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Advancing Soilless Agriculture with Sensor and Wireless Technologies: A Comprehensive Review

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ABSTRACT

The integration of sensor and wireless communication technologies in soilless agriculture, including hydroponics, aquaponics, and aeroponics, addresses critical challenges like declining arable land, climate change, and the rising global food demand. This review examines the application of various environmental sensors, including those measuring pH, TDS/EC, temperature, humidity, light, water level, DO, turbidity, and ammonia, in the monitoring and control of growing conditions. Furthermore, the review assesses the efficacy of wireless communication protocols, including Wi-Fi, Bluetooth, Zigbee, and LoRaWAN, in ensuring uninterrupted data transmission. The review elucidates the advantages of these technologies in augmenting crop yields, resource efficiency, and environmental sustainability. However, it also identifies challenges such as high initial costs, technical complexity, and data security concerns. Despite these benefits, challenges such as high initial costs, technical complexity, and data security remain. Future efforts should prioritize developing affordable, user-friendly IoT systems with integrated renewable energy solutions and optimized power consumption to ensure sustainable adoption. This review highlights the transformative potential of IoT in revolutionizing modern agriculture, fostering resilient and sustainable food systems to meet future demands.

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1. INTRODUCTION

Modern agriculture faces a myriad of challenges that threaten its sustainability and productivity. One of the most pressing issues is the decline in productive agricultural land, driven by urbanization, industrialization, and environmental degradation [1], [2], [3], [4], [5]. This reduction in arable land necessitates more efficient use of available resources to meet the growing global food demand [6], [7]. Climate change and weather fluctuations add another layer of unpredictability, affecting crop yields and overall agricultural productivity [8], [9], [10], [11], [12]. The increasing global population and rising food demand further intensify the pressure on agricultural systems to produce more with fewer resources. Traditional farming methods, while historically effective, are increasingly seen as inadequate for addressing these contemporary challenges due to their inefficiencies and limited scalability [13], [14], [15], [16], [17].

To overcome these obstacles, technological innovation has become a cornerstone of modern agricultural practices. Among the most promising technologies is the Internet of Things (IoT), which has the potential to revolutionize farming [18], [19], [20], [21]. IoT integrates a network of interconnected devices and sensors that can collect, transmit, and analyze data in real-time, providing farmers with valuable insights and enabling them to make informed decisions [22], [23], [24]. This technology can significantly enhance the efficiency and sustainability of agricultural operations by optimizing resource use, improving crop management, and reducing environmental impact [25], [26], [27].

In particular, IoT has shown remarkable potential in transforming advanced farming methods such as hydroponics, aquaponics, and aeroponics. Hydroponics, the practice of growing plants without soil using nutrient-rich water solutions, can benefit from IoT by automating the monitoring and control of water quality, nutrient levels, and environmental conditions [28], [29]. Aquaponics, which combines aquaculture and hydroponics in a symbiotic system, can leverage IoT to maintain optimal conditions for both fish and plants, ensuring mutual growth and health [30], [31], [32]. Aeroponics, a method where plants are grown in an air or mist environment without soil, can also be enhanced through IoT by precisely controlling humidity, temperature, and nutrient delivery [33], [34]. However, the implementation of IoT in agriculture is not without its challenges. High initial costs, technical complexity, data security concerns, and the need for skilled personnel can hinder widespread adoption. Moreover, the reliability and robustness of wireless communication protocols are crucial for ensuring seamless data transmission and system performance in field conditions.

Despite its potential, the integration of IoT in hydroponic, aquaponic, and aeroponic systems remains underexplored, particularly regarding the optimization of wireless communication protocols in these diverse environments. This gap highlights the need for further investigation into the practical implementation and scalability of IoT in these advanced farming systems.

This article aims to provide a concise exploration of how IoT influences and transforms hydroponic, aquaponic, and aeroponic farming methods. It examines the specific ways IoT technologies are integrated into these systems, highlighting their benefits in efficiency, sustainability, and productivity. Additionally, the article addresses the challenges faced during the implementation of IoT in agriculture and evaluates the strengths and limitations of various wireless communication protocols in sensor-based agricultural applications. By addressing these topics, this article seeks to contribute to the broader understanding of IoT's transformative role in modern agriculture and its potential to create more resilient and sustainable food systems.

2. METHODS

The methodology employed in this study is a comprehensive literature review focusing on the utilization of Internet of Things (IoT) technology in the soilless farming sector, as well as a comparative analysis of various wireless communication protocols that support data transmission in sensor-based agricultural applications (Hydroponics, Aquaponics, and Aeroponics). The research explores the use of various sensors.

In addition to the applications and sensors, a primary focus of this research is to evaluate the effectiveness of different wireless communication protocols used in agricultural IoT. These protocols include WiFi, Bluetooth, RF, Zigbee, and LoRa. Each protocol will be analyzed based on its performance in terms of latency, power consumption, range, security, implementation cost, and scalability for use in agricultural lands of varying sizes. Protocols like MQTT and LoRa, known for their efficiency in managing long-range device communication with low power consumption, will be compared with more commonly used protocols in small-scale IoT networks, such as Bluetooth and RF.

