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Review article

Applications of Internet of Things (IoT) in agriculture: A review

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ABSTRACT

This paper reviews how the Internet of Things (IoT) is transforming agriculture into a data-driven, technology-enabled sector. IoT applications in farming include soil and weather monitoring, precision irrigation, nutrient management, crop health surveillance, and post-harvest supply chain traceability. By integrating field-deployed sensors, drones, wireless networks, and cloud-based analytics, farmers can continuously track soil moisture, nutrient content, crop growth, and microclimate conditions. These insights enable real-time decision-making that improves resource-use efficiency, reduces input waste, and minimizes environmental impacts. IoT-based automation also allows remote control of pumps, fertigation systems, and spraying equipment, further enhancing labor productivity and operational sustainability. Despite these benefits, adoption remains constrained by high initial costs, limited rural connectivity, device interoperability issues, and data security concerns. Future research and policy efforts must focus on developing affordable, interoperable solutions, strengthening rural digital infrastructure, and integrating IoT with emerging technologies such as artificial intelligence and machine learning to achieve scalable, climate-resilient agriculture.

Keywords: Internet of Things (IoT), Agriculture, Sensors, Smart irrigation, Precision farming

The Internet of Things (IoT) refers to a system of interconnected devices that can collect and exchange data over the internet. These devices, ranging from everyday objects to industrial machinery, are embedded with sensors, software, and other technologies that enable them to connect and interact with each other and with us. This interconnectedness allows for automation, data-driven insights, and improved efficiency in various aspects of life and work. The integration of the Internet of Things (IoT) in agriculture marks a significant shift towards data-driven and efficient farming practices. An era of smart agriculture has begun with the advent of the Internet of Things (IoT), which has transformed conventional farming methods (Baranitharan *et al.,* 2024; Padiya *et al.,* 2023). This transformation is particularly important in India, where agricultural sustainability is threatened by yield disparities, water scarcity, and climate change (Wani, 2023). The agrometeorological service for farmers is poised to embrace and deliver new interventions through technology cross-sections such as satellite remote sensing, drone-based survey, mobile based data collection systems, IoT based sensors, using insights derived from a hybridisation of crop and AIML (Artificial Intelligence and Machine Learning) models (Sarkar *et al.,* 2023).

By integrating data analytics with advanced sensor networks, farmers can keep an eye on the temperature, moisture content, and nutrient levels of their soil. Farmers can maximize agricultural productivity and quality by making real-time modifications using sensors to collect data and advanced analytics (Baranitharan *et al.,* 2024). Farmers can reduce waste and the environmental effect of conventional farming practices by employing precision agricultural techniques to apply water, fertilizer, and pesticides. The efficient and targeted use of resources is made possible by the use of sensors that monitor soil moisture, nitrogen levels, and other relevant variables (Ray, 2017).

This review attempts to give a thorough grasp of how IoT technologies might improve production, optimize resource management, and support sustainable agricultural practices by combining the results of numerous research studies (Table 1). It looks at the various applications of IoT in agriculture and assesses how it affects productivity, resource management, environmental sustainability, and implementation challenges. the potential of IoT to transform agricultural practices and promote sustainable farming.

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Table 1: Summary of key studies on IoT applications in smart agriculture (2016-2024)

