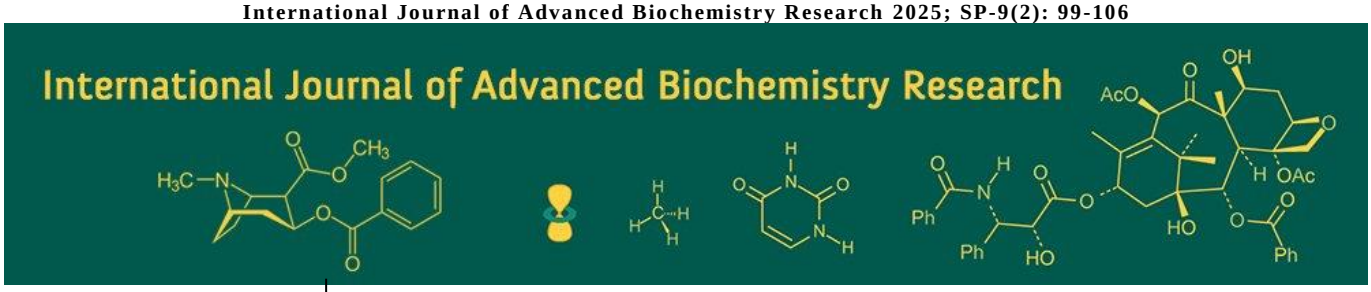

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Revolutionizing agriculture: IoT devices, applications, opportunities and challenges in smart farming

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Abstract
The Internet of Things (IoT) introduces smart devices together with sensors and automation systems which maximize agricultural resources and boost operational outcomes. IoT helps precision agriculture systems monitor real-time conditions of soil and irrigation together with weather patterns for sustainable agriculture. Through IoT applications livestock managers gain control in their fields while greenhouses can operate *via* automation and farmers can monitor their food deliveries throughout the entire supply chain to ensure quality standards. The advantages of IoT technology are balanced against vital challenges including scalability limitations as well as interoperability difficulties and environmental energy usage and security of data. The Indian market shows high adoption rates of IoT technology because government institutions and private organizations invest to support escalating food requirements throughout the nation. IOT technology enables farmers to create a sustainable and food secure future for agriculture by achieving sustainable management while meeting global food demands.

Keywords: IoT, precision agriculture, smart devices, automation systems, sustainability, food security

Introduction
The Internet of Things (IoT) functions as a revolutionary technology which transforms sectors of healthcare along with transportation and industrial automation. Agri-business stands to greatly profit from IoT implementation because it enhances output levels as well as optimizes resources consumption and sustains environmental preservation. Kevin Ashton defined Internet of Things in 1999 as the concept of linking physical devices to the internet which enables them to operate independently. According to the Food and Agriculture Organization of the United Nations (FAO) the worldwide population forecast shows 8 billion will exist by 2025 before increasing to 9.6 billion by 2050 (FAO, 2009) [18]. Precision agriculture implements various advanced technologies found in IoT systems to improve agricultural optimization processes within the framework of smart agriculture. Precision agriculture serves three core aims which combine improved agricultural output with reduced environmental strain and maximized usage of watering systems and energy supply together with fertilizer consumption (Kacira, Sase, Okushima & Ling, 2005) [27]. IoT applications in agriculture gained more attention based on the increasing number of published scientific documents (Kitchenham, 2004) [31].

Overview of IoT and Its Structure
IoT in agriculture functions with three key components including sensors and actuators and artificial intelligence technology which enhance agricultural practices and management decisions (Zaouiat & Latif, 2017) [10]. The implementation of IoT consists of interconnected devices which operate via wired and wireless links to share and gather information (Sadiku, *et al*., 2018) [34]. IoT contains three fundamental structures starting from perception layer (sensing) proceeding to network layer (data transfer) before ending at application layer (data storage and analysis) (Atzori, Iera & Morabito, 2010; Botta, de Donato, Persico & Pescape, 2014; Gubbi, Buyya, Marusic & Palaniswami, 2013) [7, 9, 21]. The evolution of IoT remains active because developers aim to increase its performance as they want complete seamless connectivity within multiple industries (Miorandi, Sicari, De Pellegrini & Chlamtac, 2012) [36].

