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Review Article

Internet of Things (IoT) in Smart Agriculture: Innovations, Applications and Future Prospects

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ABSTRACT

The Internet of Things (IoT) has emerged as a transformative technology in smart agriculture, enabling data-driven and precision farming practices. By integrating sensors, drones, wireless communication, cloud computing, and artificial intelligence, IoT facilitates real-time monitoring of soil, crops, weather, irrigation, and livestock health. These innovations improve resource efficiency, enhance productivity, reduce operational costs, and promote sustainable agricultural practices. IoT-based systems also support predictive analytics, automated decision-making, and early detection of diseases and environmental stresses. This review highlights recent advancements, practical applications, key challenges, and future prospects of IoT in agriculture, emphasizing its potential to strengthen food security and climate-resilient farming worldwide.

Keywords: *Internet of Things; smart agriculture; precision farming; wireless sensor networks; sustainable agriculture.*

INTRODUCTION

Agriculture is the backbone of global food security, yet it faces unprecedented pressure from a growing world population, climate variability, shrinking arable land, and dwindling freshwater resources. The Food and Agriculture Organization projected that food production must increase by nearly 70 percent by 2050 to meet projected demand (FAO, 2017). Traditional farming methods—reliant on intuition, fixed schedules, and uniform input application—are increasingly inadequate to confront these challenges. Against this backdrop, the Internet of Things (IoT) has emerged as one of the most promising technological paradigms for reshaping agriculture into a data-driven, precision-oriented enterprise (Qazi et al., 2022).

IoT in agriculture, often referred to as Agriculture 4.0 or smart farming, refers to the deployment of interconnected sensors, actuators, communication networks, and cloud-based analytics that collect and process information from farms in real time.

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As Pereira et al. (2020) observed, the rapid proliferation of low-cost sensors, miniaturised microcontrollers, and wireless protocols has made IoT economically and technically feasible for a wide range of agricultural use cases. Ramalingam et al. (2022) further noted that the integration of IoT with cloud computing, big data analytics, robotics, and artificial intelligence is rapidly transforming conventional approaches into intelligent agricultural ecosystems.

The rationale for synthesising IoT advances in agriculture is grounded in the convergence of three contemporary imperatives: producing more food on a fixed land base, conserving water and soil resources, and adapting to climate-induced volatility. Tzounis et al. (2017) emphasised that the connected farm represents not merely a technological upgrade but a paradigm shift in how knowledge flows between field and decision maker. By summarising and contextualising the state of the art up to 2022, this paper aims to serve as a reference for researchers, agronomists, policy makers, and students working at the intersection of agriculture and digital technology.

2. Architecture of IoT in Smart Agriculture

Most agricultural IoT systems are described using a four-layer architecture comprising the perception, network, processing, and application layers (Abid et al., 2020; & Khanna & Kaur, 2019). The perception layer consists of physical sensors and actuators that capture environmental and biological parameters—soil moisture, temperature, humidity, pH, electrical conductivity, leaf wetness, ammonia levels, animal biometrics, and crop imagery—as well as GPS trackers, RFID tags, and unmanned aerial vehicles (UAVs).

The network layer is responsible for transmitting acquired data from sensor nodes to processing platforms. Multiple wireless protocols coexist, each balancing range, bandwidth, energy consumption, and cost. Short-range protocols such as ZigBee, Bluetooth Low Energy, and Wi-Fi dominate indoor and greenhouse applications, while low-power wide-area network (LPWAN) protocols such as LoRaWAN, Sigfox, and NB-IoT have been increasingly adopted in open-field deployments owing to their long range and low power demands (Kumar et al., 2021; & Tzounis et al., 2017). The processing layer hosts cloud or edge servers that perform data fusion, storage, and analytics, often leveraging machine-learning models for prediction and decision support. Finally, the application layer delivers actionable insights to farmers through dashboards, mobile apps, and farm-management software (Ramalingam et al., 2022).

It is worth emphasising that this layered representation is conceptual rather than rigid. In practical deployments, the boundaries between layers often blur—edge gateways may perform part of the processing role, and certain sensor nodes may host lightweight machine-learning inference. Khanna and Kaur (2019) noted that the choice of architecture depends strongly on farm size, crop value, and the type of decisions that need to be supported. For a smallholder vegetable farm, a simple two-tier system with a Wi-Fi gateway and a smartphone app may suffice, whereas a large commercial vineyard or dairy operation may require multi-tier, hybrid cloud-edge architectures with redundant communication paths.

