IoT-Driven Smart Farming using Wireless Sensor Networks: Comprehensive Survey on Data Collection Techniques and Challenges

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Abstract— *Agriculture is a critical sector for global food security and economic stability, yet it faces unprecedented challenges due to rapid population growth, urban expansion, and the adverse impacts of climate change. Precision agriculture, enabled by the integration of the Internet of Things (IoT) and Wireless Sensor Networks (WSNs), offers a promising solution by enabling continuous monitoring and data-driven decision-making for optimized resource utilization and improved crop yields. WSNs, composed of spatially distributed sensor nodes, facilitate real-time collection of environmental parameters such as soil moisture, temperature, humidity, and nutrient levels, which are transmitted wirelessly to centralized systems for analysis. This paper presents a comprehensive survey of IoT–WSN technologies applied in smart farming, with a focus on wireless communication protocols including RF, Bluetooth, Zigbee, LoRa, GSM, and Wi-Fi. Each protocol is evaluated in terms of range, data throughput, energy efficiency, scalability, and reliability, highlighting their strengths, limitations, and suitability for different agricultural contexts. Comparative analysis reveals that while short-range, low-power protocols like Bluetooth and Zigbee excel in energy efficiency, they are constrained by limited coverage; GSM provides wide-area connectivity but incurs higher operational costs; and Wi-Fi offers high throughput and scalability at the expense of greater power consumption. The review identifies key challenges such as energy constraints, environmental interference, network scalability, and cost barriers, and outlines future research directions for developing low-cost, energy-efficient, and resilient IoT–WSN architectures tailored for large-scale precision agriculture.*

Keywords— IoT, WSN's, Zigbee, LoRa, Bluetooth, GSM, Wi-Fi.

I. INTRODUCTION

Agriculture remains a cornerstone of the global economy, providing food security and employment to a substantial portion of the population. In India alone, it contributes nearly 20% to the national Gross Domestic Product (GDP) and sustains the livelihoods of more than half of the workforce [1]. However, the sector faces mounting challenges arising from rapid population growth, urbanization, industrial expansion, and the escalating effects of climate change. Unpredictable rainfall patterns, prolonged droughts, rising temperatures, and extreme weather events have disrupted conventional agricultural cycles, leading to reduced yields and economic instability for farming communities [2]. The need for increased productivity, efficient resource utilization, and sustainable farming practices has driven the adoption of advanced information and communication technologies in agriculture. Among these, smart farming—powered by the convergence of the Internet of Things (IoT) and Wireless Sensor Networks (WSNs)—has emerged as a transformative paradigm capable of enhancing crop management, improving efficiency, and supporting precision agriculture.

WSNs consist of spatially distributed sensor nodes capable of autonomously collecting environmental data such as soil moisture, temperature, humidity, nutrient levels, and rainfall, and transmitting it wirelessly to a central processing unit or cloud platform for analysis. When integrated with IoT technologies, these networks enable real-time monitoring and decision-making, offering farmers unprecedented control over field conditions regardless of their physical proximity to the farm [3]. By leveraging cloud computing and big data analytics, IoT–WSN systems can optimize irrigation schedules, reduce water and fertilizer wastage, detect pest infestations and diseases at an early stage, and forecast crop yields with improved accuracy.

Studies indicate that precision agriculture solutions incorporating WSNs can reduce water usage by up to 30%, lower input costs, and increase productivity significantly [4].

Despite these advantages, deploying WSNs in agricultural environments presents several challenges. The physical scale of farmlands, often extending over several hectares, imposes limitations on communication range for short-range protocols such as Bluetooth and Zigbee. Energy efficiency is another critical factor, as sensor nodes are frequently located in remote areas where battery replacement or maintenance is logistically difficult. Environmental factors, including dense vegetation and variable weather conditions, can cause interference and packet loss, compromising data reliability. Furthermore, scalability and cost constraints must be addressed to make these systems viable for smallholder farmers as well as large-scale agricultural enterprises. No single wireless communication protocol currently meets all performance requirements in terms of range, throughput, energy efficiency, scalability, and cost-effectiveness, making comparative evaluation essential for informed decision-making.