Title and Year	Study Title/ Objective	Type of IoT Application	Technologies Used	Application Area	Key Findings	Limitations/ Challenges
IoT Innovations Revolutionizing Agricultural Practices for Sustainability (Kumar *et al.,* 2024)	Investigating how IoT technology might transform farming methods and boost agricultural output .	Sensing, Monitoring, Automation	Sensors, Actuators, Connectivity Technologies	Precision Irrigation, Soil Monitoring, Crop Health Monitoring, Animal Management	Through water conservation, fertilizer application optimization, and greenhouse gas emission mitigation, IoT can support sustainable agriculture operations.	Issues with data privacy, technical infrastructure constraints, and the rural digital divide.
A Survey on Automation Challenges and Opportunities for IoT based Agriculture (Enugala *et al.,* 2023)	To evaluate the opportunities and challenges of employing IoT technology to automate agricultural processes.	Sensing, Monitoring, Automation	Sensors, Drones, Machine Learning	Crop and Soil Management, Drone Field Surveillance, Cattle and Resource Management, Pesticide/ Fertilizer Tracking	Innovations in drone technology, precision agriculture, integrated pest management, smart irrigation systems, and livestock monitoring can result from IoT and machine learning.	Small-scale farmers' acceptance, interoperability, data storage, connectivity, hardware and software upkeep, security issues, data collecting, environmental variability, cost, infrastructure, and privacy.
IoT Solutions in Agriculture: Enhancing Efficiency and Productivity (Pawar, 2024)	To investigate how IoT solutions can be integrated into agriculture and how they can improve sustainability, productivity, and efficiency.	Sensing, Monitoring, Automation	Sensors, Data Analytics	Precision Farming, Automated Irrigation, Soil Monitoring, Pest Control	Through the use of real-time data, sophisticated analytics, and intelligent decision-making systems, IoT has the potential to influence agriculture's future.	Challenges related to implementation and adoption are not discussed in detail.
Internet of things for smart agriculture: Technologies, practices and future direction (Ray, 2017)	To review various potential IoT applications and the challenges associated with IoT deployment for improved farming.	Sensing, Monitoring	Sensors, Wireless Communication Technologies	Various agricultural applications	IoT-enabled systems can provide intelligent and smart services towards smart agriculture.	The need for further research and development to address challenges related to device compatibility, network infrastructure, and data management.
Challenges and Solution for Identification of Plant Disease Using IoT and Machine Learning (Nayak *et al.,* 2023)	To examine several disease detection techniques based on IoT deployment.	Sensing, Monitoring	Sensors, Image Processing, IoT Devices	Plant Disease Identification	Plant disease detection can benefit greatly from the use of IoT and image processing.	The availability and quality of data, the difficulties in combining various data sources, and the requirement for reliable algorithms for precise illness detection.

Internet of Things in the Field of Smart Farming: Benefits and Challenges (Dewangga and Suhono, 2020)	To talk about the Internet of Things' architecture and platform and make it possible to implement the idea of smart agriculture.	Sensing, Monitoring	Sensors, Wireless Sensor Network (WSN), Data Analytics, Cloud Computing, Middleware Architecture, Radio Frequency Identification (RFID)	Crop Cultivation, Agricultural Productivity	IoT technology has the potential to boost agricultural productivity and crop cultivation efficiency.	The requirement for additional study and advancement to solve issues with infrastructure, cost, and data security.
Smart Farming: Implementation of IoT-based Technology for Crop Monitoring and Management (Chandran, 2021)	To look into how Internet of Things-based technology can be used for crop monitoring and management.	Sensing, Monitoring, Automation	Sensors, Machine Learning, Dashboards	Crop Monitoring and Management	Internet of Things-based technology can increase the productivity and efficiency of agricultural operations by giving farmers the ability to monitor and control their crops.	Decision-making requires accurate and reliable data, and research into improving IoT-based agricultural monitoring and management systems is still ongoing. .
Review of agricultural IoT technology (Xu *et al.,* 2022)	To give a summary of the current status of IoT research in agriculture, including its primary technologies, uses, system architecture, and challenges.	Sensing, Monitoring, Automation	Sensors, Data Analytics, Wireless Communication Technologies	Various agricultural applications	IoT has the potential to successfully increase farmers' profits, reduce labor expenses, enhance product quality, and attain modernized intelligence.	The need for additional research and development to address privacy, interoperability, and data security concerns.
IoT Applications in Smart Agriculture: Issues and Challenges (Kassim, 2020)	To examine the most recent developments in Internet of Things (IoT) applications for agriculture and draw attention to the problems and difficulties, especially with network and open-source software for smart agriculture.	Sensing, Monitoring, Automation	Sensors, Network Technologies, Open-Source Software	Various agricultural applications	Issues with agriculture and food demand may be resolved by IoT and associated technologies.	Issues with data security, open-source software availability, and network infrastructure.
Internet of Things (IoT) in Agriculture - Selected Aspects (Stočes *et al.,* 2016)	To examine certain facets of IoT in agriculture, such as network solutions, platforms, standards, and equipment classification.	Sensing, Monitoring	Sensors, Platforms, Standards, Network Solutions	Various agricultural applications	IoT is frequently used in agriculture as a key means of exploring topics pertaining to the agrarian sector and rural development.	The requirement for additional study and advancement to tackle issues with data management, environmental circumstances, and infrastructure.

