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Review of IoT Networking Protocols and Sensor Integration for Smart Irrigation and Soil Monitoring

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ABSTRACT
The agricultural sector is undergoing a digital transformation to meet the demands of a growing global population, climate variability, and the need for sustainable resource management. The Internet of Things (IoT) has emerged as a critical enabler of smart agriculture, integrating sensor technologies, wireless communication networks, and data transmission protocols to support real-time monitoring and decision-making. This review paper provides a comprehensive analysis of IoT applications in agriculture, focusing on soil monitoring, smart irrigation, and precision farming. It examines key components such as wireless sensor networks (WSNs), data acquisition systems, communication protocols (e.g., LoRaWAN, Zigbee, NB-IoT), and cloud-based analytics platforms. The paper also discusses the benefits of IoT systems, including improved crop yields, reduced water and fertilizer usage, and enhanced operational efficiency. Furthermore, it outlines the current challenges in connectivity, scalability, interoperability, and energy efficiency. By synthesizing recent advancements and research trends, this review aims to guide future developments in IoT-enabled agricultural systems and contribute to the growing field of smart and sustainable farming practices.

Keywords **- Sustainable Agriculture, Internet of Things (IoT), Precision Farming, Smart Irrigation, Resource Optimization**

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I. INTRODUCTION

The Internet of Things (IoT) has emerged as a transformative technology across multiple industries, including agriculture. In the domain of smart farming, IoT refers to the seamless integration of sensor nodes, embedded systems, and wireless communication protocols to enable real-time data acquisition, transmission, and analysis. This networked ecosystem supports precision agriculture by facilitating data-driven decision-making and automating key agricultural processes.

Through the deployment of distributed sensor networks, farmers can monitor vital environmental and soil parameters such as moisture content, temperature, humidity, and nutrient levels. The data captured is transmitted via low-power wide-area networks (LPWANs) or other communication protocols such as Zigbee, LoRaWAN, and NB-IoT to cloud-based or edge-processing platforms for actionable insights [1]. These insights enable precise resource allocation in irrigation, fertilization, and pest management, reducing environmental impact and improving crop yield [2].

Moreover, IoT architectures facilitate remote monitoring in livestock farming by using connected devices to track animal health, movement, and behavior patterns. Early anomaly detection systems supported by sensor data improve animal welfare and streamline farm management practices [3].

The integration of heterogeneous data sources—including weather forecasts, market trends, and historical datasets—further enhances decision support systems in smart farming. By leveraging real-time and predictive analytics, farmers can minimize operational risks, optimize input usage, and improve productivity and sustainability.

This paper explores the underlying IoT communication frameworks, data transmission technologies, and sensor deployment strategies that form the backbone of smart agriculture systems. While numerous studies have focused on individual technologies or systems in smart agriculture, this review paper uniquely synthesizes the application of IoT communication protocols and sensor systems specifically for smart irrigation and soil monitoring. It bridges the gap between technical infrastructure and practical deployment challenges, providing an integrated view that includes hardware platforms, wireless standards, and real-world sustainability implications. Unlike other reviews, this paper consolidates findings on both wireless protocol comparison and sensor technology trends, offering a comprehensive resource for researchers developing sustainable and scalable smart farming systems.

II. LITERATURE REVIEW

2.1 Background

The application of Internet of Things (IoT) technologies in agriculture has enabled the transition from traditional farming practices to intelligent, data-driven systems that promote operational efficiency and sustainability [4]. By integrating embedded systems, wireless sensor networks (WSNs), and communication protocols, smart farming facilitates the continuous monitoring and control of environmental and agronomic parameters in real time.

Key IoT components such as Arduino-based microcontrollers, LoRa (Long Range Radio), and Zigbee provide the necessary hardware and communication infrastructure for transmitting sensor data across vast and often remote agricultural fields. These low-power, long-range wireless protocols are critical for supporting large-scale sensor deployments with minimal energy consumption. WSNs serve as the backbone of this architecture, enabling distributed sensing across multiple nodes that capture soil moisture, temperature, humidity, and crop health indicators [5], [6].