This paper provides a comprehensive survey of IoT-driven smart farming systems utilizing WSNs for agricultural data collection. It reviews the underlying architecture of IoT–WSN integration in farming, examines major wireless communication protocols—including RF, Bluetooth, Zigbee, LoRa, GSM, and Wi-Fi—and analyzes their applicability in diverse agricultural contexts. The comparative analysis covers performance metrics such as communication range, data throughput, energy consumption, scalability, and reliability, highlighting the trade-offs associated with each technology. Additionally, the paper identifies existing technical challenges, including network maintenance, security vulnerabilities, and environmental resilience, and discusses research gaps that need to be addressed for large-scale deployment. The goal of this study is to guide researchers, practitioners, and policymakers in selecting and optimizing wireless communication solutions for smart farming applications, ultimately contributing to the advancement of precision agriculture and sustainable food production systems.

II. IoT-WSN

Wireless sensor network (WSN) is used in numerous applications satisfying essential convenience and is composed of spatially distributed sensor nodes. These nodes are able to collect data from the environment to transmit it wirelessly over the server. It has an ability to operate autonomously in distributed manner. It is an expandable network and broadly used in industrial automation, home automation, patient monitoring, environmental monitoring and agriculture. But the key aspect of connecting these sensor nodes of WSN globally intricate IoT as central monitoring infrastructure [6]. IOT based WSN enhances the network by providing capabilities for remote monitoring, cloud-based data storage, and integration with other smart systems. IoT enables sensors to not only gather data but also transmit it over the internet for real-time analysis, control, and decision-making [7].

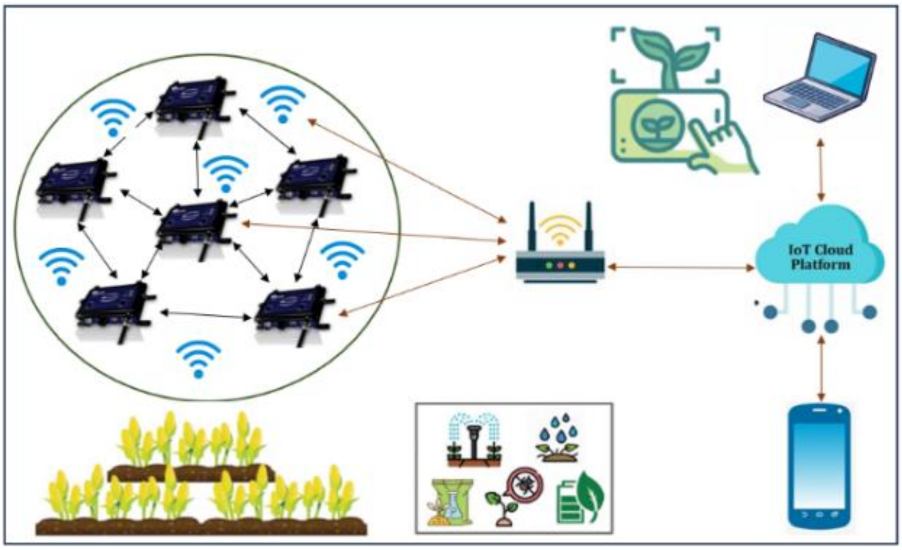

FIGURE 1: Architecture of an IoT-Based WSN

In smart farming applications, IOT based Wireless Sensor Networks provides irrigation management, crop disease and pest control, regularization and optimization of fertilizer, autonomous operation of machines for crop surveillance. Various technological approach in WSNs promotes agricultural automation to improve long term and sustained production. Through real-time field monitoring and efficient management of agricultural operations, wireless sensors and mobile networks enable farmers to collect valuable data and generate precise yield maps, supporting precision farming practices [8]. This results in the production of high-quality crops at a reduced cost, facilitated by WSNs.