Precision Agriculture Techniques and Practices: From Considerations to Applications (Shafi *et al.,* 2019)	To provide a case study of a WSN-based system and examine both local and remote sensor networks in the context of precision agriculture.	Sensing, Monitoring	Sensors, Wireless Sensor Network (WSN), Multi-spectral Imagery	Crop Health Monitoring	WSN-based systems, which offer multispectral imaging for categorization and real-time status, can be used for crop health monitoring.	Difficulties with data processing, analysis, and interpretation; also, reliable communication technologies are required.
IoT-Enabled Smart Agriculture: Architecture, Applications, and Challenges (Quy *et al.,* 2022)	To give an overview of IoT technologies and show how the industry may incorporate IoT into smart agriculture.	Sensing, Monitoring, Automation	Sensors, Wireless Sensor Networks, Cognitive Radio Ad Hoc Networks, Cloud Computing, Big Data	Various agricultural applications	IoT can boost productivity and operational effectiveness in smart agriculture.	Interoperability, privacy, and data security issues, as well as the requirement for strong communication and data analytics tools.
State-of-the-Art Internet of Things in Protected Agriculture (Shi *et al.,* 2019)	To learn more about the most recent IoT applications in protected agriculture, as well as to recognize the main technologies and system architecture.	Sensing, Monitoring, Automation	Sensors, Data Analytics, Control Systems	Plant Management, Animal Farming, Food/Agricultural Product Supply Traceability	IoT offers a wide range of potential applications in protected agriculture, which modifies climate elements and creates growth-friendly environmental circumstances using artificial methods.	Interoperability, privacy, and data security issues, as well as the requirement for strong communication and data analytics tools.
Integration of Large Language Models with IoT in Smart Agriculture to Improve Efficiency, Yield, and Quality (Feng *et al.,* 2024)	To investigate how IoT technology and large language models (LLMs) are combined in smart agriculture.	Sensing, Monitoring, Automation	Sensors, Large Language Models (LLMs), Data Analytics	Precision Agriculture	LLMs' sophisticated natural language processing skills help improve data-driven decision-making procedures.	Issues with privacy and data security, the requirement for reliable algorithms for precise disease detection, and the need for more study and development to fully realize the potential of LLMs in agriculture.

INTERNET OF THINGS (IOT) IN AGRICULTURE

Emergence of IoT

The notion of computing embedded seamlessly in everyday life was articulated by Weiser (1991). In parallel, Auto-ID research at MIT enabled large-scale object identification via RFID, laying practical foundations for networked "things." The term "Internet of Things" gained currency with Ashton (2009), while early syntheses framed IoT across device, network/middleware, and knowledge/semantics layers (Atzori *et al.,* 2010). Institutional milestones include the International Telecommunication Union (ITU, 2005) report on IoT, the formation of the IPSO Alliance (2008) to promote IP-based IoT, and Cisco Systems (2011) analyses on the era when connected "things" outnumbered people (circa 2008–2011). These key developments are now presented in Table 2, which summarizes the evolution of IoT concepts and their influence on agriculture. Building on these milestones, the agricultural sector increasingly adopted low-power sensors, wireless networks, and cloud analytics to enable precision input management and real-time decision support.

Integration of IoT with agriculture

The emergence of IoT in agriculture contributes to improved crop productivity, increased sustainability, and a revolution in resource management. All of these technologies provide the most recent data on crop health, weather, and soil moisture via sensor networks, drones, and intelligent irrigation. Producers can use this information to make educated choices about irrigation, fertilizer, and pest control methods that optimize yield while reducing waste. Using information from soil moisture, this intelligent irrigation system automatically regulates the amount of water in the soil, conserving water and enabling crop development. IoT applications extend to aquaponics farming systems that integrate aquaculture with hydroponics, real-time forestry monitoring to track environmental changes, and supply chain management platforms that ensure traceability and reduce post-harvest losses.