2.1. Hydroponics

Hydroponics is a farming method that uses nutrient-rich solutions instead of soil to support plant growth. In this system, plants are placed in grow trays, which are often filled with alternative media like rockwool, sand, or coconut fiber to support the roots and retain moisture [35], [36]. Fig. 1 illustrates a basic hydroponic system. The nutrient solution is stored in a reservoir, where its concentration is carefully regulated. A water pump, typically set on a timer, delivers the solution from the reservoir to the grow trays at regular intervals. Once the solution reaches a certain level, an overflow drains channels the excess back into the reservoir, ensuring a balanced nutrient supply and preventing waterlogging. This cyclical process allows for precise control of the growing environment, promoting optimal plant growth.

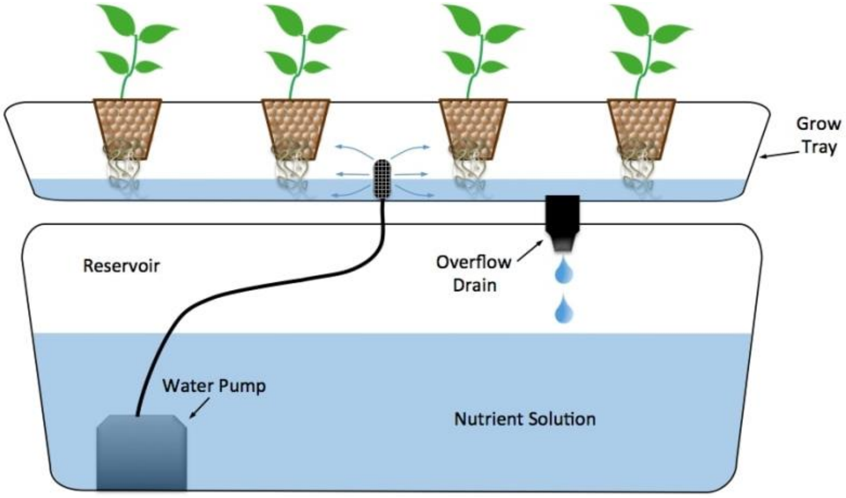

Fig. 1. Hydroponics system design

2.2. Aquaponics

Aquaponics is an integrated farming system that merges aquaculture (fish farming) with hydroponics (soilless farming) in a single system [37], [38]. In this method, water containing fish waste provides nutrients for plants, while the plants naturally filter the water for the fish. This creates a sustainable farming approach where fish and plants exist in a symbiotic relationship [39]. The fish produce ammonia, which is transferred to a bio-filter where bacteria convert it into nitrates, essential for plant growth (Fig. 2). The plants absorb these nutrients, cleaning the water, which is then recirculated back to the fish tank. This continuous process ensures efficient resource use and creates a balanced environment for both fish and plants to thrive.

By reducing water consumption and improving nutrient cycling, IoT contributes significantly to resource optimization in aquaponics, making it a more sustainable farming practice. These advancements not only enhance productivity but also minimize environmental impact, aligning aquaponics with the broader goals of modern sustainable agriculture.

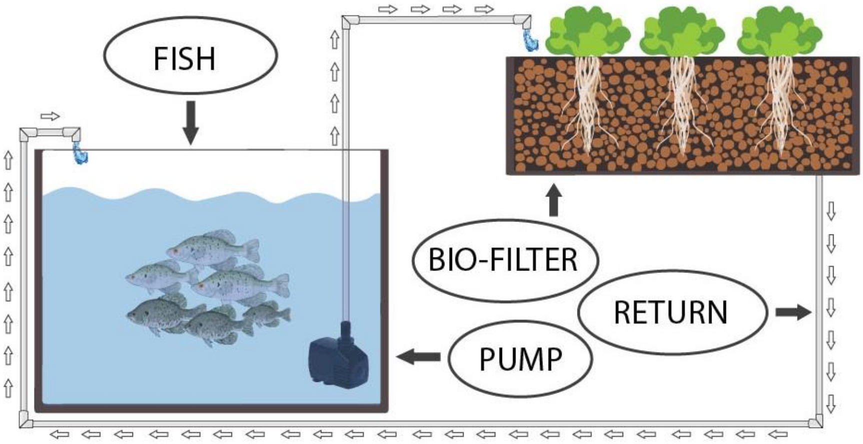

Fig. 2. Aquaponics system design

2.3. Aeroponics

Aeroponics is a soilless farming method where plants are grown in an air-based environment, with their roots periodically misted with nutrient-rich water [40]. This system, which uses pumps, timers, and spray nozzles to deliver a fine mist of nutrients, allows the roots to absorb essential nutrients and oxygen directly [41], promoting faster growth with minimal water use. Aeroponics can save up to 95% of the water used in traditional agriculture and requires less space, making it a highly efficient method for growing leafy vegetables, root crops, aromatic herbs, and medicinal plants [42]. Fig. 3 shows the aeroponics system design.

The integration of IoT technologies further enhances the efficiency and precision of aeroponics systems. IoT-enabled sensors monitor critical environmental parameters such as humidity, temperature, and mist levels in real time. These sensors provide data that can be analyzed to optimize misting intervals, nutrient concentrations, and environmental conditions, ensuring the plants receive the ideal growth environment. For example, humidity and temperature sensors can trigger automated adjustments in misting frequency to prevent root dehydration or over-saturation.