An architecture of IOT based Wireless Sensor Network depicts multiple sensor nodes connected in a mesh topology, transferring the collected sensor data to the master node. This master node communicates with the cloud and user applications for further computing and control actions. Thus, the master node acts as a mediator between the user and the sensor nodes, which are located far from the user [9].

Each sensor node is equipped with multiple modules of required sensors, such as humidity, temperature, soil moisture, water level, fertilizer, wind speed, and flow, among others. These sensor nodes must be connected to a controller unit to collect and store data for further computation [10]. For an IoT-based wireless sensor network, a wireless communication module is necessary to link the sensor nodes with the master node, where all the sampled data will be transmitted.

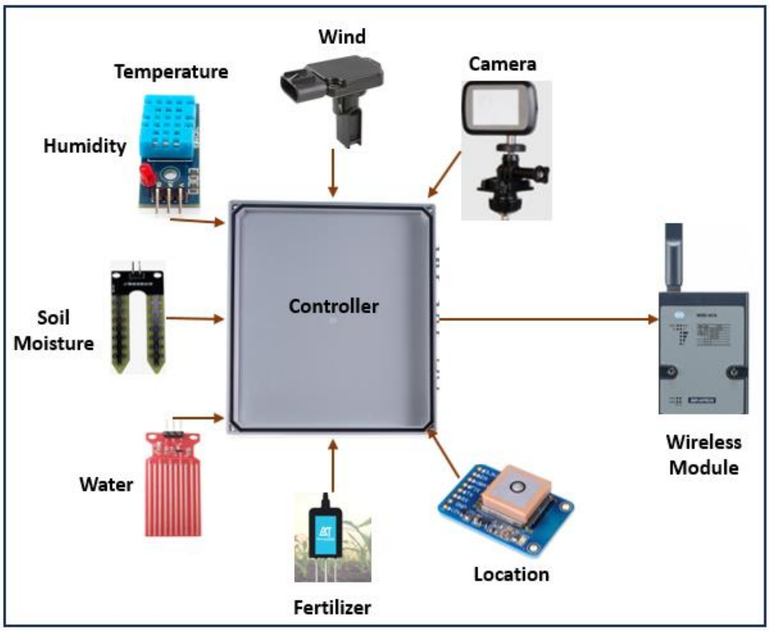

FIGURE 2: Sensor Node for Precision Agriculture in WSN

III. STATE OF ART TECHNOLOGIES IN IOT BASED WIRELESS SENSOR NETWORK

In Wireless Sensor Networks (WSNs), the core technologies are generally similar, but each research implementation often involves a customized network configuration with different wireless communication modules. In the context of IoT-based WSNs for smart farming, precise and extensive real-time field data is collected through various communication protocols, including RF based Bluetooth, Zigbee, GSM, WiFi, SigFox, and LoRaWAN. The primary goal of each protocol is to ensure efficient, sustainable, and accurate data transfer over long distances, while minimizing packet loss, power consumption, and optimizing connectivity. Sensors are strategically placed to monitor parameters such as temperature, humidity, soil moisture, wind speed, water levels, fertilizer requirements, location, and capture necessary camera images. The data collected by each sensor is transmitted to a master node, forming the IoT-WSN network. This large-scale data is then analysed and predicted to support informed decision-making for irrigation management, resource allocation, and timely interventions to enhance crop growth. The performance of the WSN is influenced by the varying characteristics of each communication module, including range, efficiency, and power consumption, which have a significant impact on the network’s effectiveness in different applications [11][12].

3.1 RF Based Smart Irrigation:

In the Design of Wireless Sensor Network (WSN) with RF Module for Smart Irrigation System in Large Cultivated Areas by Radi et al., a model for smart irrigation is proposed. The model divides the cultivated area into smaller zones, each managed by its own WSN for automatic irrigation. The RF-based wireless communication system is employed to transmit sensor data to the cloud, operating at a frequency of 2.4 GHz. The system uses a star topology for data transmission, and the performance is tested over distances of 50m, 100m, and 150m [13]. This approach demonstrates the feasibility of using RF communication in large agricultural areas for efficient irrigation management.