IoT-enabled devices not only monitor field parameters but also make it possible to control equipment from a distance, automate the process of farming operations, and give warning signs for predictive analytics changing traditional methods of farming into data-driven ones. Such technology-driven transformation directly supports the call for climate-resilient and sustainable agriculture through digital empowerment of smallholders (Wani, 2023). Such integration raises productivity, brings down labor costs, and reduces environmental degradation due to agriculture. Though IoT adoption in agriculture is sure to grow, issues such as the cost of devices and equipment, connectivity in rural areas, and even data security issues need to be addressed for extensive implementation and longer sustenance. These barriers are consistent with broader structural divides in Indian agriculture, where smallholders often lack access to modern tools and infrastructure (Wani, 2023).

Smart farming, also known as Agriculture 4.0, is a data-driven, highly efficient sustainable agriculture method that has replaced traditional farming due to the Internet of Things revolution. Farmers can precisely and remotely monitor and control a variety of farming activities thanks to the Internet of Things' combination of sensors, linked devices, and real-time data analytics. Coupled with automated irrigation systems, IoT devices in the form of soil moisture sensors and weather stations have optimized water use, reduced waste, and facilitated good crop health. IoT-powered drones and unmanned vehicles also serve to monitor crops, analyze soils, and spray pesticides with much greater productivity. In Real-Time data collected in the field, farmers can arrive at decisions on planting, fertilizing, and harvesting, thus increasing yields and resource efficiency. They use big data analytics alongside IoT to develop predictions for Weather conditions, pest outbreaks, and other hazards, which it could encounter. Globally, the IoT revolution is an imperative enhancement in agriculture for meeting sustainable requirements and reducing environmental impacts while attaining a continually increasing population's growing food demands. Future technological advancements hold great promise for further revolutionizing farms through improved automation, precision, and innovations in sustainable farming in light of climate change and food security issues.

The evolution of agriculture demonstrates a clear progression from traditional, labor-intensive methods to highly advanced, technology-driven practices (Table 2). Agriculture 1.0, beginning around 1784, relied mainly on human and animal labor. With the advent of mechanization around 1950, Agriculture 2.0 introduced tractors and heavy machinery, significantly improving efficiency. By the late 20th century, Agriculture 3.0 incorporated automation, digital tools, and high-speed data to streamline farming operations. Nowadays, smart agriculture is represented by Agriculture 4.0, which emerged around 2017. It combines big data, robotics, artificial intelligence, and Internet of Things (IoT) technology to maximize farming's sustainability and production (Friha *et al.,* 2021). Table 2 presents major technological milestones and time periods associated with them to demonstrate the role of every innovation towards modernizing agriculture. From manual labour and tractors to IoT, AI, and big data, the string of technological developments has consistently changed the face of agriculture. Table 2 emphasizes how this development journey progressed historically while adopting key innovations along with this transition toward smart and precision agriculture.

Fig. 1 compares wheat yields under IoT-enabled precision agriculture with traditional methods in Punjab, India. Adapted data (Adamides *et al.,* 2020; Alahmad *et al.,* 2023) indicate that IoT-based management produced substantially higher yields (8 t ha^{-1}) compared to conventional practices (5 t ha^{-1}). This highlights the productivity benefits of sensor-based and data-driven farm management. Fig. 2 shows soil moisture fluctuations during a 24-hour cycle in IoT-enabled irrigation systems (Adamides *et al.,* 2020; Gadage, 2019). The monitoring framework-maintained soil moisture within optimal ranges by triggering irrigation events only when thresholds were reached. This closed-loop control prevented both under- and over-irrigation, demonstrating the efficiency gains from IoT-driven irrigation scheduling.