IoT systems can also improve nutrient delivery by dynamically adjusting the composition of the nutrient solution based on plant growth stages. Actuators connected to IoT controllers manage pumps and spray nozzles, ensuring precise and efficient nutrient distribution. These features not only optimize water and nutrient use but also enhance plant growth rates and crop quality.

By leveraging IoT technologies, aeroponics achieves unparalleled efficiency in resource use, making it a promising solution for sustainable and space-efficient agriculture, particularly in urban or resource-constrained settings.

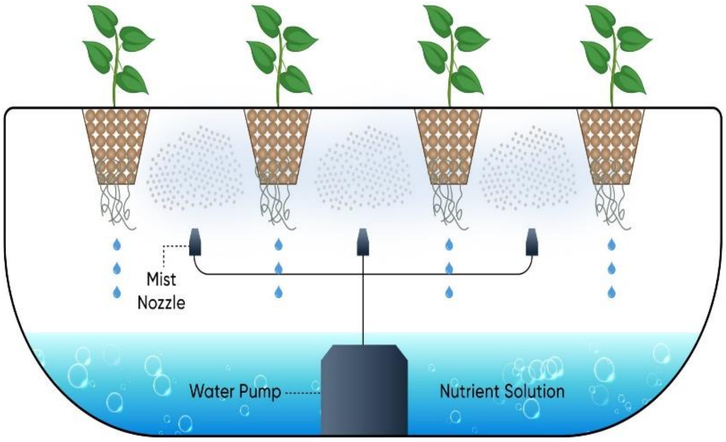

Fig. 3. Aeroponics system design

The nutrient solution is stored in a reservoir, where it is prepared at the proper concentration and pH for optimal plant growth. A water pump transfers the solution to mist nozzles, which convert the liquid into fine particles that are sprayed onto the plant roots. The roots absorb the mist, ensuring a constant supply of nutrients and water. Any excess solution is collected and recirculated back to the reservoir, maintaining a controlled and efficient growing environment. This cyclical process allows for rapid and healthy plant growth in a highly sustainable system.

3. THE ROLE OF THE IOT IN SOILLESS AGRICULTURAL PRACTICES

The IoT can be defined as a network of physical objects that are connected to the internet and can communicate with each other [43]. These objects, often referred to as "smart devices," are equipped with sensors, hardware, and software that enable them to collect, send, and receive data. The primary benefits of IoT in agriculture include the ability to monitor and control the environment in real-time, process automation, and increased efficiency.

3.1. Benefits of IoT in Agriculture

3.1.1. Environmental Sensors Monitor and Control

The IoT enables real-time monitoring and control of the plant growth environment through various sensors. pH sensors [44], [45], [46], [47] assess the acidity or alkalinity of nutrient solutions, while TDS/EC sensors [38], [45], [47] measure the concentration of dissolved solids and nutrient levels. Temperature sensors [45], [46], [47], [48] and relative humidity sensors [46] monitor the surrounding atmospheric conditions. Light sensors (Lux meters) [46], [49] measure light intensity, while water level sensors [48], [50] ensure adequate water supply. Additionally, dissolved oxygen (DO) sensors [38], [47], ammonia sensors [38], and nitrate and nitrite sensors [38] evaluate critical water quality parameters. The data generated by these sensors is used to manage automated systems that maintain optimal conditions, including cooling, heating, and ventilation systems. Table 1 summarizes the essential sensors and systems for each method, highlighting their roles and significance in ensuring the health and growth of plants and, in the case of aquaponics, fish.

Table 1. Comparison of sensors usage in hydroponics, aquaponics, and aeroponics systems

Sensor	Hydroponics	Aquaponics	Aeroponics
pH Sensor	✓	✓	✓
TDS/EC Sensor	✓	✓	✓
Temperature Sensor	✓	✓	✓
Relative Humidity Sensor	✓	✓	✓
Light Sensor (Lux Meter)	✓	-	✓
Water Level	✓	✓	✓
DO Sensor	-	✓	-
Turbidity Sensor	-	✓	-
Ammonia Sensor	-	✓	-
Nitrate and Nitrite Sensor	-	✓	-

Based on Table 1, each sensor plays a critical role in maintaining optimal conditions for plant growth and, in aquaponics, for aquatic life. The pH sensor is essential in all systems to keep nutrient solutions within the ideal range for plant uptake and, in aquaponics, for fish health. The TDS/EC sensor measures nutrient concentration in hydroponics and aeroponics, and overall water quality in aquaponics. temperature and relative humidity sensors are crucial across all systems to create a suitable environment for plant growth, with humidity being especially important in aeroponics, where roots are exposed to air. The light sensor is critical in hydroponics and aeroponics for ensuring adequate light for photosynthesis but is not required in aquaponics. Water level sensors help prevent over- or under-watering and ensure consistent misting in aeroponics. In aquaponics, the DO sensor maintains adequate oxygen levels for fish and plant roots, while ammonia, nitrate, and nitrite sensors are vital for monitoring nutrient levels and preventing toxic ammonia buildup.