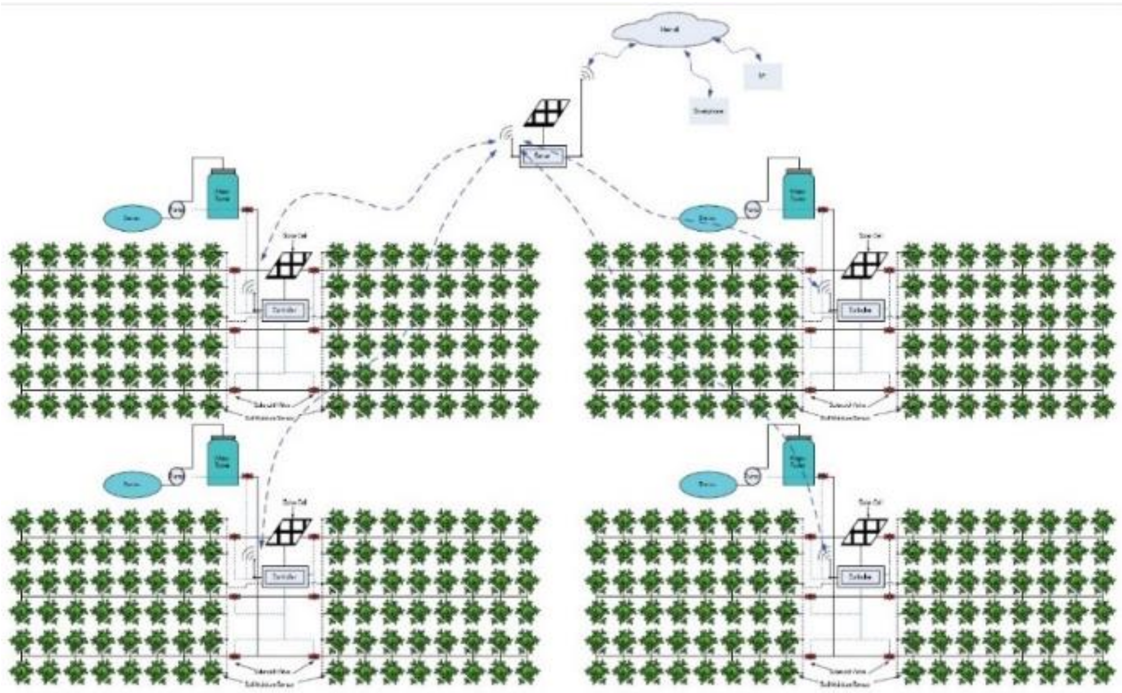

FIGURE 3: Smart Irrigation System using RF based WSN

3.2 Bluetooth Based WSN:

Bluetooth is most popular and globally used protocol for having low cost, short-range, low power consumption and reasonable throughput. The Bluetooth based WSNs uses Bluetooth technology for communication between various nodes. These networks enable the collection and transmission of data from multiple sensors to master hub for processing and analysis. This communication is completely transparent and indispensable for future oriented automation concepts. Bluetooth is a short-range wireless communication technology that enables devices to connect and exchange data over distances typically ranging from 1 meter to 100 meters, depending on the Bluetooth version and the environment [14].