IoT Layers in Agriculture

1. The perception layer contains multiple sensor technologies that include Wireless Sensor Networks (WSN) alongside Radio-Frequency Identification (RFID) and Near Field Communication (NFC). The collection of environmental data about soil moisture and temperature alongside humidity becomes possible through these technologies to optimize farming operations (Welbourne *et al*., 2009) [58].
2. Through network layer technology sensors can connect to either cloud platforms or computational systems for communication purposes. The data transmission process works efficiently through wireless communication protocols consisting of ZigBee, Sigfox, LoRa and 6LoWPAN (Gubbi *et al*., 2013) [21]. These protocols enable stable networking that supports instant monitoring and decision processes (Suhonen, Kohvakka & Kaseva, 2012) [54].
3. The application layer utilizes AI and big data analytics jointly with cloud computing capabilities to process distributed data after collection. The top layer contains decision systems which optimize irrigation and pest control activities as well as complete farm management processes. Cloud infrastructure connects to sensor networks through middleware solutions to achieve smooth data integration (Zorzi, Gluhak, Lange & Bassi, 2010) [63]. Industrial Internet of Things (IIoT) and Agriculture.

The Industrial Internet of Things (IIoT)

The Industrial Internet of Things (IIoT) applies IoT solutions across three main industrial domains of manufacturing operations and logistics systems and agricultural operations. IIoT expands across the agricultural sector by bringing together intelligent autonomous equipment alongside predictive analytics and cooperative human-machine systems that boost efficiency as well as productivity levels. IIoT allows agricultural businesses to implement next-generation sensors and automation technologies throughout their operation which produces improved output at decreased operational expenses (Suhonen, Kohvakka & Kaseva, 2012) [54].

The mechanism of middleware integrates cloud infrastructure and Service-Oriented Architecture (SOA) along with sensor networks in a generic way to deliver suitable deployment tools (Ghosh & Das, 2008) [20]. Artificial intelligence algorithms, machine learning technologies and model-based decision systems automatically process stored agricultural data for correction and integration before using them to derive knowledge for unmeasurable phenomena. The Internet of Things (IoT) has gradually established itself as a critical operational component in daily life during the recent period. (Abdullahi *et al*., 2021; Talavera *et al*., 2017) [1, 55]. The Internet of Things (IoT) is the technology which links embedded devices to internet connections through the technology field. The technology consists of actuators together with network connectivity and transducers and sensors which enable devices to exchange information and collect data (Singh *et al*., 2014) [52]. Advanced technologies including IoT form an integral part of the smart agriculture movement which applies systematic technological integration to the agricultural domain. The main purpose of this system rests on enhancing both agricultural yield quantity while also improving crop quality output (Muntjir, *et al*., 2017; Srilakshmi *et al*., 2018) [37, 53]. Through IoT technology farmers obtain remote capabilities to monitor their agricultural operations alongside controlling them. The innovative technology enables both the straightforward creation and detailed supervision of expansive agricultural businesses (Jaiganesh, *et al*., 2017) [25]. The implementation of IoT has extended over multiple fields along with smart farming which Ahmed *et al*. (2018) [38] examines. The IoT exists in various forms such as smart farming (Ahmed *et al*., 2018) [38] and connected drones (Chen & Wang, 2018) [13] among other situations. Agriculture provides a vital function for global economic systems and Indian citizens sustain their living through agricultural activities (Arunlal & Rajkiran, 2018) [6]. The primary objective of IoT involves connecting physical entities to digital elements through digital communication systems and information transfers (Vermesan, 2010) [57]. Scientists studied how sensors could gather data about ground parameters specifically soil temperature and moisture content and weather forecasts that allowed them to automate irrigation procedures (Alhasnawi, *et al*., 2020) [4]. This research investigates the difficulties faced in implementing IoT in agriculture through security enhancements for smart farming based on Farooq, *et al*. (2019) [19]. The research analyzes essential subjects by discussing advanced technologies together with industry patterns and government standards. A different study investigates IoT-enabled smart farming with comprehensive detail in its analysis. The research analyzes relevant scholarly works about smart farming and precision agriculture and IoT integration in smart agriculture using literature review methodology. Smart farming with IoT benefits from this research which delivers essential information about research methodologies and classification networks as well as citation bursts (Huo, *et al*., 2024) [23]. Liu, *et al*. (2020) [60] studied industrial agricultural situations while analysing industrialized agro-production models in operation. The availability of several agricultural land-based robots enables farming operations and extends human capabilities for various task types Pretto *et al*., 2020 [44] and Jiang, *et al*. 2019 [42] developed real-time disease identification for apple leaves by utilizing improved CNNs as a deep learning approach. The IETF constrained restful environments (CoRE) working group Shelby and co-authors describe Constrained Application Protocol (CoAP) as an IoT based application layer protocol. The protocol offers REST-based web transfer functionalities together with HTTP functions. The CoAP performs efficiently through UDP enabling better IoT applications. Crop development and output performance observation remains crucial for agricultural management across cultivation periods. IoT enables farmers to monitor and handle livestock operations. The farmer can track livestock through remote surveillance by using IoT devices. Maroto-Molina and his colleagues created a low-cost IoT-based system for livestock monitoring with GPS collars connected to Sigfox network and Bluetooth tags (2019). The WiLD network serves as a wireless sensor network-based solution that implements fog computing architecture for intelligent agricultural observation according to Ahmed *et al*. 2018 [38].

