such as SHAP (SHapley Additive exPlanations) and LIME (Local Interpretable Model-agnostic Explanations) are enhancing transparency in agricultural AI systems, helping farmers understand and trust the recommendations generated by machine learning models (Omdena, 2025).

2.3 Unmanned Aerial Vehicles (UAVs) and Remote Sensing

Drones equipped with multispectral, hyperspectral, RGB, and thermal cameras have revolutionized crop monitoring by providing high-resolution aerial imagery that enables rapid assessment of crop health, soil conditions, and pest outbreaks across large areas (Yang et al., 2017). UAV-based remote sensing offers significant advantages over traditional ground surveys, including faster coverage, higher spatial and temporal resolution, reduced labour requirements, and the ability to access difficult terrain (Joshi, 2025). Vegetation indices derived from drone imagery, such as NDVI and Normalized Difference Red Edge (NDRE), provide quantitative measures of crop vigour, biomass, and stress levels, enabling targeted interventions and variable rate applications (Ren et al., 2020). The integration of deep learning algorithms with UAV remote sensing data has further advanced capabilities in crop disease detection, yield estimation, and crop lodging assessment (Frontiers, 2024).

2.4 Big Data Analytics and Cloud Computing

The agricultural sector generates an enormous volume of data, with projections indicating that each farm will produce over two million data points per day by 2030 (BankBarn, 2023). Big data analytics platforms integrate satellite imagery, weather records, soil sensor readings, field activity logs, and machinery data to provide comprehensive farm management insights (EOS Data Analytics, 2025). Cloud computing infrastructure enables farmers to store, process, and access this data remotely, facilitating real-time decision-making regardless of geographic location. Precision agriculture platforms such as EOSDA Crop Monitoring combine satellite images, weather analytics, field activity records, and machinery readings in unified dashboards to deliver actionable insights for crop management (EOS Data Analytics, 2025). The market for machine learning in yield prediction alone is expected to grow at an annual rate of 26.5% through 2032.

2.5 Blockchain Technology in Agricultural Supply Chains

Blockchain technology has emerged as a transformative tool for enhancing transparency, traceability, and trust in agricultural supply chains (Zhao et al., 2022). By utilizing distributed ledger technology, blockchain enables all stakeholders in the supply chain to access immutable transaction records, creating a transparent and reliable source of data from farm to consumer (AgUnity, 2025). Blockchain-based traceability systems address critical challenges including food fraud prevention, rapid identification of contamination sources during foodborne illness outbreaks, and compliance with regulatory requirements. Innovative dual storage models combining blockchain with the InterPlanetary File System (IPFS) have been developed to alleviate storage pressures on the blockchain while maintaining data integrity and privacy (Zhao et al., 2022). Smart contracts deployed on platforms such as Ethereum automate the recording and verification of traceability information across production, logistics, processing, and sales stages of the agricultural supply chain.