TABLE 1
PERFORMANCE ANALYSIS WITH RESPECT TO DISTANCE

Slaves Node	Distance (m)	Time (h)	Period (s)	Data Packet		Data Loss (%)
				Potency	Actual	
1	50	72	5	51840	51862	-0.04%
2	100	72	5	51841	51862	0.00%
3	200	72	5	51841	22243	87.09%

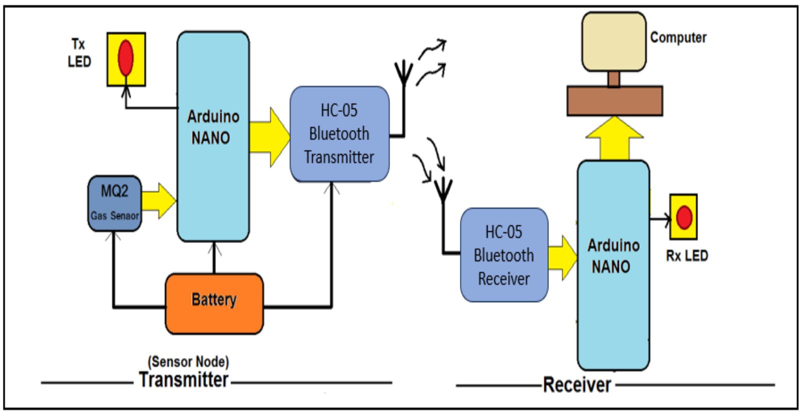

FIGURE 4: Bluetooth Based Wireless Sensor Network using Arduino controller

It is observed that this prototype has a good performance up to the distances less than 100 m. Hence it is concluded that vegetation affects data transmission and have data losses when distance increases.

3.2.1 Challenges of Bluetooth-Based WSNs:

Limited Range: Bluetooth has a relatively short range compared to other wireless communication technologies (e.g., Zigbee or LoRa). This can be a limitation in large agricultural fields unless mesh networks or multiple gateways are used to extend the coverage.

Interference: Bluetooth operates in the 2.4 GHz frequency band, which can be crowded and prone to interference from other devices (e.g., Wi-Fi networks, microwaves). This can affect data transmission reliability.

Security Concerns: Wireless communication networks are susceptible to cyber-attacks, and securing Bluetooth networks can be challenging, especially in large-scale deployments.

Battery Life: While Bluetooth Low Energy devices are power-efficient, the battery life of sensors can still be a concern in remote agricultural areas, requiring regular maintenance.

3.3 Zigbee based WSN:

Helmy Fitriawan etal in his research of ZigBee Based Wireless Sensor Networks and Performance Analysis in Various Environments achieved Zigbee based wireless sensor network for low data rate application. Here two nodes as stated in fig.1 have considered i.e. sensor node and master node. Sensor node collects all data reading from all kinds of sensor connected and sampled using the Atmega controller unit. Xbee S2 wireless module is used as communication channel for controller unit and master node with frequency 2.4 GHz band at 250 kbps RF data rate [14]. Both types of nodes are prepared in order to see performance of WSN in LOS and NLOS communications. The zigbee protocol supports network topology as peer to peer, star and mesh and Trans-receive data messages in the network [20].

TABLE 2
MAXIMUM THROUGHPUT WITH RESPECT TO BAUD RATE AND PACKET SIZE

Baud Rate	Data Size							
	10	20	30	40	50	60	70	80
9600	2	2.5	3	4	4.5	5	6	6.5
19200	3.5	4	5	6	7	8	9	10
38400	3.75	5	7	9	10	12	13	14
57600	4	6	8	10	12	14	15	17
115200	4	8	10	13	15	16	18	20

TABLE 3
MAXIMUM TRANSMISSION DELAY WITH RESPECT TO BAUD RATE AND PACKET SIZE

Baud Rate	Packet Size							
	10	20	30	40	50	60	70	80
9600	50	60	80	80	90	100	110	120
19200	30	38	42	50	55	60	65	70
38400	28	30	35	40	42	44	46	50
57600	22	24	26	28	30	34	36	40
115200	20	22	24	26	28	29	30	32

For the research, it has been concluded that the maximum throughput is increases as the baud rate increases with increasing packet size. It is also observed that the transmission delay reduces with higher baud rate and increases with packet size.