3. Enabling Technologies and Innovations

Several technological innovations underpin the rapid maturation of agricultural IoT. Wireless Sensor Networks (WSNs) form the sensing backbone, with miniature, battery-powered nodes distributed across fields, orchards, and livestock barns. Advances in microelectromechanical systems (MEMS) and energy-harvesting devices have substantially reduced node size and energy footprint (Jawad et al., 2017). Cloud computing platforms—including ThingSpeak, AWS IoT, Microsoft Azure IoT, and Google Cloud IoT—provide elastic storage and computational capacity, while edge and fog computing reduce latency by performing analytics closer to the data source (Verdouw et al., 2021).

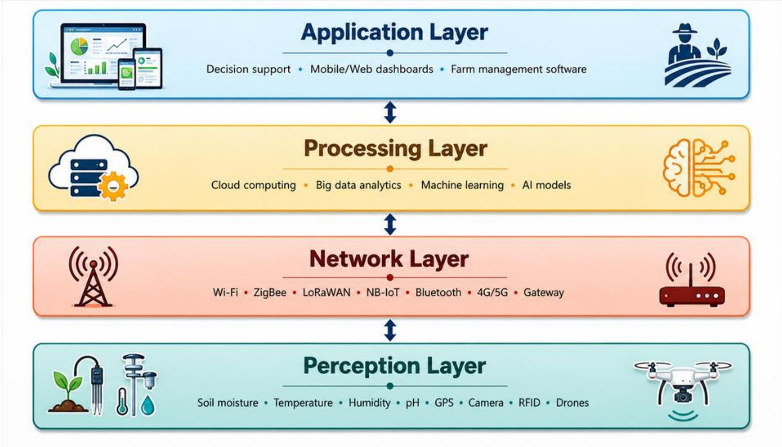

Figure1. Four-layer IoT architecture commonly applied in smart agricultural systems

Unmanned aerial vehicles equipped with multispectral and hyperspectral cameras have become indispensable for site-specific crop scouting, vegetation index mapping (e.g., NDVI), and variable-rate input application (Maes & Steppe, 2019). Robotics—including autonomous tractors, weeding robots, and harvesting machines—integrate IoT data with computer vision to perform highly targeted operations. Blockchain technology, although still emerging, is being explored to ensure data integrity and traceability across agricultural supply chains (Lin et al., 2020). Together, these innovations enable closed-loop systems that sense, decide, and actuate autonomously, marking a clear departure from traditional farming.

4. Applications of IoT in Smart Agriculture

4.1 Precision Irrigation and Water Management

Water-related applications account for the largest share of IoT deployments in agriculture (Madushanki et al., 2019). IoT-enabled smart irrigation systems combine soil-moisture probes, weather forecasts, and crop evapotranspiration models to schedule irrigation precisely when and where it is needed. Field trials reported water savings of 20 to 50 percent compared to conventional schedules, often without yield penalty (Goap et al., 2018; & Kamienski et al., 2019).

4.2 Crop Monitoring and Disease Detection

Continuous monitoring of canopy temperature, leaf wetness, and spectral signatures allows early detection of biotic and abiotic stresses. Machine-learning models trained on UAV imagery have achieved high accuracy in detecting fungal diseases, nutrient deficiencies, and pest outbreaks (Liakos et al., 2018). Yassin et al. (2022) demonstrated a cloud-enabled IoT platform that monitored tomato plantations in real time, enabling timely interventions and reducing input wastage.

4.3 Smart Greenhouses

Greenhouses are ideal candidates for IoT integration owing to their enclosed environment. Automated control of temperature, humidity, carbon dioxide, light, and irrigation is achieved by feedback loops between sensors and actuators (Shi et al., 2019). Such systems have been shown to increase yields, improve product uniformity, and reduce energy consumption.

4.4 Livestock Monitoring

IoT collars, ear tags, and rumen boluses continuously monitor animal location, body temperature, heart rate, rumination, and feeding behaviour. These data streams support early disease detection, oestrus monitoring, and welfare assessment, especially in extensive grazing systems (Neethirajan, 2020). Geofencing applications allow livestock managers to monitor and constrain animal movement without physical fencing.