Applications of IoT in the agriculture sector

Agriculture is being revolutionized by the Internet of Things through real-time monitoring systems that boost productivity, efficiency, and sustainability. IoT devices, such sensors and drones, monitor crop health, soil conditions, and weather patterns continually, enabling data-driven decisions about pest management, fertilization, and irrigation. By optimizing resource utilization, this precision farming technique reduces waste and adverse environmental impacts. Fig. 3 shows how these elements work together for the best farm management, illustrating the extensive IoT foundation that makes these agricultural applications possible.

Sensors used in IoT-based agricultural systems

The entire farming process will be improved by the real-time data collected by sensors in IoT-based agricultural systems. To help farmers make informed decisions, these gadgets will track a number of variables, including crop health, temperature, humidity, and soil moisture. Sensor technology combined with IoT platforms facilitates agricultural operations by optimizing resource usage, enhancing productivity, and sustainability. Analog sensors measure continuous signals and provide a range of values (like voltage) representing the physical quantity. Digital sensors provide discrete, binary data (e.g., 0s and 1s) to indicate specific states or readings. Table 3 describes some of the agricultural sensors and its properties for further detail.

Table 2: Timeline and technological achievements in IoT

Period	Generation	IoT evolution stage	Technological focus	Key milestones in IoT development
Pre-1990	Generation 1.0 (or) Agriculture 1.0 – Conventional Systems	Pre-Internet ("Human-to-Human") Traditional Agriculture	Manual operations, mechanization, early automation tools; basic telephony & SMS; Use of human and animal sources	1780: Mechanization begins; 1950s–1980s: Tractors, machines, basic farm mechanization; 1969: ARPANET; 1982: First networked vending machine; 1989: First IoT device.
1990–2000	Generation 2.0 (or) Agriculture 2.0 – Digitisation & Computerisation	Internet of Content (Web 1.0) Mechanized Agriculture	Computers, satellites, sensors, early internet; e-mail & online information sharing; Use of powered machinery	1990: First Internet-controlled toaster; 1993: First webcam; 1994: Wear Cam; 1995: GPS v1; 1999: Kevin Ashton coins "IoT"; 2000: First smart refrigerator (LG).
2000–2015	Generation 3.0 (or) Agriculture 3.0 – Smart Data Collection & Processing	Internet of Services (Web 2.0) Automated Agriculture	Mobile devices, database software, cloud storage, M2M communication; e-commerce & productivity tools; Use of high-speed development	2003: RFID commercialized; 2005: ITU publishes first IoT report; 2008: Connected devices outnumber humans; 2011–2014: Smart cities emerge; 2015: IoT goes mobile with smartphones.
2015–Present	Generation 4.0 (or) Agriculture 4.0 – Intelligent Data-Driven Systems	Internet of People (Web 3.0) → Internet of Things (Web 4.0) Smart agriculture	AI, ML, big data analytics, blockchain, automation; social media to M2M communication, predictive analytics, automation; Use of IoT, AI, Bigdata, UAV, Robotics etc.,	2016: AWS IoT Core launched; 2017–2019: AI & blockchain in IoT; 2020: 5G deployment; 2021: >10B active IoT devices; 2022: WEF cites IoT as top tech driver.

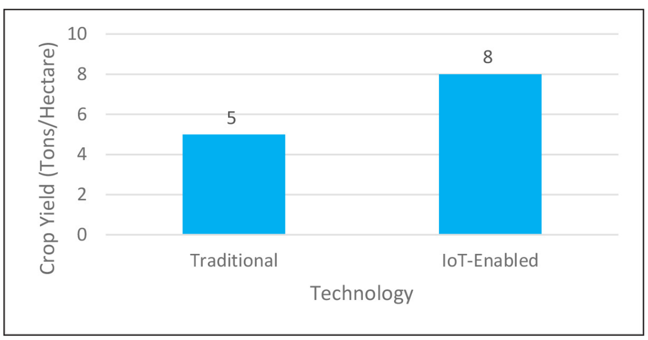


Fig. 1: Crop yield (t ha^{-1}) in wheat fields: IoT-enabled vs. traditional methods. Source: Adapted from Adamides *et al.,* (2020); Alahmad *et al.,* (2023).