3.4 GSM based WSN:

Dedi Satria etal in his research of Implementation of wireless sensor network (WSN) on garbage transport warning information system using GSM module proposes a prototype of waste management using wireless sensor network and GSM as communication medium. Here the sensor information is transferred in the form of GSM based communication SMS [15].

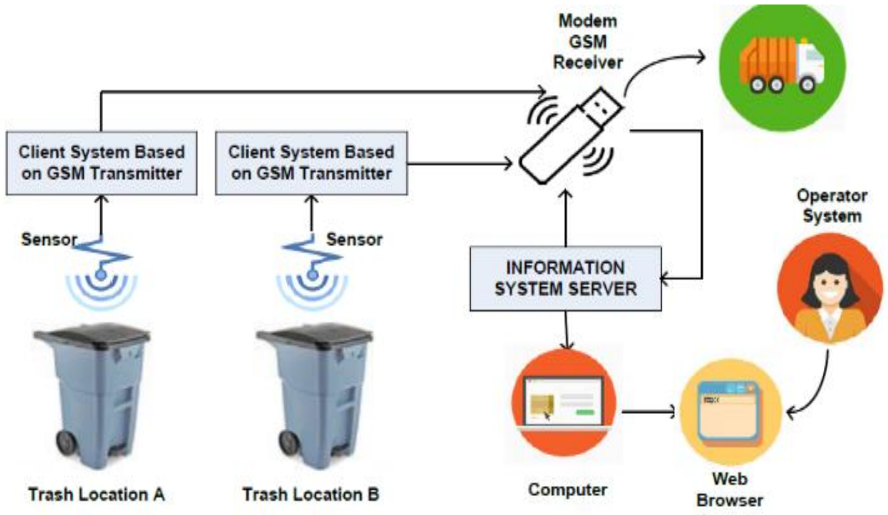

FIGURE 5: Waste Management using GSM based wireless sensor network

Above system is a concept of WSN to send data from client to server using messaging communication and the results are going to display on the web server. All the garbage data will be immediately transported to the officer for further actions.

The above prototype removes the limitation of range, distance, data loss using GSM. But, for each SMS, operator will need to pay cost. The GSM module will require a networking SIM with SMS recharge. So every time, operator need to check the recharge. Also the type of data communication is in the form of SMS where you can send limited sensor data. It is feasible only for few sensors. But when number of sensors increases, single SMS will not be able to send data due to character limitations.

3.5 Wifi Based WSN:

Gerard Rudolph Mendez etal in "A WiFi based Smart Wireless Sensor Network for an Agricultural Environment" monitored environmental parameters using sensor node where a controller unit is used WSN802G module. This prototype has inbuilt wifi module which can be used to transmit data wirelessly over the server [16].

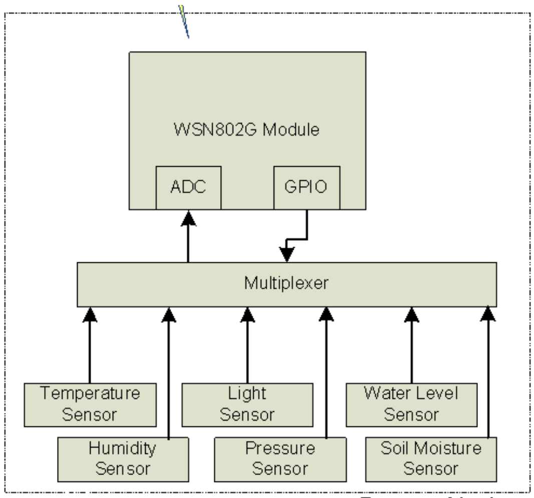

FIGURE 6: WSN802G based sensor node

This WSN802G module uses IEEE 802.11 standard to communicate sensor node with server for 2.4 GHz frequency. It requires operating voltage of 3.0V to 3.63V with two 10 bits analog to digital converter for sensor inputs. This protocol has three different modes of operations. In first mode sensor node can be sleep with timer, in farming, a comparative framework was developed based on key performance parameters reported in peer-reviewed literature and technical standards. The parameters include communication range, throughput, energy consumption, failure rate, security features, and scalability potential.

second mode serial data node can be sleep with timer and in third mode, both sensor and serial data node can be sleep with auto reporting. The module can sleep until the wake up call after the timer ends.