3. IoT-Based Smart Farming Systems

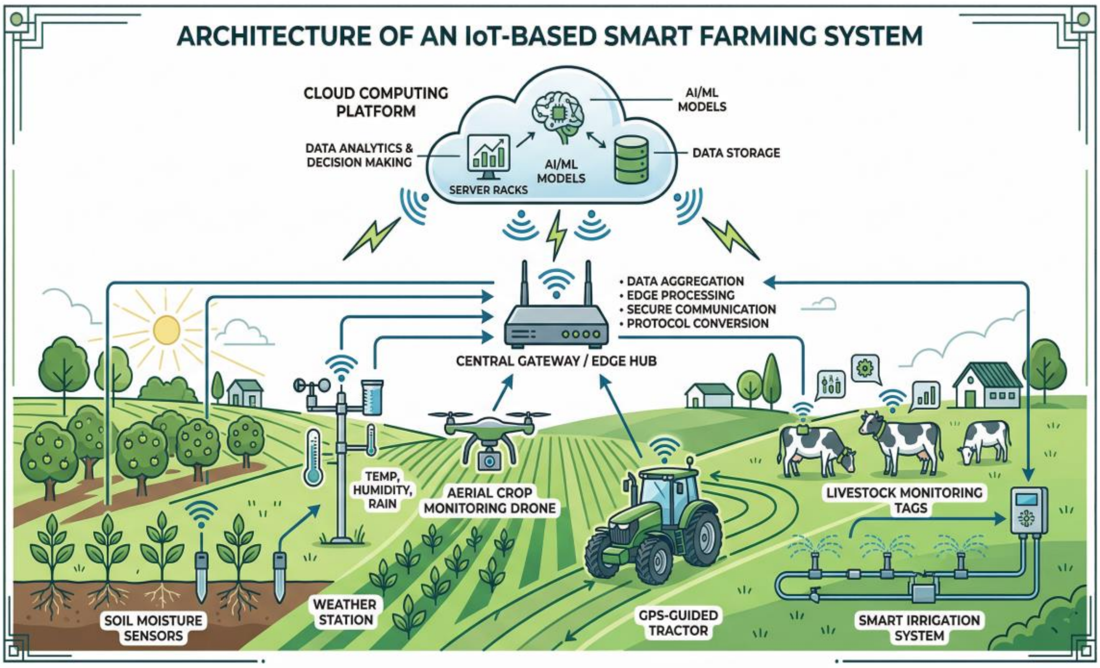

Figure2. Architecture of an IoT-Based Smart Farming System

3.1 Smart Irrigation Systems

IoT-based smart irrigation represents one of the most impactful applications of digital agriculture, addressing the critical challenge of water management in farming. These systems incorporate soil moisture sensors, weather sensors, humidity sensors, and temperature sensors that continuously monitor environmental conditions in real time (Kanimozhi & Vadivel, 2024). Data collected by these sensors is transmitted to cloud-based platforms where advanced algorithms and machine learning techniques analyse current soil moisture levels, weather forecasts, plant requirements, and local water restrictions to determine precise irrigation schedules (Bwambale et al., 2022).

Research by Abdel-Sattar et al. (2026) demonstrated that IoT-based smart irrigation systems can reduce water consumption by up to 47% while achieving a 43% increase in crop yield compared to traditional irrigation methods. Their study, employing an ESP32 microcontroller connected to multiple sensors including soil moisture (SEN0308), ultrasonic module (HC-SR04), temperature and humidity (DHT22), and light intensity (BH1750) sensors, showed that maintaining optimal soil moisture thresholds through automated monitoring significantly improved water use efficiency in lettuce production. The system also enabled remote monitoring and control through mobile applications, allowing farmers to manage irrigation from anywhere with internet connectivity.

3.2 Precision Crop Management

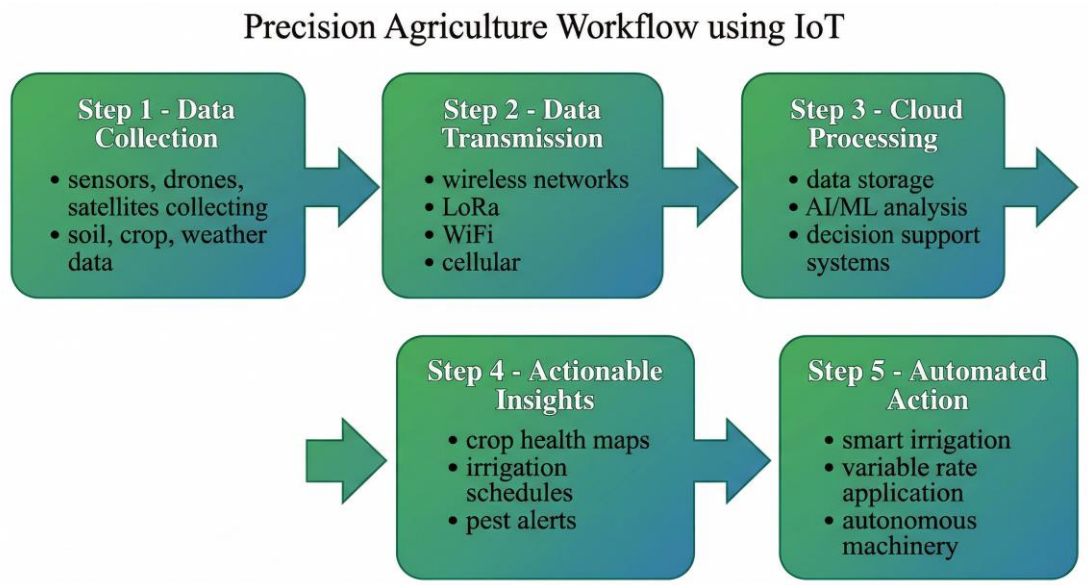

Figure3. Precision Agriculture Workflow Using IoT

Precision crop management utilizes IoT sensors, satellite imagery, and AI analytics to optimize every aspect of crop production from planting to harvest. Variable rate technology (VRT) enables tailored applications of fertilizers, pesticides, and water based on specific field characteristics identified through sensor data and spatial mapping (Tenreiro et al., 2023). GPS-guided autonomous machinery ensures accurate operation in planting, spraying, and harvesting, reducing waste and improving efficiency (Latino et al., 2022).