3.1.2. Process Automation

IoT facilitates the automation of various agricultural processes, which improves efficiency and consistency [51]. Automated irrigation systems use data from sensors to regulate the provision of water and nutrients according to crop needs, ensuring that crops get the right nutrients at the right time [52]. Automated nutrient spraying systems in aeroponic farming also play an important role, regulating the supply of nutrients according to the needs of the plants [53]. In aquaponic farming, an automated fish monitoring and feeding system regulates the provision of food according to the schedule and needs of the fish, ensuring consistent and optimal feeding [54].

3.1.3. Enhanced Crop Management

IoT technology empowers farmers to monitor crop growth and identify potential issues, such as pests or diseases, at an early stage. Sensors and cameras collect real-time data on plant health, enabling predictive algorithms to analyze potential threats before they escalate, allowing farmers to take proactive measures [37], [55], [56], [57], [58]. By tracking environmental changes and plant responses, farmers can make informed decisions that enhance crop yields and quality. This proactive approach not only improves overall productivity but also contributes to sustainable agricultural practices.

4. WIRELESS COMMUNICATION PROTOCOL IN AGRICULTURAL IOT

In the rapidly advancing field of precision agriculture and smart farming, the implementation of Internet of Things (IoT) technologies is essential for improving productivity, sustainability, and efficiency. Wireless communication protocols are crucial in these systems, facilitating seamless data exchange among devices, sensors, and control systems. Choosing the right protocol is key, as it influences the performance, reliability, and cost-effectiveness of agricultural IoT applications. Given that devices in agricultural environments often operate in remote or challenging conditions with limited power and connectivity, it is important to select protocols that balance power consumption, communication range, data throughput, network reliability, and ease of deployment. This section offers an in-depth look at the most commonly used wireless communication protocols, outlining their features, advantages, and limitations to guide stakeholders in implementing effective IoT solutions. Table 2 shown the Comparison of Wireless Communication Protocols for Agricultural IoT Applications.

Table 2. Comparison of wireless communication protocols for agricultural IoT applications

Protocol	Range	Network Size	Data Rates	Power Consumption
Wi-Fi	100 m	Large	1Mb/s-6.75Gb/s	High
Bluetooth	10-100 m	Very Small	1-24Mb/s	Low
Zigbee	100 m (indoors), 1 km (outdoors)	Very Large	250kb/s	Medium
LoRaWAN	10-15 km	Very Large	0.3-50 kb/s	Low

Table 2 compares Wi-Fi, Bluetooth, Zigbee, and LoRaWAN, focusing on their range, network size, data rates, and power consumption, highlighting their suitability for different agricultural IoT applications. Wi-Fi provides high data rates but has limited range and high-power consumption, making it better for localized, power-rich environments. Bluetooth is energy-efficient with moderate data rates but supports only small, short-range networks. Zigbee balances moderate power use and range with low data rates, making it suitable for large, dispersed sensor networks. LoRaWAN stands out for its long-range communication and low power consumption, ideal for remote agricultural areas with minimal data transfer needs.

5. SENSORS AND WIRELESS COMMUNICATION IN AGRICULTURE

Enriko, I. K., A., et. al., [50] evaluated the implementation of ultrasonic sensors using the LoRaWAN protocol for monitoring water levels in aquaponic ponds. The ultrasonic sensors, specifically the Milesight EM310-UDL, demonstrated high accuracy in water level measurements, with an average accuracy of 95% and a maximum of 100% across various distances. The LoRaWAN protocol significantly extended battery life due to its low power consumption, with calculations indicating a battery lifespan of approximately 1 year at 1-minute transmission intervals and 11 years at 10-minute intervals. The system's wireless communication efficiency and reliability make it a promising solution for enhancing the monitoring and management of aquaponic systems, contributing to sustainable agricultural practices. Future work could focus on integrating the system with automated water filling mechanisms and exploring additional applications such as parking monitoring and trash bin management.

J. Chaiwongsai [45] research presents an automatic control and management system designed for tropical hydroponic cultivation, optimizing the control of humidity, temperature, water level, pH, and electrical conductivity (EC) to suit tropical climates. By grouping sensors in a wireless sensor network using Wi-Fi communication, the system reduces data exchange and provides efficient multisensor data fusion. It allows automatic or manual control of environmental factors, sends real-time sensor data and notifications via an Android app, and stores data history for monitoring through a web application. Tested in a hydroponic farm in northern Thailand, the system demonstrated stable Wi-Fi connectivity, real-time data transmission, and accurate sensor performance. However, EC and pH sensors were bulkier due to larger batteries, affecting portability. Overall, the system effectively managed the growing environment, offering ease of monitoring and reliable performance for commercial use.

Ullah, A., et.al [46] developed a vertical hydroponics system integrated with the Internet of Things (IoT) technology to monitor and control environmental parameters, including temperature, humidity, water level, and pH. The system employs an ESP32 microcontroller to oversee the operation of actuators, including water pumps, and enables remote control via a mobile application. In particular, users can direct the functionality of the system, such as initiating the water pump and refilling the backup tank, directly from their mobile devices, thereby enhancing the efficiency and convenience of hydroponic management.