Common IoT Devices in Agriculture

The integration of the Internet of Things (IoT) in agriculture has revolutionized traditional farming practices by

introducing a wide range of smart devices and systems. These innovations enhance efficiency, optimize resource utilization, and boost productivity. Below are some notable IoT devices transforming the agricultural landscape:

- **Smart Irrigation Systems:** Automated irrigation controllers, including mobile-based pump-set/motor controllers and Internet-of-Pumps solutions, ensure precise water distribution. The study Stated that the IoT-based smart irrigation management systems with regard to efficient water resource usage in precision farming. The research also focused on using sensors to collect data on ground parameters, for instance, soil temperature and moisture, as well as weather forecast data, including environmental conditions, to predict irrigation requirements and automate the irrigation process (Alhasnawi, *et al*., 2020) [4].
- **Water Management Sensors:** Devices such as water supply meters, ground water level sensors, and soil moisture sensors enable real-time monitoring of water usage and soil conditions.
- **Advanced Monitoring Systems:** Groundwater monitoring nodes, wireless sensor nodes, and weather gauges (measuring wind, humidity, temperature, etc.) provide essential data for informed decision-making.
- **Integrated Sensor Nodes:** Multi-sensor nodes combining soil moisture, temperature, and humidity sensors, as well as complete setups including rain gauges and water monitoring nodes, optimize irrigation practices such as Alternate Wetting and Drying (AWD).
- **Automated Agricultural Machinery:** Autonomous tractors, drones and robotic systems for spraying, weeding, and harvesting enhance efficiency and reduce labor dependency.
- **Smart Farming Applications:** Mobile apps for sowing, harvesting, and watering, along with soil health meters, provide real-time guidance and analytics.
- **Livestock and Aquaculture Management:** Chips in animals for tracking, pond automation systems like Pond Guard and Shrimp Talk, and automatic feeders streamline livestock and aquaculture operations (Navarro, *et al*., 2020) [39].
- **AI-Powered Imaging and Analysis:** Cameras as sensors for image and video-based crop monitoring, yield-mapping imagery *via* remote sensing and picture-based insurance apps like WheatCam provide data-driven insights.
- **Renewable Energy Solutions:** Solar panels and windmills offer sustainable power sources for farming operations.
- **Precision Agriculture Tools:** GPS for accurate positioning, food processing plants on wheels, and POS/smart card/Kisan Credit Card (KCC) systems enhance logistics and financial accessibility.
- **Security and Monitoring Devices:** Neck-mounted triggers for cattle boundary management and intrusion detection systems for farms ensure livestock safety and property protection.
- **Smart Communication Platforms:** Mobile phones integrated with IoT apps facilitate real-time monitoring, alerts, and expert consultations via SMS or online platforms.

Applications of Internet of Things (IoT) in Agriculture

The Internet of Things (IoT) transforms various sectors especially agriculture through efficiency improvements while maximizing resource optimization and improving production efficiency. Through IoT implementation in agriculture managers gain real-time surveillance which helps them accomplish precision agriculture technology while operating smart greenhouses for livestock oversight and automated farming systems thereby improving sustainability and decreasing environmental footprints. The document examines IoT applications in agriculture while drawing evidence from Saini and Prakash (2020) [45] and Ravindra (2020) [50].