Real-time crop health monitoring through IoT sensor networks allows early detection of disease, pest infestations, and nutrient deficiencies before they cause significant damage. Plant stress sensors, including chlorophyll fluorescence and thermal imaging sensors, detect physiological changes in crops that precede visible symptoms, enabling preventive interventions (Rahman et al., 2024). This predictive approach to crop management has been shown to significantly reduce pesticide usage while maintaining or improving crop quality. Additionally, IoT-based precision nutrient management systems can calculate field-specific nutritional plans and estimate the carbon footprint of fertilizer applications, helping farmers optimize both productivity and environmental outcomes (Agmatix, 2025).

3.3 Livestock Monitoring and Management

IoT-based livestock monitoring systems use wearable devices, electronic tags, and environmental sensors to track animal health, behaviour, and welfare in real time. Monitoring devices attached to animal collars or ear tags track daily activities including feeding habits, movement patterns, rumination, and reproductive cycles (Frontiers, 2025). Environmental sensors in barns and pastures monitor temperature, humidity, air quality, and other conditions that affect animal welfare and productivity. Smart feeding systems integrated with IoT sensors optimize feed distribution based on individual animal requirements, reducing waste and improving nutrition.

Automated milking systems in dairy operations use sensors to monitor milk yield, quality, and animal health indicators during each milking session. These technologies collectively enable farmers to manage larger herds more effectively, detect health issues early through behavioural anomaly detection, and improve overall animal welfare and productivity. The CARI Journals (2025) report that IoT integration in livestock management has improved animal health tracking and traceability, contributing to a 25% increase in overall livestock management efficiency in pilot programmes across India, the Netherlands, and Brazil.

3.4 Smart Greenhouse Management

IoT-enabled greenhouse systems represent a controlled environment application of digital agriculture, where sensors monitor and regulate temperature, humidity, light intensity, carbon dioxide levels, and irrigation within enclosed growing spaces. Automated control systems adjust environmental parameters in real time to maintain optimal growing conditions, enabling year-round production regardless of external weather conditions (Abdel-Sattar et al., 2026). The integration of soilless cultivation techniques, including hydroponics and aeroponics, with IoT devices has further enhanced controlled environment agriculture, offering faster plant growth, improved yields, and superior nutrient absorption with minimal water usage (Science Direct, 2024). These systems are particularly relevant for urban and peri-urban farming where land availability is limited.

4. Applications and Global Case Studies

Table1. Global Applications of IoT in Digital Agriculture

Country/Region	Technology Applied	Application Area	Key Outcomes
Netherlands	IoT Sensors, AI, Robotics	Smart Greenhouses	30% water savings
India	Mobile Platforms, IoT	Crop Advisory Services	8-15% income increase
Brazil	Satellite Imaging, IoT	Precision Irrigation	30% water reduction
USA	Drones, AI, Big Data	Crop Monitoring	25% yield increase
China	UAVs, IoT Sensors	Pest and Weed Control	30% less pesticide use
Ethiopia	Digital Platforms	Farmer Advisory	Reach 30M farmers
Australia	IoT, Remote Sensing	Livestock Monitoring	Improved welfare tracking

Source: Compiled from Frontiers (2025); World Bank (2025); Digi International (2025); CARI Journals (2025)

Countries across the globe have adopted IoT-based farming solutions with varying degrees of success. The Netherlands leads in smart greenhouse technology, utilizing IoT sensors, AI, and robotics to achieve year-round production with significant reductions in water and energy use (Frontiers, 2025). In India, the integration of mobile platforms and IoT-based advisory services has improved farmer incomes and market access, though challenges with infrastructure and digital literacy persist (World Economic Forum, 2025). Brazil has successfully deployed satellite imaging and IoT-based precision irrigation systems, achieving up to 30% reduction in water consumption (EOS Data Analytics, 2025). The USA has leveraged drones, AI, and big data analytics for large-scale crop monitoring and yield prediction, achieving up to 25% increases in crop yields (Digi International, 2025).