Banjao, J., et.al., [47] developed a cloud-based monitoring system for abiotic factors in an aquaponics setup, utilizing an array of sensors to measure DO, EC, pH, water temperature, and water level. The system integrates an ESP32 microcontroller and ThingSpeak IoT platform, enabling real-time monitoring and data visualization via a mobile application named Virtuino and a web server accessible through an IP address. Wireless communication in the system is facilitated by WiFi, allowing the ESP32 microcontroller to establish a connection to the internet and transmit sensor data to the ThingSpeak cloud. This wireless communication ensures that users can remotely access and monitor the abiotic parameters of their aquaponics system in real-time, enhancing the system's usability and reliability. The experimental setup, comprising a small aquarium and a grow bed with Hydroton clay pebbles, demonstrated the system's effectiveness in continuously updating and displaying abiotic parameters, thereby facilitating easier and more accurate monitoring compared to traditional manual methods. The results, summarized on ThingSpeak, highlight the system's potential to enhance the sustainability and productivity of aquaponics systems, particularly for urban farming applications. Future work could focus on automating the optimization of abiotic conditions in real-time and exploring the cultivation of additional plant species.

F. Supegina, et.al., [49] developed a cloud-based monitoring system for hydroponic farming, utilizing an ESP8266 Wi-Fi module to enable real-time data transmission to the ThingSpeak IoT platform. The system, controlled by an Arduino Uno, integrates various sensors to monitor temperature, humidity, water level, nutrient content, and plant height, and employs actuators such as a fan, LED grow lights, and a water pump to maintain optimal growing conditions. Wireless communication in the system is facilitated by WiFi, allowing the ESP8266 module to establish a robust connection to the internet and transmit sensor data to the ThingSpeak cloud. The hydroponic setup was conducted in a closed room, with LED grow lights and LED bulbs used to simulate sunlight. Results over a 15-day observation period showed that plants grown under LED grow lights maintained healthier green foliage and reached a height of 6 cm, while those under LED bulbs grew taller but exhibited yellowish, withered leaves. The system's accuracy was validated through comparisons with thermo-hygrometers and lux meters, demonstrating reliable performance in temperature, humidity, and light intensity measurements. The average data update time on ThingSpeak was 2.4 seconds, ensuring timely monitoring. The study concluded that while LED bulbs promoted faster stem growth, LED grow lights were more effective in maintaining overall plant health, highlighting the importance of light quality in hydroponic systems. Future work could focus on optimizing the system's automation and expanding the range of plant species tested.

Sadek, N., et.al., [53] presents a smart hydroponic and aeroponic greenhouse system based on Internet of Things (IoT) technology, designed to enhance sustainable crop production and address water scarcity and population growth challenges. The greenhouse, installed in Egypt, integrates various IoT (Wi-Fi) sensors to monitor temperature, humidity, light intensity, and TDS, and automates environmental control through a microcontroller and actuators. The system supports both hydroponic and aeroponic cultivation methods, using nutrient-rich water solutions to optimize plant growth. Key results show that the system saves 80-90% of water and fertilizer compared to traditional agriculture, doubles productivity per area, and reduces yield time to 45 days. The TDS, relative humidity (RH), and temperature (T) were closely monitored and maintained within optimal ranges, ensuring healthy plant growth. The developed system also includes a dynamic website and mobile application for remote monitoring and control, enhancing user convenience and system efficiency. However, challenges such as high initial costs, maintenance requirements, and the need for skilled technicians remain. Future work will focus on reducing operational costs, exploring renewable energy sources, and expanding the system's applicability to a broader range of crops.

Rozie, F., et.al., [54] presents an advanced water quality management system for catfish ponds using aquaponics and IoT technology, integrated with a fuzzy logic control system to monitor and regulate temperature and ammonia levels. The system employs various sensors to measure parameters such as pH, turbidity, TDS, DO, and water level, and uses a Raspberry Pi as a web server to store and process data. The fuzzy logic controller adjusts the speed of an AC motor water pump to maintain optimal water quality, with early warning notifications sent to farmers via TelegramBot if parameters deviate from set thresholds. Experimental results demonstrate the system's effectiveness in reducing temperature and ammonia levels, with the fuzzy control system achieving a 99.99% accuracy level. The system also supports real-time monitoring and manual intervention, enabling farmers to maintain ideal conditions and prevent fish mortality. This integrated approach addresses the challenges of water and land limitations, enhances food security, and provides a sustainable solution for aquaculture and hydroponic vegetable cultivation.

Pramana, R., D.A., & Baswara, R., A., C., [59] successfully designed and implemented an aeroponic system for growing microgreen crops, specifically caisim mustard greens, integrating IoT technology via ThingSpeak for real-time temperature and humidity monitoring and employing Tsukamoto Fuzzy Logic to optimize watering intervals. The aeroponic system, controlled by an ESP32 microcontroller, used DHT22 sensors to measure environmental conditions and a relay to manage the water pump. The Tsukamoto Fuzzy Logic Controller, based on nine fuzzy rules, adjusted the watering intervals according to temperature and humidity, resulting in a significant reduction in power consumption—3.6 times lower than continuous 24-hour watering. Over a 30-day period, the caisim mustard plants grew to an average height of 25 cm, with 9 leaves and a leaf width of 8 cm, demonstrating the effectiveness of the system in enhancing plant growth and resource efficiency. This research underscores the potential of integrating modern technology in agriculture to achieve sustainable and productive urban farming practices.