Smart Farming

Farmers implement Information and Communications Technology (ICT) systems with agriculture to develop automated processes which optimize farming operations. Through IoT-based smart farming systems operators achieve better resource management as well as real-time monitoring which strengthens the agricultural production system. The system relies on sensors together with automated systems and artificial intelligence capabilities to maximize water distribution paired with soil quality examination alongside increased harvest rates (Saini & Prakash, 2020; Ravindra, 2020) [45, 50]. A research study confirmed how integrating IoT technology in agriculture enables smart farming system development to boost sustainability and boost resource efficiency and modern agriculture productivity levels (Dhanaraju, *et al*., 2022) [15]. The government provides backing for IoT integration in agriculture while major corporations make investments toward progressive farm management systems. The research discusses both challenges and benefits of IoT implementation in smart agriculture by examining wireless sensors together with their applications throughout soil preparation and crop monitoring and irrigation systems and pest detection and supervision stages (Ayaz, *et al*., 2019) [8].

Greenhouse Farming

Greenhouse farming, one of the earliest forms of smart farming, benefits significantly from IoT integration. Real-time data collection from IoT sensors allows monitoring essential greenhouse factors that include lighting, humidity, soil condition, temperature and pressure. The integration of this technology ensures perfect environmental conditions for crops to produce better yields with minimum human involvement (Lopez-Morales, *et al*., 2021) [24].

IoT-Enabled Irrigation Systems

Useful IoT solutions offer water amounts appropriate for irrigation and determine proper irrigation timing according to Lopez-Morales *et al*. (2021) [24]. The irrigation sector has progressed significantly because of implementing IoT-based pressurized water distribution technologies. Irrigation systems employing IoT sensors achieve water efficiency through their ability to transmit accurate water volumes that depend on soil moisture and environmental elements. Through its application the system minimizes water usage and enhances agricultural growth (Chalimov, 2020) [12].

Agricultural Drones

Drones play a crucial role in modern precision agriculture by providing real-time aerial data to farmers. These drones

are equipped with sensors and cameras to perform field analysis, assess crop health, and generate actionable insights. Notably, drones can spray fertilizers 40 times faster than manual methods, significantly reducing labor costs and improving efficiency (Bamigboye & Ademola, 2016) [17].

Weather Monitoring and Predictive Analytics

Weather conditions play a pivotal role in agricultural productivity. IoT-enabled weather stations monitor parameters such as temperature, humidity, light intensity, and soil moisture. This data aids in predictive analytics, allowing farmers to make informed decisions about crop cycles, irrigation, and pest control (Yu & Teng, 2014; Khelifa *et al*., 2015) [61, 30].

IoT in Livestock Management

The adoption of IoT technology establishes effective livestock tracking systems which use smart tags and sensors. The tracking devices collect data about animal position and wellness together with their behavioural patterns to help farmers better handle their livestock population. By using IoT-powered tracking tags farmers benefit from satellite tracking that creates virtual boundary systems for their domesticated animals while lowering their losses and tracking their movements (Jayaraman *et al*., 2015) [26]. Precision livestock farming emerged as a main application of livestock farming with monitoring systems and early warning alerts as well as management control functions (Scalera, A., *et al*., 2013) [51].

Aquaculture and Fisheries

IoT applications in fisheries primarily focus on water quality monitoring and aquaculture information systems. Sensors track parameters such as water temperature, pH levels, and oxygen content, ensuring optimal conditions for aquatic species. This technology contributes to sustainable fish farming and enhances productivity (Xing, *et al*., 2013) [59].

Food Safety and Supply Chain Management

Food traceability is a significant application of IoT in the agri-food sector. IoT-enabled tracking systems ensure end-to-end visibility in the supply chain, allowing real-time monitoring of food quality and safety. The Electronic Product Code Information Services (EPCIS) standard plays a crucial role in codifying supply chain events, ensuring transparency and reducing food fraud (Liu, *et al*., 2012; Li & Shan, 2013) [33, 32].