The World Bank's Digital Agriculture Roadmap (DAR) initiative, launched in Ethiopia in 2025, aims to reach 30 million farmers, increase farmer income by 8% within five years, and unlock US$90 million for digital agriculture investments (World Bank, 2025). This programme has attracted interest from over 150 stakeholders, including 25 donors and 50 private sector companies, demonstrating the growing global commitment to digital agriculture transformation. Similar roadmaps are being developed for Kenya and other low- and middle-income countries to address the persistent digital divide in agriculture.

5. Challenges and Opportunities

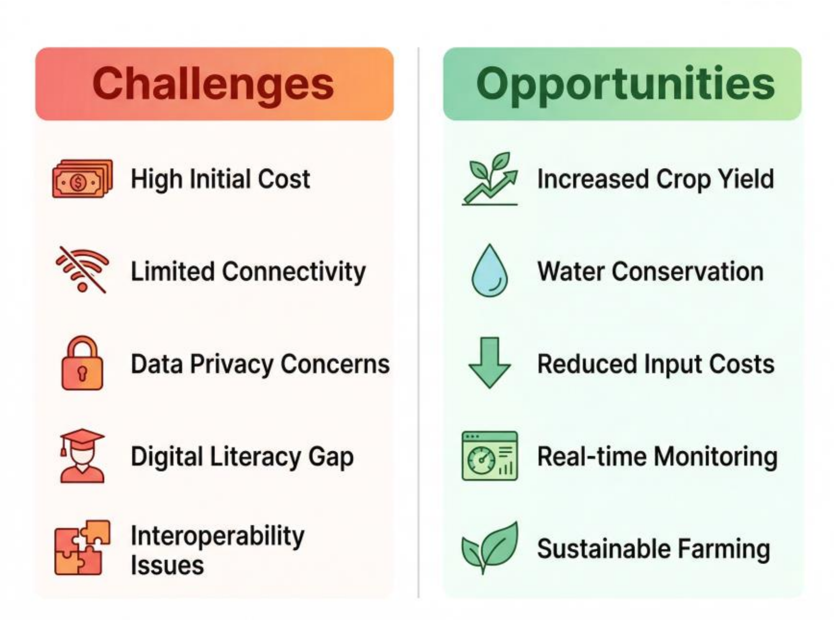

Figure4. Challenges and Opportunities in Digital Agriculture

5.1 Challenges

Despite the transformative potential of digital agriculture, several systemic challenges hinder widespread adoption, particularly among smallholder farmers in developing regions:

- **High Initial Investment Costs:** The acquisition of IoT sensors, drones, GPS-guided machinery, and associated software platforms requires substantial upfront capital investment that remains prohibitive for many smallholder farmers (Smidt & Jokonya, 2022). Smallholder farmers often lack access to credit and financial resources needed to adopt these technologies.
- **Limited Rural Connectivity:** Inadequate internet infrastructure in rural and remote agricultural areas hampers real-time data transfer and the effective use of cloud-based digital farming tools (Mazwane et al., 2022). Less than 10% of potential end-users in LMICs currently use digital agricultural tools (World Bank, 2025).
- **Data Privacy and Security Concerns:** The collection and storage of sensitive agricultural data raise concerns about

privacy, cybersecurity, and data ownership, particularly when proprietary farm data is shared with third-party platforms (Greenaria, 2024).

- **Digital Literacy Gaps:** Many farmers, particularly in developing regions, lack the technical skills required to effectively operate and maintain digital agricultural tools, creating a significant barrier to adoption (Abdulai et al., 2023).
- **Interoperability Issues:** The lack of standardized protocols and compatibility between different proprietary technologies hinders seamless integration of digital farming solutions across platforms and devices (FarmNest, 2026).