Chandranata, A., et.al., [60], developed a microcontroller-based aeroponic lettuce plant nutrition control system and the Internet of Things (IoT) to address the issue of reduced agricultural land in urban areas. The system employs a TDS sensor to maintain the ppm value of the nutrient solution between 560 and 840 ppm, a DHT22 sensor to detect temperature and humidity, and an ultrasonic sensor to measure the water level in the box. The system is capable of automatically regulating the nutrient and water pumps based on sensor readings, with low average sensor errors (2.29% for TDS, 1.13% for temperature, 1.08% for humidity, and 2.32% for water level). The experimental results demonstrate that the system is capable of maintaining the ppm value of the nutrient solution within the standard range, regulating the watering duration based on environmental conditions, and monitoring plant growth through a smartphone application, thereby enhancing the efficiency and productivity of urban agriculture.

Pastor, Z., et.al., [61], research project resulted in the development of a water monitoring and energy management system for an automatically controlled aquaponics system. The system comprises several principal components, including sensors for monitoring temperature, pH, and DO in the water, pumps for water circulation and aeration, and an energy management system comprising a mains AC power source, photovoltaic (PV) panels, and backup batteries. The system is designed to operate autonomously, with the capacity to transition to alternative power sources, such as solar or wind energy, in the event of a disruption in the main electrical supply. Wireless communication is facilitated via Bluetooth Low Energy (BLE) to monitor water parameters and battery status via a mobile application on a smartphone. Additionally, the system is equipped with automated pump control based on monitored water parameters, as well as a local display (LCD) for monitoring system conditions. Power consumption estimates indicate that the system can operate for up to one day with a backup battery, and the implementation of a wind turbine can enhance energy security. Future plans include further development of applications for system management, wind turbine design, and optimized battery charging controllers.

Kuncoro, C., B., D., et.al., [62], presents the development of an aeroponic root room temperature conditioning system for the cultivation of mini-tuber potato seeds. The system is designed to maintain the root room temperature between 10°C and 20°C, which has been identified as the optimal temperature range for potato growth. The air conditioning system employs a vapor compression cycle, comprising key components such as a compressor, condenser, evaporator, and thermal expansion valve. The root room temperature is monitored and controlled via an Arduino Uno microcontroller, a temperature sensor, and a Bluetooth module for wireless data transmission. The results of the field experiment demonstrate that the implementation of controlled root chamber temperature conditions can lead to a 77% increase in the number of stolons and seed potato mini-tuber yield compared to uncontrolled temperature conditions. The statistical analysis, which employed both ANOVA and t-test, confirmed that the difference in seed potato yield between the controlled and uncontrolled root chambers was highly significant. These findings indicate that the establishment of optimal root chamber temperature conditions can markedly enhance the yield of mini-tuber potato seed cultivation through the utilisation of aeroponic techniques.

Varughese, I., R., et.al., [63], develops an automated monitoring system for hydroponic tomato cultivation, utilizing pH, TDS, temperature, and humidity sensors in conjunction with an Arduino Uno microcontroller. The system is designed to monitor and control essential parameters for optimal tomato growth, including pH (5.5-6), TDS (1400-3500 ppm), temperature (18-28°C), and humidity (35-65%). The sensors are connected to an Arduino Uno, which is programmed to send alert notifications to the Android app via a Bluetooth HC-05 module if the parameters exceed the optimal range. Test results demonstrate that the system can monitor parameters in real-time and send notifications with precision, thus assisting farmers in time management and crop maintenance. The system is anticipated to enhance the efficiency and yield of tomato hydroponics and has the potential to be widely applicable, including in residential settings and in space missions.

Samijayani, O., N., et.al., [64] presents the implementation of a hybrid wireless sensor network (WSN) system based on ZigBee and WiFi technology for the monitoring of hydroponic systems. The system employs a network of four routers (sensor nodes) and a single coordinator node to monitor a range of hydroponic water parameters, including TDS, pH, and turbidity. The routers are linked to the coordinator via ZigBee, while the coordinator is connected to the Internet via WiFi ESP8266. A series of tests were conducted to evaluate the system's performance, including an assessment of the Received Signal Strength Indicator (RSSI), throughput, and packet loss/error. The test results demonstrated a decline in RSSI and throughput of the hybrid ZigBee-WiFi network, exhibiting a reduction of approximately -10 dBm and 0.13 kbps, respectively, in comparison to the ZigBee network alone. Furthermore, the distance between nodes was found to have an adverse impact on throughput. This system has the potential to assist farmers in remote monitoring and decision-making based on real-time sensor data, although the performance of the ZigBee and WiFi combination was observed to be suboptimal.

Emge, A., et.al., [65], develops a wireless-based temperature and humidity monitoring system for hydroponic plants, utilizing the Xbee module. The system comprises two Xbee nodes, designated as the sending node and the receiving node. The sending node employs a DHT11 sensor in conjunction with an Arduino Uno microcontroller to ascertain the temperature and humidity, while an Xbee is utilized as the data transmitter. The receiving node comprises an Xbee linked to an Arduino Uno and an LCD for the display of data. Tests were conducted to evaluate the sensor response, wireless performance, and the overall system. The test results demonstrate that the DHT11 sensor is capable of accurately detecting temperature and humidity with an average error of 0.75°C and 3%. Data can be transmitted and received wirelessly over distances of up to 240 meters outdoors without obstructions and 70 meters indoors with obstructions. The system was successfully implemented for temperature and humidity monitoring in a hydroponic plant environment, although further improvements to the system model are necessary to enhance detection accuracy.