The collected data is transmitted to centralized or edge-based computing platforms for further processing. Cloud computing environments are often employed to store, manage, and analyze this data at scale. Through data analytics and machine learning algorithms, actionable insights are derived to support informed decision-making in irrigation scheduling, fertilization planning, and pest control. This technological ecosystem not only enhances productivity but also contributes to the development of sustainable agricultural infrastructure by reducing resource waste and minimizing environmental impact.

The integration of IoT-enabled networking technologies in agriculture exemplifies a paradigm shift toward scalable, adaptive, and environmentally conscious farming practices. This work explores the communication protocols, sensor technologies, and data processing frameworks that collectively define the IoT landscape in sustainable agriculture.

The primary objective of this study is to present a detailed technical analysis of how Internet of Things (IoT) technologies are integrated into smart farming to support sustainable agricultural practices. Specifically, this work examines the underlying data transmission protocols, soil monitoring sensor architectures, and irrigation control systems that form the backbone of IoT-driven agricultural infrastructure. The study investigates how technologies such as LoRa, Zigbee, NB-IoT, and wireless sensor networks enable reliable communication and real-time data exchange in diverse farming environments.

Additionally, this paper aims to highlight the role of embedded platforms (e.g., Arduino) and cloud-based analytics in optimizing the collection, transmission, and utilization of environmental data. Through this analysis, the study seeks to demonstrate how IoT-enabled systems can enhance operational efficiency, reduce resource consumption, and support the development of scalable, adaptive, and sustainable farming solutions.

2.2. Synthesis of Findings and IoT-Driven Sustainable Agriculture

Efficient and reliable data transmission is the backbone of IoT-enabled smart agriculture, ensuring seamless communication among distributed sensors, devices, and cloud-based platforms. This interconnected architecture supports sustainability by enabling real-time monitoring, precision control, and data-driven decision-making across farming operations.

1. Sensor Networks and Data Acquisition

IoT-based agriculture leverages distributed sensor networks to acquire real-time environmental and agronomic data. These sensors—responsible for measuring soil moisture, temperature, humidity, pH levels, and crop vitality—serve as input nodes in a wireless sensor network (WSN). The collected data is preprocessed and transmitted through communication protocols to central gateways for further analysis, laying the foundation for data-informed, sustainable practices [7].

2. Wireless Communication Technologies

A variety of communication protocols are employed to ensure low-power, long-range, and high-reliability data transmission. Protocols such as LoRaWAN, Zigbee, Wi-Fi, NB-IoT, and satellite links are selected based on deployment scale, terrain, and power constraints. LoRa and Zigbee are preferred in rural or remote fields for their mesh and star topology capabilities, ensuring robust connectivity across sensor nodes. Satellite imaging complements terrestrial data by offering remote-sensing capabilities that enhance macro-level decision-making in sustainable land use and crop health monitoring [8], [9].

3. Edge Processing and Real-Time Monitoring

Edge-enabled IoT devices perform on-site data processing and anomaly detection before transmission, minimizing latency and reducing bandwidth usage. This localized intelligence enables real-time responses to critical events such as water shortages or pest infestations. Data is accessible to stakeholders through IoT dashboards and mobile applications, ensuring rapid intervention and adaptive farm management strategies [10].

4. Cloud Integration and Scalable Infrastructure

Sensor data is transmitted securely to cloud infrastructure, where it is stored, integrated, and managed at scale. Cloud platforms provide elastic storage and computing capabilities for processing high-frequency, high-volume agricultural data. This supports centralized monitoring, remote diagnostics, and predictive analytics, enabling smarter resource allocation and reduced environmental footprint [11].

5. Big Data Analytics and Predictive Modeling

IoT platforms employ data analytics and machine learning models to uncover patterns and predict outcomes related to crop yield, irrigation cycles, and pest outbreaks. These insights empower farmers to implement site-specific strategies, minimizing resource wastage and maximizing productivity. Data-driven optimization contributes to the resilience and sustainability of agricultural systems [12], [13].

6. Decision Support Systems (DSS)

Real-time alerts and automated rule-based decision engines enhance responsiveness in smart farms. DSS systems integrate multi-modal data streams to recommend or execute timely actions, such as activating irrigation based on soil dryness thresholds or adjusting fertilizer use according to nutrient levels. These automated interventions are key to sustainable resource management [14], [15].