5.2 Opportunities

The opportunities presented by digital agriculture are vast and continue to expand with technological advancement:

- **Enhanced Resource Efficiency:** IoT-based precision agriculture enables optimized use of water, fertilizers, and pesticides, with studies reporting water savings of 30-47% and yield increases of 25-43% (Abdel-Sattar et al., 2026; & Digi International, 2025).
- **Climate Adaptation:** AI-powered predictive analytics help farmers adapt to changing climate conditions by providing real-time weather forecasts, crop selection recommendations, and early warning systems for agricultural disruptions (Gemtou et al., 2024).
- **Improved Market Access:** Digital platforms and blockchain-based supply chain systems connect farmers directly to markets, reducing intermediaries and improving transparency in pricing and product traceability (AgUnity, 2025).
- **Sustainable Agriculture:** Precision agriculture technologies reduce carbon footprints by decreasing fertilizer and pesticide applications, improving soil health, and enhancing biodiversity through targeted interventions (Fraser & Campbell, 2019; & Farooqui et al., 2024).
- **Economic Empowerment:** Data-driven decision-making reduces economic uncertainty by up to 40%, enabling farmers to make informed financial decisions regarding resource allocation, crop insurance, and loan negotiations (Omdena, 2025).

6. Future Perspectives

The future of digital agriculture lies in the continued convergence and maturation of multiple technology streams. Agriculture 5.0, with its emphasis on human-machine collaboration, represents the next frontier where advanced IoT networks, robotics, and AI work alongside farmers to create resilient, sustainable agricultural systems (da Silveira & Amaral, 2022; & Ross & Maynard, 2021). Key future trends include the development of integrated platforms capable of managing all crop and livestock types through unified IoT ecosystems, and the adoption of edge computing to reduce latency and bandwidth requirements in connectivity-limited areas (Mansoor & Chung, 2024).

The integration of multi-omics data analysis, combining genomics, proteomics, and metabolomics with IoT sensor data, will enable unprecedented precision in crop management, breeding programmes, and pest resistance development (Abioye et al., 2023). Autonomous agricultural systems, including self-driving tractors, robotic harvesters, and drone swarms for crop spraying, will become increasingly prevalent as AI and robotics technologies mature. Furthermore, the proliferation of 5G networks and satellite-based internet services, such as Starlink, will address connectivity challenges in rural areas, expanding the reach of digital agriculture to underserved farming communities globally.

Explainable AI (XAI) techniques will enhance transparency in agricultural decision support systems, building farmer trust in technology-generated recommendations. The development of affordable, modular, and open-source IoT solutions tailored to smallholder farming contexts will be critical for democratizing access to digital agriculture technologies in developing countries. National digital agriculture roadmaps, as pioneered by the World Bank in Ethiopia and Kenya, will provide frameworks for coordinated investment, policy development, and stakeholder collaboration to accelerate the digital transformation of agriculture worldwide.

CONCLUSION

Digital agriculture and IoT-based farming systems represent a transformative force in global food production, offering intelligent, data-driven solutions to the complex challenges facing modern agriculture. This comprehensive review has examined the key technologies underpinning digital agriculture, including IoT sensors, artificial intelligence, UAVs, big data analytics, blockchain, and cloud computing, and demonstrated their diverse applications in smart irrigation, precision crop management, livestock monitoring, and supply chain traceability.

The evidence presented in this review clearly demonstrates the significant benefits of IoT-enabled farming, including substantial improvements in crop yields (up to 25%), dramatic reductions in water consumption (30-47%), decreased pesticide usage (up to 30%), and enhanced supply chain transparency through blockchain technology. Global case studies from the Netherlands, India, Brazil, USA, China, Ethiopia, and Australia illustrate the versatility and scalability of these technologies across different agricultural contexts and scales of operation.

However, realizing the full potential of digital agriculture requires addressing persistent challenges related to high initial costs, rural connectivity gaps, data privacy concerns, digital literacy deficits, and technology interoperability. These barriers disproportionately affect smallholder farmers in developing countries, who represent the majority of the global agricultural workforce. Multi-stakeholder collaboration involving governments, technology developers, research institutions, and farmer organizations is essential to creating supportive policy frameworks, investing in rural digital infrastructure, and developing affordable, user-friendly digital tools tailored to local contexts.

Looking ahead, the convergence of Agriculture 5.0 principles with emerging technologies such as edge computing, 5G connectivity, autonomous systems, explainable AI, and multi-omics integration promises to further revolutionize agricultural practices. The path toward sustainable, climate-resilient, and food-secure agriculture increasingly depends on the successful democratization of digital technologies, ensuring that the benefits of the digital agricultural revolution reach farmers of all scales and regions. Continued investment in research, development, and capacity building will be crucial to harnessing the full transformative potential of digital agriculture and IoT-based farming systems for global food security and environmental sustainability.

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All authors participated in drafting, revising, and approving the manuscript.

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