4.5 Supply Chain and Food Traceability

IoT-enabled RFID tags, environmental sensors, and blockchain ledgers track agricultural products from farm to fork, monitoring temperature, humidity, and shock during transport. This enhances food safety, reduces post-harvest losses, and strengthens consumer trust (Lin et al., 2020). End-to-end traceability is particularly valuable for high-value commodities such as dairy, seafood, fresh produce, and organic certified crops, where provenance affects both safety and price premium.

4.6 Precision Fertilisation and Soil Health

Variable-rate fertilisation guided by IoT-enabled soil sensors and electrochemical probes allows farmers to apply nitrogen, phosphorus, and potassium according to the spatial variability of soil nutrient status. Khanna and Kaur (2019) reported significant reductions in fertiliser use and nutrient runoff when prescription maps generated from sensor and UAV data were combined with controlled-release application technologies. Long-term monitoring of soil organic carbon, salinity, and microbial activity also supports regenerative agriculture practices.

4.7 Aquaculture and Apiculture

Although less frequently highlighted, IoT applications in aquaculture and apiculture have matured rapidly. Sensors monitoring dissolved oxygen, pH, ammonia, and water temperature support real-time decisions in fish and shrimp farms, while connected hive monitors track bee colony weight, internal temperature, and acoustic signatures to detect swarming or colony stress (Pereira et al., 2020). These applications illustrate the breadth of agricultural IoT beyond conventional crop and livestock farming.

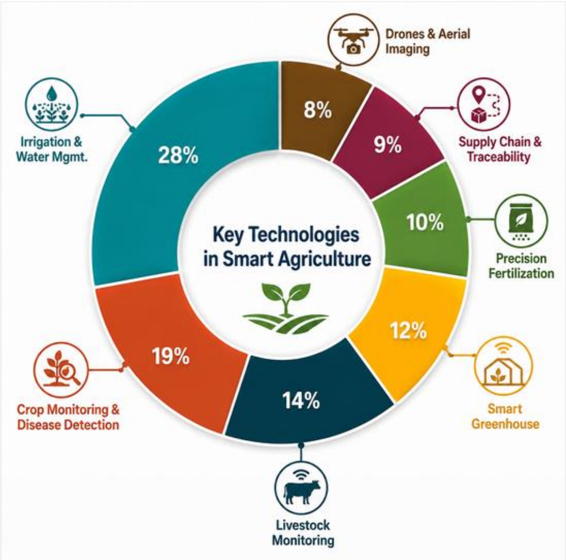

Figure2. Approximate distribution of IoT application domains in smart agriculture