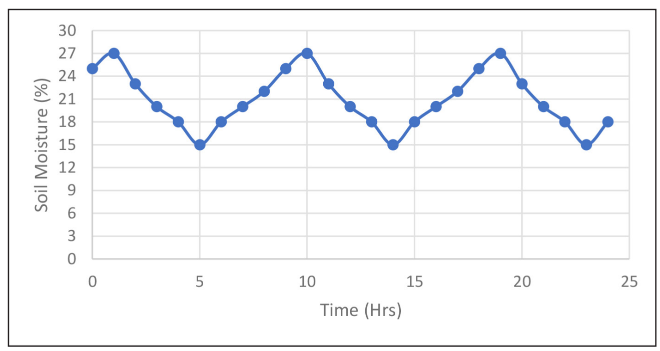


Fig. 2: Soil moisture fluctuations (%) over a 24-h cycle in IoT-enabled irrigation. (Adapted from Adamides *et al.,* (2020); Gadage (2019).

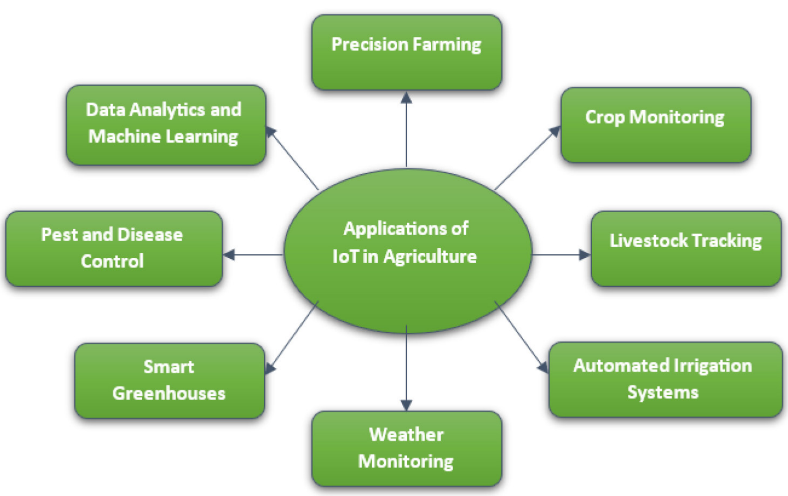
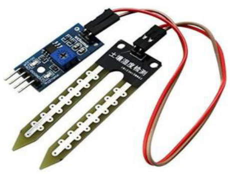
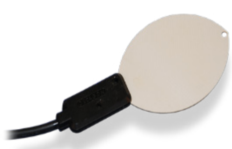


Fig. 3: Applications of IoT in agricultural sector

Table 3: Sensors used in IoT-based agricultural systems

Name of the Sensor	Image	Measured Parameter	Measurement Range	Cost Range (In rupees)	Data Output (Analog/ Digital)	Sensor Lifespan
Soil Moisture and Temperature Sensor (RS 485)		Measure Soil Moisture and Temperature	Moisture: 0% to 100% of saturation Temperature: -40 °C to +80 °C	3,500 – 4,500	Analog	2 – 5 years
Soil Moisture Sensor		Measures Soil Moisture	0% to 100% of saturation	50 – 150	Analog and Digital	6 months – 1 Year
Soil Moisture Sensor (MP406)		Measurements of soil moisture levels.	0-100 VSW%	68,000 – 69,000	Analog	20 years
pH Sensor		Monitor and maintain the pH level of the crops.	pH Measuring Range: 0-14	19,000 – 20,000	Analog	6 Months – 2 years
Temperature And Humidity Sensor (DHT11)		To monitor temperature and humidity.	Temperature Range: 0-50°C Humidity Range: 20-90%RH	100 – 150	Digital	1 Year
Temperature And Humidity Sensor (DHT22)		To monitor temperature and humidity.	Temperature Range: -40~80°C Humidity Range:٪١٠٠-٠RH	300 – 350	Digital	1 Year
Lws Leaf Wetness Sensor		To detect moisture on leaf surfaces.	0 to 100% Wetness	800 – 2,500	Analog	2 Years
Sdi-12 Leaf Wetness Sensor Tbslws1		To detect moisture on leaf surfaces.	0 to 100% Wetness	14,500 – 15,500	Digital	2 – 5 Years
Soil Npk Sensor – Jxbx – 3001		It measures nitrogen (N), phosphorus (P), and potassium (K) levels in the soil,	0-1999 mg/kg	7,000 – 7,500	Analog	3 – 5 Years