Hsiao, S., J., and Sug, W., T., [66], research project develops a wireless sensor network (WSN)-based system for the coexistence of fish and vegetables, with the objective of providing intelligent environmental monitoring and control. The system employs the Arduino Mega 2560 microcontroller as the primary control board and the ZigBee communication protocol for wireless data transmission. The system comprises a variety of sensors, including those for measuring temperature and humidity, lighting, water temperature, pH, DO, and water level. The data collected by the sensors is transmitted to the terminal computer via ZigBee, and the C# graphical interface is employed for monitoring and control purposes. Additionally, the system employs fuzzy theory for environmental analysis and control, and stores sensor data in an Excel sheet for subsequent analysis. Test results demonstrate that the system is capable of maintaining water temperature, pH, and DO within optimal ranges, thereby enhancing the efficiency and success of fish and vegetable farming. The system can be controlled remotely and has the potential to be applied in large-scale aquaculture in the future.

Wang, W., et.al., [67], presents an innovative approach to teaching computational intelligence by integrating an aquaponics system into the curriculum, emphasizing project-based learning. The system, which combines aquaculture and hydroponics, uses PLC, LabVIEW, and OPC technology to monitor and control water quality parameters, such as temperature, pH, DO, and conductivity. The project aims to teach students about soft measurement techniques, including multiple linear regression (MLR), partial least squares (PLS), support vector regression (SVR), and backpropagation (BP) neural networks, through hands-on experimentation. Students are tasked with selecting auxiliary variables, acquiring and preprocessing data, establishing soft sensor models, and correcting models online. The evaluation of the teaching method shows a significant improvement in student engagement, practical skills, and exam performance, with a pass rate of 70%. The project's interdisciplinary nature, involving aquaculture, PLC control, LabVIEW programming, and sensor technology, enhances students' comprehensive professional abilities and promotes the implementation of research and teaching. However, the study acknowledges limitations in the limited data and auxiliary variables, suggesting future improvements to the system for more in-depth research.

Eraliev, A., and Bracco, G., [68] utilized ZigBee-enabled sensors to monitor essential environmental variables, including soil moisture, temperature, and humidity, which were instrumental in the automation of irrigation systems. The system was designed as a low-power wireless sensor and actuator network (WSAN) with the objective of optimizing energy efficiency through the reduction of power consumption. The use of ZigBee communication further reduced energy costs associated with data transmission, enabling sensor nodes to operate on battery power for extended periods. With an 800mAh Li-ion battery (3.7V rated), the research device achieved an impressive battery life of approximately 734 days, eliminating the need for frequent battery replacements or recharging. This resulted in a significant reduction in energy consumption compared to traditional irrigation methods.

Tolentino, L., K., et.al., [69], introduces an IoT-based modular device for automated water monitoring and correction in aquaculture, utilizing LoRaWAN for data transmission. The device, named AQUAlity, integrates multiple water quality sensors (pH, oxidation-reduction potential, temperature, DO, TDS, water level, and turbidity) and actuators (aerator, water filter, peristaltic pump, water pump, fish feeder, and heater) to monitor and correct water parameters in real-time. The system transmits data to a smartphone application via LoRaWAN, enabling remote monitoring and control. The device's performance was validated by comparing its readings with those from a multimeter provided by the Bureau of Fisheries and Aquatic Resources-National Inland Fisheries Technology Center (BFAR-NIFTC), showing a low percentage difference of less than 2%. The AQUAlity device is designed to be cost-effective, user-friendly, and capable of maintaining optimal water conditions, thereby enhancing fish growth and preventing fish kills. Future work aims to reduce the device's size and weight, implement wireless connections for actuators, and integrate solar panels for sustainability.

Febriana, K., et.al., [70] presents an Internet of Things (IoT)-based multi-sensor monitoring system designed to enhance the productivity of hydroponic farming. The system incorporates a multitude of sensors for the monitoring of essential parameters, including solution temperature, pH, TDS, EC, ambient temperature, humidity, and light intensity. The system employs both WiFi and LoRaWAN technologies to ensure reliable data transmission over extended ranges, rendering it suitable for both local and remote monitoring. The microcontroller board, based on ESP32 and RA01H SoCs, is capable of supporting multiple sensors and includes an expansion board with Grove connectors, facilitating implementation and future scalability. The system employs ThingSpeak for the collection and analysis of data in a cloud-based environment, facilitating real-time monitoring through the use of web and mobile applications. Notable characteristics include an I2C adapter for transforming analog/digital sensors to I2C protocol, thereby enhancing sensor connectivity and reliability. Future endeavors intend to miniaturize the I2C adapter, reduce power consumption, and integrate Bluetooth mesh networking to extend coverage and optimize system performance. The proposed system addresses the challenges of nutrient balance and environmental control, thereby contributing to more precise and efficient hydroponic farming practices.