7. Multi-Source Data Integration

Comprehensive farm management systems merge IoT-derived sensor data with external data sources such as meteorological forecasts, historical crop performance, and commodity prices. This fusion of data supports end-to-end decision-making—from crop planning to market delivery—promoting operational efficiency and ecological sustainability [16], [17].

2.3. Technologies Employed for Sustainable Infrastructure in Modern Agriculture

The deployment of intelligent and energy-efficient technologies is fundamental to building sustainable agricultural infrastructures. These technologies enhance data acquisition, enable real-time monitoring, and support informed decision-making, which collectively optimize input use, reduce waste, and increase productivity. The following technologies represent key enablers of sustainability in modern smart farming systems:

1. Arduino-Based Sensor Platforms

Arduino, an open-source microcontroller platform, is widely adopted for developing custom low-cost IoT devices in agriculture. These devices integrate capacitive soil moisture sensors, temperature, humidity, and light intensity detectors to collect real-time environmental data. Wireless modules allow the seamless transmission of this data to a central processing unit, supporting adaptive irrigation and resource optimization strategies [18], [19].

2. LoRa (Long Range) Communication

LoRa technology supports long-range, low-power data transmission, making it ideal for large-scale agricultural deployments. Sensors embedded across expansive farmland can communicate effectively over several kilometers, enabling precision monitoring of soil health, crop status, and climatic variables with minimal energy consumption. LoRa’s scalability and low maintenance requirements contribute significantly to lowering the ecological footprint of sensor networks [20], [21].

3. Zigbee-Based Wireless Systems

Zigbee offers low-data-rate, short-range wireless communication with minimal energy consumption, suitable for intra-farm sensor networks. These systems connect multiple nodes—such as temperature and humidity sensors—to a central gateway, supporting real-time environmental monitoring and automation. Zigbee’s mesh topology enhances network robustness and extends battery life in agricultural monitoring applications [22].

4. RFID (Radio Frequency Identification)

RFID technology enhances traceability and inventory management in agriculture. RFID tags can track crop batches, monitor environmental conditions, and automate fertilization or irrigation schedules. Integration with sensor data and automation systems supports efficient farm operations, reduces manual errors, and contributes to overall sustainability goals [23].

5. NodeMCU (ESP8266-Based IoT Module)

NodeMCU integrates Wi-Fi-enabled microcontrollers for efficient soil monitoring and environmental sensing. It supports the collection of real-time data on parameters such as soil moisture and temperature, with capabilities for remote monitoring via cloud platforms. This cost-effective module facilitates scalable deployment of smart farming solutions [24].

6. Raspberry Pi for On-Site Processing

Raspberry Pi acts as a central processing hub for integrating sensor inputs and executing data analytics locally. It supports automated irrigation, environmental control, and real-time visualization, reducing reliance on external computing resources. Its affordability and versatility make it an accessible tool for developing scalable smart farming applications [25].

7. Precision Farming Systems

Precision agriculture integrates smart boards, GPS-enabled devices, and wireless sensor networks to enable site-specific management of farming operations. By continuously monitoring key environmental parameters and combining them with spatial data, these systems enable fine-tuned interventions that reduce input overuse and enhance sustainability [26].

8. Smartphone-Based Soil Imaging

Smartphone imaging combined with machine learning offers a non-invasive and accessible method to estimate soil properties such as texture, color, and moisture content. Image analysis tools predict soil organic matter and fertility levels, enabling farmers to make informed soil management decisions using only widely available mobile technology [27].

9. Fuzzy Logic Controllers for Soil Health

Fuzzy logic-based systems are used to process uncertain and imprecise sensor data in dynamic agricultural environments. By incorporating variables such as soil type, historical rainfall, and crop requirements, fuzzy logic enhances irrigation and fertilization scheduling, ensuring optimal resource allocation under variable conditions [28].

Table 1. Comparison of technologies employed for sustainable infrastructure in modern agriculture.