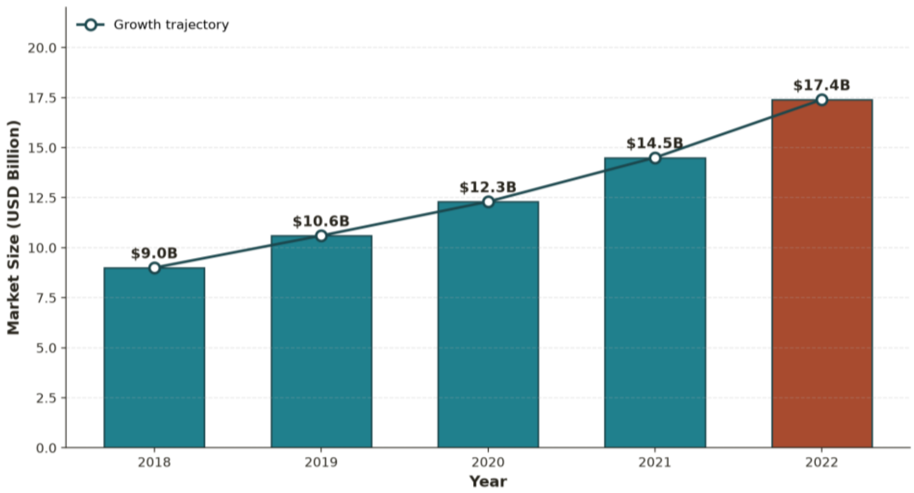

Figure3. Estimated global smart-agriculture market size between 2018 and 2022

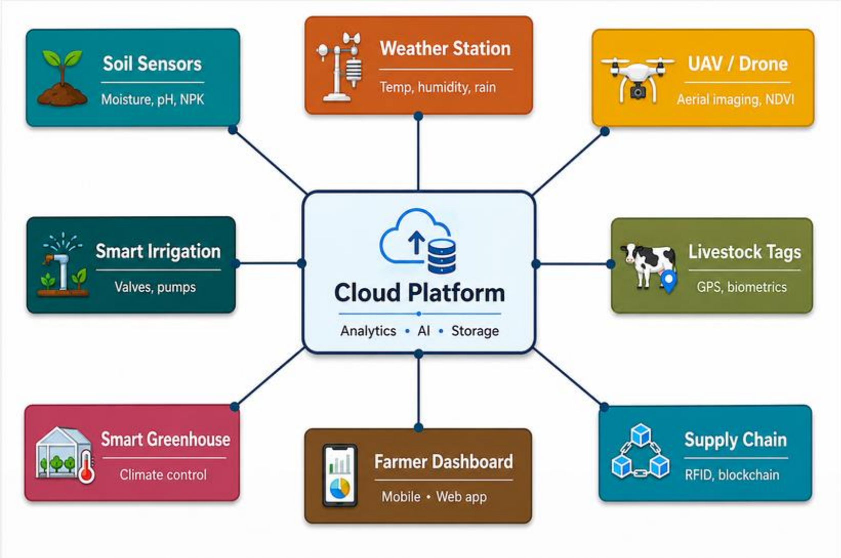

Figure4. Conceptual schematic of an IoT-enabled smart farm ecosystem linking field, livestock, and supply-chain modules through a cloud platform

5. Market Growth and Global Adoption

The global smart-agriculture market has experienced sustained growth. MarketsandMarkets (2022) estimated the market at approximately USD 17 billion in 2022, almost doubling from USD 9 billion in 2018, with a compound annual growth rate (CAGR) close to 12 percent. North America and Europe lead in adoption, while Asia-Pacific—particularly India and China—is the fastest-growing region, driven by government initiatives, smallholder digital programmes, and expanding rural connectivity (Ramalingam et al., 2022). India's Digital Agriculture Mission (2021–2025) and similar national programmes in Brazil, Israel, and the Netherlands are accelerating field-scale deployment.

6. Benefits of IoT in Agriculture

The literature consistently reports multidimensional benefits of IoT adoption. Quantitatively, IoT-enabled precision irrigation has been associated with water savings of up to 30 percent, yield increases of around 25 percent, fertiliser and pesticide reductions of 20 percent, and labour cost reductions of more than 20 percent (Qazi et al., 2022; & Ramalingam et al., 2022). Qualitatively, IoT systems contribute to environmental sustainability by reducing the leaching of agrochemicals, supporting biodiversity, and lowering greenhouse-gas emissions from over-irrigation and machinery use (Walter et al., 2017). They also enable evidence-based policymaking, improved farmer livelihoods, and food security in vulnerable regions. At the farm-management level, real-time dashboards reduce the cognitive load on farmers by converting raw data streams into clear, prioritised alerts, while historical data archives create a foundation for benchmarking, insurance products, and credit scoring tailored to farming communities (Walter et al., 2017; & Ramalingam et al., 2022).

7. Challenges and Limitations

Despite its promise, the adoption of IoT in agriculture is constrained by several persistent barriers. High initial investment in sensors, gateways, and software remains the most frequently cited barrier (Abid et al., 2020). Connectivity in remote rural areas is often inadequate, and many regions lack reliable electricity, limiting continuous operation of sensor nodes. Standardisation across hardware vendors, communication protocols, and data formats is incomplete, hampering interoperability and large-scale integration (Tzounis et al., 2017).

Data privacy, ownership, and cybersecurity are also major concerns. As farms become increasingly connected, sensitive information about yields, prices, and farm operations is exposed to cyber threats and potential misuse (Gupta et al., 2020). Furthermore, digital literacy among smallholder farmers, who form the bulk of agricultural producers in developing countries, remains limited. Energy constraints, sensor calibration drift, and harsh environmental conditions also complicate long-term deployment.