The implementation of sensor and wireless communication technologies has revolutionized modern agricultural practices, particularly in specialized systems such as hydroponics, aeroponics, and aquaponics. These technologies enable real-time monitoring and control of critical environmental parameters, enhancing the efficiency, productivity, and sustainability of agricultural operations. Table 3 summarizes the application of various sensors and wireless communication protocols in different agricultural systems, highlighting the specific types of sensors used and the communication technologies employed. This overview provides a comprehensive view of how these technological advancements are being leveraged to address the unique challenges and requirements of each agricultural type, from maintaining optimal water quality in aquaponic systems to controlling environmental conditions in hydroponic and aeroponic setups.

Table 3. Application of sensor and wireless communication technology in agriculture system

Ref	Year	Agriculture Type	Sensors	Wireless Communication
[45]	2019	Hydroponics	Humidity, Temperature, Water Level, pH, and EC	Wi-Fi
[46]	2019	Hydroponics	Temperature, Humidity, Water Level, and pH	Wi-Fi
[47]	2020	Aquaponics	Temperature, EC, DO, pH, and Water Level	Wi-Fi
[49]	2021	Hydroponics	Temperature, Humidity, Ultrasonic, Light Sensor, and Water Level	Wi-Fi
[50]	2024	Aquaponics	Water Level	LoRaWAN
[53]	2024	Hydroponics & Aeroponics	TDS, Temperature, RH, and Light Intensity	Wi-Fi
[54]	2020	Aquaponics	Temperature, pH, DO, TDS, Ammonia, Water Level and Turbidity	Wi-Fi
[59]	2024	Aeroponics	Temperature and Humidity	Wi-Fi
[60]	2024	Aeroponics	Temperature, Humidity, TDS, and Water Level	Wi-Fi
[61]	2019	Aquaponics	Temperature, pH, and DO	Bluetooth
[62]	2021	Aeroponics	Temperature	Bluetooth
[63]	2021	Hydroponics	Temperature, Humidity, pH, and TDS	Bluetooth
[64]	2020	Hydroponics	TDS, pH, and Turbidity	Zigbee and Wi-Fi
[65]	2020	Hydroponics	Temperature and Humidity	Zigbee
[66]	2020	Aquaponics	Temperature, pH, and DO	Zigbee
[67]	2020	Aquaponics	Temperature, EC, pH, and DO	Zigbee
[68]	2021	Aeroponics	Temperature and Humidity	Zigbee
[69]	2020	Aquaponics	Temperature, Humidity, pH, TDS, Turbidity, Water Level, and DO	LoRaWAN
[70]	2024	Hydroponics	Temperature, Humidity, TDS, EC, pH, and Light Intensity	LoRaWAN and Wi-Fi

6. CONCLUSION

The incorporation of sensor and wireless communication technologies in soilless agriculture, including hydroponics, aquaponics, and aeroponics, has significantly enhanced efficiency, productivity, and sustainability. In the face of challenges such as shrinking arable land, climate change, and rising food demand, the Internet of Things (IoT) emerges as a transformative force in modernizing agriculture.

Environmental sensors, such as those measuring pH, TDS/EC, temperature, humidity, and DO, enable real-time monitoring and automation of nutrient delivery, irrigation, and environmental control. These advancements reduce human intervention, minimize errors, and optimize resource utilization.

Wireless communication protocols, including Wi-Fi, Bluetooth, Zigbee, and LoRaWAN, play a crucial role in ensuring efficient data transmission. For example, ZigBee-enabled systems have extended sensor battery life up to 734 days, significantly reducing energy consumption, while IoT-based aeroponics reduced power use by 3.6 times through optimized watering intervals. Similarly, LoRaWAN-enabled ultrasonic sensors in aquaponics achieved high accuracy and extended battery life, demonstrating the efficiency of IoT solutions in agriculture.

Despite these benefits, significant barriers remain. High initial costs arise from setting up advanced sensors and communication systems, while technical complexity necessitates specialized expertise, limiting accessibility for small-scale farmers. Data security concerns further hinder broader adoption. Scaling IoT solutions for resource-constrained operations, especially in developing regions, requires affordable technology, user-friendly systems, and adequate training. Additionally, the integration of renewable energy sources, such as solar panels, offers potential for enhanced sustainability but poses challenges in ensuring reliable power supply under varying conditions.

Future research should prioritize overcoming these barriers through the development of cost-effective, secure, and user-friendly IoT solutions. For example, integrating IoT systems with renewable energy has the potential to reduce dependency on conventional energy sources, lowering operational costs and environmental impact. However, innovative approaches are needed to address challenges such as power reliability in low-sunlight conditions.

In conclusion, the integration of IoT and wireless communication technologies in soilless agriculture represents a transformative step toward sustainable and efficient food production. Addressing cost and technical barriers while incorporating renewable energy solutions will be pivotal in unlocking the full potential of these technologies. Furthermore, scaling these innovations for small-scale farmers, particularly in developing countries, can contribute significantly to global food security and environmental sustainability. With continued advancements in technology and research, IoT holds immense promise in reshaping the future of agriculture to address pressing global challenges such as climate change, resource scarcity, and rising food demands.

Author Contribution

All authors contributed equally to the main contributor to this paper. All authors have read and agreed to the published version of the manuscript.

Conflict of Interest

Declare conflicts of interest or state “The authors declare no conflict of interest.”

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