Reference No.	Arduino	LoRa	Zigbee	RFID	NodeMCU	Raspberry Pi	Fuzzy Logic	Cell Phone Images
[18]	√							
[19]	√							
[20]		√						
[21]		√						
[22]			√					
[24]					√			
[25]						√		
[27]								√
[28]							√	
[29]	√							
[30]	√							
[31]				√				
[32]	√							
[33]	√							
[34]		√						

These technologies support sustainable infrastructure in agriculture by improving resource management, reducing waste, and enhancing efficiency. Their integration into farming practices helps promote environmental stewardship and supports the development of resilient and sustainable agricultural systems

2.4. Advancement in Soil Moisture Sensing for Sustainable Farming

Soil moisture monitoring sensors are vital components in sustainable agriculture, providing real-time data on soil moisture levels to optimize water use and reduce waste. By accurately measuring soil moisture, these sensors help farmers apply the right amount of water, which is crucial for sustainable irrigation practices [29]. This precision prevents over- or under-irrigation, thus conserving water resources and reducing the risk of water stress or waterlogging, which can adversely affect plant health and yield [30].

Furthermore, soil moisture sensors facilitate the monitoring of soil water availability over time, allowing for the identification of trends and patterns in moisture levels [31]. This information is essential for making informed decisions about irrigation scheduling and planning, leading to more efficient water usage and enhanced crop productivity [29]. Integration with automated irrigation systems allows for remote management and adjustment based on real-time data, minimizing manual labor and ensuring precise irrigation even in extensive agricultural operations [32], [33].

Overall, soil moisture monitoring sensors are crucial for sustainable farming by providing essential insights into soil water content. They enable effective irrigation management, conserve water resources, and contribute to optimized crop production.

Several types of soil moisture sensors contribute to sustainable infrastructure in agriculture:

1. Tensiometers – These sensors measure soil moisture by evaluating the tension or suction created by soil water potential. They use a ceramic tip connected to a water-filled tube, which provides data on soil moisture as the soil dries out, promoting efficient water use.

2. Capacitance Sensors – Utilizing the dielectric constant of the soil, capacitance sensors measure soil moisture with two electrodes that create an electrical field. Changes in the dielectric constant due to varying soil moisture levels are detected, facilitating accurate moisture measurement and supporting water conservation efforts [34], [35].

3. Time Domain Reflectometry (TDR) Sensors – TDR sensors determine soil moisture by sending an electromagnetic pulse through a soil probe. The reflected pulse, altered by soil moisture content, allows for precise moisture level calculations, aiding in sustainable water management practices [19].

4. Electrical Resistance Blocks – These sensors gauge soil moisture based on electrical resistance changes between two electrodes inserted into the soil. The variations in resistance with soil moisture levels help in maintaining optimal irrigation and supporting sustainable water usage.

5. Neutron Probe – By emitting fast neutrons and measuring the number of slow neutrons returned, neutron probes assess soil moisture content. This

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method supports sustainable irrigation by providing accurate moisture measurements, reducing unnecessary water application.

6. Photovoltaic-Powered Soil Moisture Sensors – These self-sustaining sensors use solar energy to operate, combining soil moisture sensing technology with photovoltaic cells. They offer a sustainable solution with reduced reliance on external power sources and lower operational costs, although performance may vary.

8. Disposable Soil Moisture Sensors – Designed for one-time or limited use, disposable sensors offer a cost-effective solution for gardening and small-scale agriculture. While convenient and affordable, their accuracy and durability may be limited compared to reusable sensors. Selecting between disposable and reusable options depends on specific project needs and sustainability goals [36].

2.5. Wired vs Wireless Soil Moisture Sensors: Implications for Sustainable Agricultural Infrastructure

The choice between wired and wireless soil moisture sensors significantly influences the sustainability, scalability, and efficiency of agricultural monitoring systems. Both configurations offer unique benefits and trade-offs related to connectivity, installation, power management, and environmental impact.

Wired soil moisture sensors rely on physical cabling to transmit data, offering highly stable and interference-free communication. This makes them ideal for small-scale applications requiring consistent and accurate moisture readings. Their high reliability stems from a direct connection, which minimizes signal loss [37], [38]. However, installation can be complex and labor-intensive, involving extensive trenching and wiring, which may disturb soil structure and ecosystems. Wired systems often require direct power sources, making them less suitable for remote or off-grid locations and reducing their sustainability in large or geographically dispersed farms.

In contrast, wireless soil moisture sensors utilize wireless communication protocols such as LoRa, Zigbee, or Wi-Fi, which support broader coverage and ease of deployment. These systems are especially effective in large-scale and remote farming contexts, enabling wide-area monitoring without the need for physical wiring [9]. Wireless nodes can be powered using batteries or solar panels, supporting energy efficiency and reducing dependency on grid-based power [10]. Despite these advantages, wireless systems are more susceptible to signal interference from environmental factors and may require data repeaters or mesh networks for consistent communication.