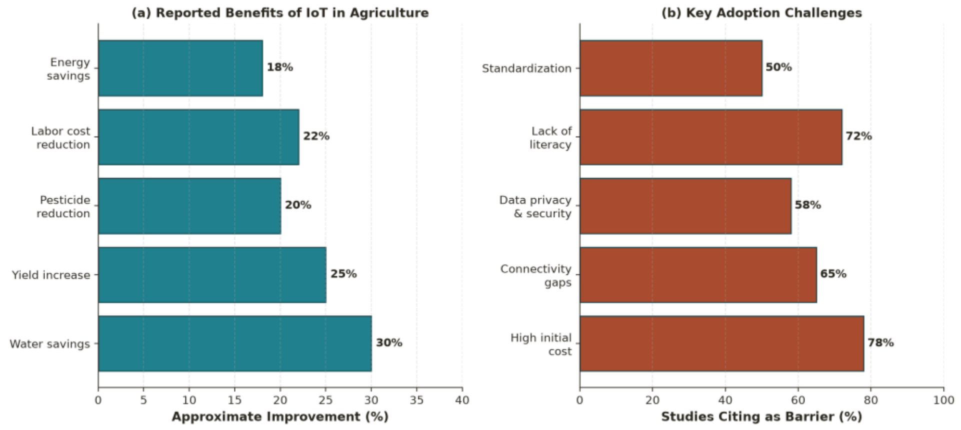

Figure5. Reported benefits (a) and adoption challenges (b) of IoT in smart agriculture

8. Future Prospects

Several emerging trends are likely to shape the next decade of agricultural IoT. The convergence of IoT with artificial intelligence—particularly deep learning and reinforcement learning—will enable predictive analytics for yield forecasting, pest outbreak prediction, and autonomous decision-making (Liakos et al., 2018). Edge and fog computing will reduce reliance on continuous cloud connectivity and improve latency-sensitive applications such as autonomous robotics. The rollout of 5G and the expansion of satellite-based IoT, including low-Earth-orbit constellations, promise to bridge the rural connectivity gap.

Climate-smart agriculture will increasingly depend on IoT data to monitor greenhouse-gas emissions, soil carbon sequestration, and water footprints. Open data platforms, interoperability standards, and digital twins of farms will support evidence-based policy and supply-chain transparency (Verdouw et al., 2021). Finally, business-model innovations such as Farming-as-a-Service (FaaS) and cooperative IoT deployments may significantly lower the cost barrier for smallholder farmers, accelerating equitable adoption.

From a policy perspective, governments will need to align agricultural extension services, data-protection legislation, and rural infrastructure investment with the technological trajectory of IoT. Public–private partnerships, farmer producer organisations, and university-led demonstration farms can serve as effective vehicles for technology diffusion. In India, for example, Krishi Vigyan Kendras and state agricultural universities are well positioned to act as bridges between IoT innovators and smallholder farmers (Ramalingam et al., 2022). Research priorities for the near future include the development of self-powered and biodegradable sensor nodes, lightweight federated-learning algorithms suitable for resource-constrained edge devices, and standardised data ontologies for agriculture. Equally important is the inclusion of social-science perspectives that examine farmer behaviour, gender dynamics, and the ethical implications of data-driven agriculture, ensuring that technological progress translates into inclusive and sustainable outcomes.

CONCLUSION

The Internet of Things has emerged as a cornerstone technology in the ongoing transformation of global agriculture. By integrating sensors, networks, cloud platforms, and intelligent applications, IoT enables farmers to monitor, analyse, and optimise virtually every dimension of crop and livestock production. Applications span precision irrigation, disease detection, smart greenhouses, livestock surveillance, and supply-chain traceability, delivering measurable gains in productivity, sustainability, and resource efficiency. Nevertheless, widespread adoption is constrained by high costs, fragmented standards, connectivity limitations, data security concerns, and digital-literacy gaps, particularly in developing regions. Continued advances in artificial intelligence, edge computing, low-power wide-area networks, and equitable business models are expected to overcome these barriers and drive the next wave of agricultural innovation. For nations such as India, where smallholder farming dominates, strategic investment in IoT-enabled smart agriculture holds transformative potential for ensuring food security, environmental stewardship, and rural prosperity in the decades ahead.

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Conceptualization, writing, and revision were performed by all authors. All authors approved the final manuscript.

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