Precision Agriculture

Precision agriculture involves the use of electronic sensors and IoT devices to collect, analyse, and act on spatial and temporal data. It includes technologies such as remote sensing, automated irrigation, and predictive crop modelling to enhance efficiency and sustainability. Many studies highlight the benefits of IoT in precision agriculture, focusing on sustainability, pest management, and early warning systems (Min, *et al*., 2014) [35].

IoT-Enabled Smart Devices in Agriculture

Several IoT devices have been developed to enhance agricultural productivity, including:

- **Wireless Nodes:** Sensors for soil temperature, humidity, and moisture (Khattab *et al*., 2016) [29].
- **Smart Irrigation Systems:** Automated irrigation controllers and sensors (Lopez-Morales, *et al*, 2021) [24].
- **Drones and Autonomous Tractors:** Used for crop monitoring, fertilization, and field analysis (Sadiku, *et al*., 2018) [34]
- **Weather Stations:** Real-time environmental monitoring (Bamigboye, *et al*., 2016) [17].
- **GPS Tracking Devices:** Used for mapping and location tracking (Brewster, *et al*. (2016) [11].
- **Automated Spraying Robots:** Reducing labor and improving efficiency.
- **IoT-Enabled Value Chain Management:** Enhancing logistics, traceability and supply chain transparency.

Advantages of IoT in Agriculture

The integration of IoT in agriculture offers numerous benefits, including:

1. **Enhanced Decision-Making:** IoT-based data analytics help farmers make informed decisions on crop cycles, irrigation, and resource allocation (Reiche, *et al*., 2012; Kaloxylos, *et al*., 2013) [47, 28].
2. **Increased Efficiency:** Smart farming techniques reduce resource wastage and increase overall productivity.
3. **Environmental Benefits**: IoT applications aid in groundwater conservation, reduce carbon footprints, and prevent fertilizer runoff.
4. **Reduced Manual Intervention:** Automation minimizes the need for human labor, reducing costs and increasing operational efficiency.
5. **Improved Crop Yields**: Precision farming techniques ensure optimal conditions for plant growth, leading to higher yields.
6. **Cost Savings:** Efficient resource utilization reduces operational costs, maximizing profitability.

Progress of IoT in World Agriculture

Global agricultural operations experience major practice transformations through Internet of Things implementation in agriculture. Drones serve as essential agricultural innovations that will assist throughout the complete crop lifecycle management cycle by providing capabilities for soil and field analysis and the execution of planting activities and spraying procedures as well as real-time monitoring and irrigation management and plant health evaluation. Research from the United Nations Global Compact (2000) shows that 80% of agricultural enterprises expect digitizing agriculture will make them more competitive (2000). The United States has shown increased implementation of IoT devices in agriculture since 2015 when 30 million devices were adopted until reaching 75 million by 2020. The implementation of drones in agriculture led to a digital revolution which implies an estimated industry value over US$127 billion for drone-based solutions across all sectors. Markets and Markets (2014) demonstrates that digital-based agricultural services maintain a 12.2% annual growth rate from 2014 until 2020. The digital agriculture market was predicted to extend to US$15 billion during 2021. A survey shows digital agriculture holds the potential to provide decreased competition advantages for 80% of agribusinesses (United Nations Global Compact, 2000).

Progress of IoT in Indian Agriculture

The Indian agricultural sector has experienced substantial improvements through IoT technology because technology giants have formed alliances with government institutions. Through their partnership with Microsoft's Azure FarmBeats the companies Infosys and Tata Consultancy Services as well as SkyMet and Indian Space Research Organization (ISRO) have established a comprehensive agricultural technology data network of providers and sensors. The Andhra Pradesh state government alongside the Bill & Melinda Gates Foundation and Dalberg Advisors have launched 'SmartFarming 4 AP' as one of their key initiatives. The government initiative delivered services directly to solve major difficulties that small and marginal farmers in the state experience. The Indian government supports farmers by establishing two major digital information systems through e-NAM for market access and I-KISAN for improved decision making. Despite numerous technology systems in existence they remain separate systems because they lack connections between banking services together with agricultural information and market data. The field of IoT in agriculture benefits from the creative approaches developed by numerous Indian startup organizations. SatSure uses satellite imagery and IoT-based analytics together with weather data to give farmers insurance coverage against loss in addition to financial security through their data analytics company. Radio Monsoon operates as a safety platform for southern Indian fishermen who receive immediate weather reports via maritime communication channels. Another pioneering initiative is Krishi Suchak, an application developed by Bangalore-based Nubesol Technologies. Functioning like WhatsApp, this app enables smallholder farmers to seek advice from agricultural experts, ensuring timely decision-making and improved crop management. In summary, IoT-driven advancements in both global and Indian agriculture continue to revolutionize traditional farming methods. With increasing adoption of smart technologies, digital platforms, and data-driven decision-making tools, the agricultural sector is poised for sustained growth and enhanced efficiency in the years to come.