Wireless sensor networks (WSNs) are often integrated with centralized gateways that collect and process data, delivering real-time information to farmers through web platforms or mobile applications [39]. The flexibility of wireless systems supports adaptive irrigation strategies, allowing users to respond dynamically to environmental changes.

Moreover, hybrid systems incorporating low-altitude remote sensing platforms—such as drones or unmanned aerial vehicles (UAVs)—alongside Internet of Things (IoT) devices and machine learning algorithms further enhance spatial resolution and data granularity [40], [41]. These technologies can map soil moisture variability across fields and optimize irrigation scheduling. Solar-powered irrigation pumps, often linked to these systems, exemplify sustainable practices in rural and resource-limited settings by reducing manual labor, increasing water-use efficiency, and promoting renewable energy use [42].

In summary, while wired sensors provide consistent performance for localized monitoring, wireless systems, especially when integrated with smart technologies, offer scalable and sustainable solutions for modern precision agriculture.

2.6. IoT-Driven Innovations for Sustainable Irrigation Management

The integration of Internet of Things (IoT) technologies into irrigation systems represents a transformative shift in sustainable agricultural practices. IoT enables real-time data collection, remote control, and predictive analytics, all of which contribute to resource-efficient irrigation and enhanced crop productivity. IoT systems utilize a network of field-deployed sensors that continuously monitor critical environmental parameters, including soil moisture, temperature, humidity, and weather conditions. This real-time data allows for precision irrigation, where water is applied only when and where it is needed, significantly reducing water wastage and ensuring optimal soil conditions [43], [44]. The shift from manual scheduling to automated, sensor-driven irrigation helps farmers mitigate risks related to over-irrigation or drought stress, thereby improving both water-use efficiency and crop health [45], [46].

One of the most impactful features of IoT-enabled systems is remote irrigation control. Farmers can access system dashboards via smartphones or computers to activate pumps, adjust flow rates, and schedule irrigation events based on real-time field data [47], [48]. This remote accessibility supports labor savings and better adaptation to changing weather conditions. The use of optimized IoT-based parallel server environments further enhances operational efficiency by ensuring low-power consumption and seamless communication between distributed sensor nodes [49]. In addition, the adoption of robust routing protocols for wireless sensor networks, such as DEEC and EDEEC, plays a critical role in improving network reliability and data transmission in field conditions [50].

IoT platforms also support predictive analytics by leveraging historical data and weather forecasts to recommend future irrigation schedules. This capability enhances proactive farm management, reduces resource wastage, and contributes to more consistent crop yields [51], [52]. Insights derived from IoT systems guide broader decisions related to soil health monitoring, fertilizer planning, and energy optimization. Energy sustainability is further reinforced through the integration of IoT with solar-powered irrigation systems. These setups reduce dependency on fossil fuels and electricity grids, making them especially valuable for farms in off-grid or water-scarce regions [53].

IoT technologies also enable early warning systems for environmental threats such as frost, providing alerts that help prevent crop damage [54]. Moreover, the integration of IoT with farm management software allows for centralized oversight, facilitating data-informed decisions and long-term sustainability planning. By enhancing automation, decision-making, and efficiency, IoT-driven irrigation systems support environmentally responsible agriculture and help address the global challenge of water scarcity. Their scalability and flexibility make them suitable for both smallholder and commercial farms, offering a pathway to more resilient and data-centric agricultural ecosystems [33].

2.7 Algorithmic Approaches for Smart Irrigation Control

Recent research emphasizes the importance of intelligent algorithms to enhance decision-making in IoT-enabled irrigation systems. Fuzzy logic controllers (FLCs) are widely adopted for their ability to manage vague and imprecise data, especially in environments where soil and weather conditions vary dynamically. These systems translate sensor data into rule-based decisions, enabling context-aware irrigation control [28].

On the other hand, machine learning models such as Random Forests have shown strong potential in predicting soil moisture levels based on historical environmental data. These predictions support anticipatory irrigation planning, contributing to more sustainable water usage and higher crop productivity [33].