Soil 7 In 1 Sensor		Used to measure soil N, P, K, pH, EC, Moisture, and Temperature	Temperature: -45°C-115°C Moisture: 0-100% PH: 3-9 EC: 0-10000us/cm NPK: 0-1999mg/kg	12,000 – 13,000	Digital	5 – 7 Years
So-411 Oxygen Sensor		Measures oxygen levels in the Soil	0 to 100 % O2	50,000 – 52,000	Analog	5 – 10 Years
Wind Speed Sensor		Wind speed sensor is a physical device used to measure wind speed	Wind Speed: 0-70m/s Wind Direction: Measures from 0° to 360°.	9,500 – 10,000	Digital	5 – 10 Years
5-In-1 Weather Sensor		Weather Sensor measures temperature, humidity, wind speed, wind direction, and rain.	Temperature: -40°C to 70°C Humidity: 1% to 99% Wind Speed: 0 to 99 mph Wind Direction: 0° to 360° Rainfall: 0 to 100 inches	18,000 – 19,000	Digital	5 – 10 Years
LT150 Agricultural Light Sensor		To monitor light levels and help farmers make decisions about their crops	0 to 150 KLux	3,500 – 4,500	Analog	Over a Year

METHODOLOGY TO DEPLOY AN IOT SETUP IN AGRICULTURE

The effective implementation of IoT in agriculture requires a structured methodology to optimize resources, enhance yield, and ensure long-term sustainability. This process begins by defining clear objectives such as improving irrigation efficiency, reducing fertilizer waste, or monitoring crop health and proceeds through the following integrated steps:

Needs assessment and system design (components)

- Identify crop type, soil characteristics (e.g., loamy soil's balanced moisture retention and drainage), and environmental conditions.
- Select suitable IoT architecture (centralized, distributed, or hybrid) based on farm size, available infrastructure, and connectivity options.
- Determine hardware requirements: sensors, microcontrollers, actuators, and power supply systems (solar, battery, or grid).

Sensor selection and placement (components and connections)

- Choose sensors for soil moisture, pH, temperature, humidity, and nutrient content.
- Position sensors using GPS-based mapping to ensure representative and accurate data collection.
- Connect sensors and actuators securely to microcontrollers (Arduino, ESP32, Raspberry Pi), ensuring weatherproofing for field deployment.

Network and communication setup (communication technologies)

- Select communication technology based on location:
  - Wi-Fi for high-connectivity zones
  - LoRaWAN for long-range, low-power needs
  - GSM/4G/5G for rural areas without fixed

internet access

- Integrate the chosen hardware with power management systems for continuous operation.

Data acquisition and transmission (communication protocols)

- Use microcontrollers to collect and preprocess sensor data.
- Implement protocols such as MQTT or HTTP for efficient, secure data transfer.
- Enable encryption (TLS/SSL) to protect data integrity and privacy.

Analytics and decision-making (coding and cloud)

- Store data on cloud platforms such as ThingSpeak, AWS IoT, or Azure IoT Hub for visualization and analysis.
- Apply AI and machine learning algorithms for predictive irrigation, nutrient management, and anomaly detection.
- Use dashboards or mobile applications to provide real-time insights and alerts to farmers.

Automation and control (coding and connections)

- Link IoT outputs to actuators (solenoid valves, automated pumps, fertigation systems) for closed-loop control.
- Automate irrigation and fertilization schedules based on real-time soil data, weather forecasts, and crop growth stages.

Testing, calibration, and maintenance

- Conduct pilot trials to verify system performance in actual agricultural environments.
- Schedule regular calibration of sensors and updates to firmware/software to ensure reliability under changing environmental conditions (Ali *et al.,* 2015; Quy *et al.,* 2022).