New Opportunities and Perspectives on the Internet of Things (IoT) for Indian Agriculture

India is on the path to becoming the most populous country in the world. As of 2019, its population stood at approximately 1.37 billion and is projected to reach 1.64 billion by 2050. To meet the rising food demand, agricultural production must increase by at least 20% over the next three decades. Over 70% of rural households in India derive their survival from agriculture while the workforce that depends on this sector directly or indirectly constitutes more than 60% of the working population. The sector experienced substantial expansion after the 1960s because of high-yielding varieties (HYVs) technology together with chemical fertilizers. Technology developments over the past years emphasize both boosting agricultural productiveness and sustainability in Indian agriculture systems. The Internet of Things (IoT) serves as a disruptive technology which will transform modern agricultural operations. Through IoT applications in agriculture farmers can make data-based decisions together with automated precision techniques to achieve high productivity levels and sustainable agriculture outcomes. NABARD designed regulatory policies for incorporating IoT solutions with financial inclusion schemes to boost sustainable agricultural practices. Through the implementation of IoT technology farmers obtain the ability to run their farming operations independently from state supervision. Through proper decision-making farmers achieve better resource utilization and reduced costs and enhanced profits. Digital financial solutions powered by IoT help clients handle their deals in better ways and gain full visibility into their financial transactions and tightly monitor their expenses. The implementation of IoT technology helps farmers to improve their productivity as well as supports agricultural GDP development while preserving long-term sustainability. Government policies advance innovative technologies through their support of infrastructure development and their promotion of value creation along with agricultural business expansion and their generation of rural employment and their maintenance of fair economic living conditions for farmers.

The Need for New Technologies in Indian Agriculture

The majority of Indian farmers especially those operating smaller farm units experience obstacles when trying to obtain agricultural extension services even after technological progress occurred. Progress in the Green Revolution together with agricultural advancements created deeper divisions between farmers who are technologically advanced versus those who are resource limited. Indian agriculture currently faces major environmental consequences because farmers have abused electrical and mechanical and chemical-based agricultural technologies by overusing them yet this destroys long-term sustainability. Indian agriculture faces problems with labor shortages together with limited resources and a decreasing trend in agricultural profitability. The Internet of Things presents a promising solution to farm management problems that creates stable economic conditions for agricultural work. The implementation of Internet-connected precision agriculture systems enables farmers to track information from sensors alongside drone and automatic irrigation systems thereby maximizing resource efficiency while cutting labor needs and improving total operational performance. Rural farms gain three main benefits from smart technologies through hazard risk reduction and enhanced yield predictions together with sustainable agricultural practices. The adoption of IoT technology coupled with other smart solutions will establish a technology-intensive farming infrastructure that protects the Indian agricultural sector from future disturbances. Through government backing combined with infrastructure projects and educational programs about IoT farmers will receive empowerment to push agriculture toward transformation in India.

Adoption of IOT in agriculture

Internet of Things (IoT) technology has revolutionized agriculture by carrying out automated farming processes and improving agricultural efficiency while increasing production levels. Current livestock management practices which use cattle detection services need substantial manual involvement to function properly therefore they increase operational expenses while elevating power usage and water consumption levels. IoT-based systems acquire environmental parameters including temperature, humidity,

soil moisture and pH which produce precise data to drive better choices and optimize resource utilization. IoT technologies operate as the foundation for smart agriculture to manage water and land resources effectively because the global agriculture sector serves an expanding population base. Such systems allow farmers to effectively manage crops through automated monitoring of temperature control along with humidity management alongside soil condition regulation without human intervention. The efficiency of farming operations has increased because IoT applications now cover pest control and weather monitoring and nutrient management and greenhouse management tasks. The utilization of IoT technology in agriculture enables water preservation as well as the reduction of fertilizer waste and energy costs. The technology provides affordable approaches to collect and manage data to enhance livestock health outcomes and production levels. The Internet of Things resolves worker deficits by introducing machine control for daily tasks which leads to operational efficiency increases and lowered expenditures while increasing yield production and breeding period optimization by detecting heat cycles. An IoT-based approach analyzes waste to generate new profit streams which results in sustainable alongside profitable operations in farming businesses.