III. CHALLENGES, RESEARCH TRENDS, AND PRACTICAL CONSIDERATIONS

3.1. Challenges and Opportunities in Integrating IoT for Sustainable Agriculture

The implementation of Internet of Things (IoT) technologies in agriculture represents a transformative step toward sustainable food production and environmental stewardship. Applications such as precision farming, automated irrigation systems, climate-adaptive crop management, and real-time monitoring of soil and water conditions are revolutionizing agricultural practices. Despite the promise of these innovations, several challenges must be addressed to achieve scalable, inclusive, and long-term adoption.

3.1.1. Challenges

a. Data Security and Privacy:

The increasing use of IoT in agriculture introduces significant concerns regarding data governance. Ensuring the confidentiality, integrity, and availability of data is essential to fostering trust among farmers, agribusinesses, and policymakers. Without secure data protocols and privacy safeguards, the risk of unauthorized access or misuse could hinder the adoption of smart technologies [55].

b. Interoperability of Systems:

Agricultural IoT ecosystems typically involve diverse sensors, platforms, and software. The lack of standardized communication protocols and compatibility between devices impedes data integration and system efficiency. Addressing interoperability through open standards and universal APIs is essential for developing cohesive, scalable solutions [56].

c. Digital Divide and Infrastructure Gaps:

Limited access to internet connectivity, smart devices, and digital literacy—particularly in rural and developing regions—poses a substantial barrier to adoption. Reducing this gap requires targeted infrastructure development, affordable technologies, and user-oriented training to ensure equitable access [57].

d. Capital and Knowledge Investment:

Transitioning from conventional to technology-driven farming necessitates considerable financial investment and technical training. Farmers often lack both the capital to invest in IoT systems and the knowledge to manage and interpret data. Public–private partnerships and institutional support are essential to overcome these constraints [58].

3.1.2. Opportunities

a. Precision Resource Management:

IoT facilitates data-driven decisions, enabling optimized use of water, fertilizers, and energy. By delivering real-time insights into soil moisture, weather conditions, and plant health, IoT promotes efficient resource allocation and minimizes waste, directly contributing to environmental sustainability.

b. Climate Adaptation and Resilience:

Real-time environmental monitoring enables farms to adapt to weather fluctuations, pest outbreaks, and shifting climatic patterns. This adaptability strengthens resilience against climate change impacts and supports long-term food security in vulnerable regions.

c. Sustainable Agricultural Practices:

IoT supports sustainable practices such as drip irrigation, integrated pest management, and organic cultivation by providing accurate, actionable data. These practices help maintain soil fertility, conserve water, and reduce agrochemical usage—key goals in sustainable agriculture.

d. Scalability and Accessibility:

The modular design of many IoT systems makes them scalable across different farm sizes and types—from smallholder farms to industrial operations. Furthermore, solar-powered sensors and low-power wide-area networks (LPWANs) improve feasibility in off-grid or resource-limited areas, enhancing the inclusiveness of smart agriculture solutions.

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IV. CONCLUSION

The integration of IoT into agriculture presents a vital opportunity to transform conventional farming into a data-driven, climate-resilient, and resource-efficient enterprise. By leveraging real-time monitoring and automation, IoT technologies enable precision agriculture practices that are both environmentally and economically sustainable.

However, widespread adoption depends on overcoming existing barriers, including data security concerns, system interoperability, the rural digital divide, and limited investment capacity among smallholder farmers. Policymakers, industry stakeholders, and researchers must collaborate to develop inclusive frameworks, subsidized technology programs, and farmer-centric training models. This review contributes to the literature by offering an integrative perspective on sensor deployment, wireless technologies, and sustainable IoT architecture in smart irrigation. It serves as a reference for future studies aiming to implement or optimize IoT-driven agricultural systems.

With supportive infrastructure and sustainable design, IoT-driven agricultural systems can enhance productivity while minimizing ecological impact. As global food demand continues to rise and environmental pressures intensify, IoT will play a central role in building resilient agricultural ecosystems that support both human and planetary health.

Future research could explore the integration of AI-based decision-making algorithms with real-time sensor data for predictive irrigation and adaptive resource management. Furthermore, developing lightweight protocols optimized for ultra-low-power agricultural deployments could enhance scalability.

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