This structured methodology aligns with the 5C Framework for IoT in agriculture-like Connection (sensing and networking), Conversion (data preprocessing), Cyber (secure storage and digital platforms), Cognition (analytics and AI-driven insights), and Configuration (closed-loop automation). Integrating these elements ensures scalable, efficient, and sustainable smart farming systems.

CURRENT RESEARCH DEFICIENCIES IN IOT FOR AGRICULTURE

While IoT holds great promise for transforming agriculture, significant research and implementation gaps remain. Addressing these gaps is critical to fully leverage IoT for improving productivity, resource efficiency, and sustainability.

Adoption barriers

Cost and low adoption: High initial investment in IoT hardware, maintenance, and connectivity infrastructure continues to hinder widespread adoption, particularly among small and marginal farmers. Studies show that adoption of precision agriculture technologies remains uneven, with large-scale farms adopting at significantly higher rates than smaller holdings, largely due to affordability and access to capital.

Lack of standardization: The absence of universal technical standards results in fragmented solutions and poor interoperability between devices from different manufacturers, which increases integration costs and slows scaling (Bahari *et al.,* 2024).

Connectivity issues: Limited broadband and mobile network coverage in rural agricultural regions remains a significant obstacle to cloud-based IoT applications. Research reports that in many developing regions, fewer than 40% of smallholder farms have consistent 3G/4G access, creating a "digital divide" that restricts real-time monitoring and control capabilities.

Theoretical underpinning

There is a clear gap in research using formal theoretical models to guide IoT adoption studies in agriculture. Technology–Organization–Environment (TOE) Framework model can be adapted to examine technological readiness, organizational capacity, and environmental factors influencing IoT adoption (Bahari *et al.,* 2024). Using TOE as a basis for empirical studies can help identify the most significant determinants and inform targeted interventions.

Practical implementation challenges

Effective governance, storage, and interpretation of IoT-generated data remain underexplored, leading to underutilization of potentially valuable insights for decision-making. Successful IoT integration requires bridging the gap between modern sensor-driven agriculture and traditional farming methods to ensure cultural acceptance and operational feasibility. Across the studies reviewed, the challenges to IoT adoption in agriculture can be systematically interpreted using the Technology–Organization–Environment (TOE) framework. In the technology dimension, recurring issues such as lack of interoperability, data privacy concerns, and limited scalability are prominent in the literature. The organization dimension is reflected in findings on farm size, managerial capacity, and financial readiness, which consistently influence the likelihood of IoT adoption, with larger and better-resourced farms showing higher uptake. The environment dimension is visible in external factors repeatedly highlighted by prior studies, including rural connectivity infrastructure, government policy support, and access to agricultural markets. By framing these literature-derived challenges within the TOE model, this review emphasizes that successful IoT integration in agriculture requires coordinated advances across all three domains. This perspective also provides a conceptual basis for future empirical studies to test targeted interventions, such as standardization protocols, rural broadband expansion, and farmer capacity-building programs.

Despite these deficiencies, the transformative potential of IoT in agriculture remains considerable. Overcoming these challenges will require coordinated efforts in developing standardized protocols, enhancing rural connectivity, providing training for farmers and technicians, and applying robust theoretical frameworks to guide both research and implementation.

CONCLUSIONS

This review synthesized recent research on IoT applications in agriculture and highlighted their potential to improve productivity, efficiency, and sustainability. IoT technologies—such as soil and weather sensors, wireless networks, drones, and data analytics—are enabling real-time monitoring, precise input application, and automation of key farm operations. These capabilities reduce water and fertilizer waste, enhance crop yields, and mitigate environmental impacts. However, adoption remains constrained by high upfront investment, limited rural connectivity, device interoperability issues, and concerns regarding data privacy and security. Additional challenges include lack of skilled manpower, uneven access for smallholders, and the absence of unified research frameworks. Future progress will require affordable, scalable IoT solutions, rural broadband expansion, standardization protocols for interoperability, and farmer-focused training programs. Integration with artificial intelligence, machine learning, and blockchain can further strengthen decision support and supply chain traceability. Coordinated support from policymakers, researchers, and industry will be essential to scale IoT-enabled smart farming and deliver climate-resilient, resource-efficient agriculture.

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