Challenges

As the integration of Internet of Things (IoT) technologies into agriculture advances, several critical challenges need to be addressed to ensure its widespread adoption and optimal use. These challenges span various aspects, from scaling up adoption and ensuring interoperability to overcoming hardware and energy management issues.

Scaling and Interoperability Challenges

One of the most pressing issues is scaling up the usage of interoperable IoT technologies beyond early adopters, especially among farmers and food companies. Many existing solutions are complex and costly, making them less accessible to the majority of users, especially small-scale farmers. To overcome this barrier, the simplification of these technologies and improvements in affordability are crucial. This would ensure that IoT solutions are attractive, usable, and beneficial for a broader audience, which is essential for the sustainable growth of IoT in agriculture. Additionally, appropriate business models are necessary to support very small companies. These models should include a systematic economic analysis of costs and benefits, helping stakeholders understand the value proposition and enabling cost-effective implementation.

Ensuring reliable and stable wireless communication, particularly in remote areas such as fields or stables, is another challenge. These areas often have limited coverage and bandwidth, which can affect the performance of IoT systems. To address this, improving wireless communication infrastructure and using technologies with robust coverage capabilities are critical.

Another major hurdle is the development of trustworthy security, privacy, and data ownership solutions. In IoT networks, which involve a vast number of stakeholders ranging from small and medium enterprises (SMEs) to large corporations and authorities, managing data securely and ensuring that the rights of all stakeholders are respected is essential. This requires strong encryption, access control mechanisms, and clear frameworks around data usage and ownership.

Hardware and Energy Management Challenges

In terms of hardware, IoT devices must remain functional and reliable for long periods, often in challenging environmental conditions. Many of these devices operate on battery power, and ensuring long battery life is a significant concern. In addition, the fabrication, delivery, and disposal of IoT hardware contribute to environmental waste, including both solid and toxic waste. As IoT technology proliferates, managing the environmental impact of these devices will become increasingly important. Energy management remains a critical challenge, particularly in systems with a large number of devices. In cases where a node is responsible for routing communication tasks for multiple devices, its disconnection from the network can lead to a partial or even total network failure. This underlines the importance of robust energy management strategies to ensure network continuity and reliability.

Interoperability and Networking Challenges

The main challenge stems from data exchange needing to become smooth across diverse technological frameworks. Different devices and systems can share information through open application programming interfaces (APIs) and service-oriented architecture (SOA) technology and semantic web technology. To implement IoT-based agriculture organizations need a worldwide standard framework that facilitates the approach. The absence of standardized protocols together with frameworks creates device and system incompatibilities that reduces the efficiency and scalability of IoT solutions.

Networking as well as area coverage problems emerge as critical issues that affect the performance of large-scale IoT systems. Several IoT devices depend on low-power wide-area networks (LPWAN) for long-distance connections although these types of networks experience areas without coverage. It is crucial to establish enough coverage throughout rural and remote networks because this ensures continuous data transmission between IoT devices and central systems. It becomes crucial for IoT-based agricultural systems to investigate technology advancements that will both widen coverage and boost energy conservation to improve system performance.

Conclusion

The Internet of Things (IoT) is revolutionizing agriculture by enhancing productivity, optimizing resource usage, and ensuring sustainability. Through precision farming, real-time monitoring and automation, IoT addresses critical agricultural challenges such as water scarcity, climate change, and labor shortages. While the adoption of IoT in agriculture continues to grow, challenges related to interoperability, security and energy management must be addressed for seamless implementation. Government policies and private investments are crucial in driving IoT-based smart farming. As technology evolves, IoT will play a significant role in global food security, making agriculture more efficient, resilient, and sustainable for future generations.

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