IV. COMPARATIVE ANALYSIS

To evaluate the suitability of wireless communication protocols for IoT-enabled smart

TABLE 4
COMPARATIVE PERFORMANCE OF WIRELESS PROTOCOLS FOR IOT-BASED WSNS IN SMART FARMING

Wireless Protocol	Typical Range (m)	Throughput (kbps/Mbps)	Energy Consumption (mW)	Failure Rate (%)*	Security Level	Scalability Potential
Bluetooth	10–100	1–3 Mbps	15–35	~5–8	Low	Low
Zigbee	10–100	20–250 kbps	25–40	~3–6	Moderate	Low–Moderate
GSM	1,000–35,000	~85–128 kbps	200–300	~2–5	Low	Moderate
WiFi	50–100	6–600 Mbps	500–1000	~1–3	High	High

The analysis demonstrates that **Bluetooth** offers low power consumption and reasonable throughput for short-range, localized applications, but its limited coverage severely constrains scalability. **Zigbee** provides slightly higher reliability and moderate energy efficiency; however, its range is still insufficient for large-scale deployments without extensive mesh networking. **GSM** offers extensive coverage, enabling deployment in remote areas without additional infrastructure, though its low throughput limits its suitability for high-data-rate applications such as real-time imaging. **Wi-Fi** excels in throughput and scalability, supporting data-intensive smart farming tasks, but its higher power requirements may limit use in battery-powered sensor nodes.

Given the diversity of agricultural environments, these results suggest that protocol selection should be application-driven, with hybrid or multi-tier architectures often providing the best balance between range, power efficiency, and data capacity.

V. CONCLUSION

The integration of Internet of Things (IoT) technologies with Wireless Sensor Networks (WSNs) is reshaping modern agriculture by enabling real-time monitoring, data-driven decision-making, and optimized resource utilization. This study reviewed the fundamental architecture of IoT–WSN systems in smart farming and presented a comparative evaluation of major wireless communication protocols—RF, Bluetooth, Zigbee, LoRa, GSM, and Wi-Fi—based on range, throughput, energy efficiency, scalability, and reliability. The findings reveal that no single protocol offers a universally optimal solution; instead, selection should be application-specific. Short-range, low-power protocols such as Bluetooth and Zigbee are energy-efficient and cost-effective for localized deployments, whereas LoRa achieves a balanced trade-off between long-range coverage and low energy consumption. GSM delivers wide-area connectivity but at higher operational and energy costs, while Wi-Fi supports high data rates and scalability but is less suited to remote areas without infrastructure.

Key challenges remain, including the need for improved energy management in off-grid deployments, enhanced resilience against environmental interference, cost-effective solutions for smallholder farmers, and robust cybersecurity measures to protect agricultural data. Future work should explore hybrid communication architectures that integrate multiple protocols, energy harvesting methods to prolong network lifetime, and adaptive topologies capable of self-healing under adverse conditions. Addressing these challenges will enable IoT–WSN solutions that are more accessible, efficient, and sustainable, accelerating the adoption of precision agriculture and strengthening global food security.

VI. FUTURE SCOPE

While Wi-Fi-based WSN deployments demonstrate high data throughput and scalability, their limitations in terms of power consumption, infrastructure dependency, and cost highlight the need for further innovation in wireless communication for smart farming. Future research should focus on developing hybrid communication models that combine the strengths of multiple protocols to achieve wide-area coverage, low energy consumption, and cost efficiency. Incorporating energy harvesting mechanisms, optimizing duty cycles, and leveraging low-power wide-area network (LPWAN) technologies such as LoRa or NB-IoT may address the shortcomings of current solutions. Additionally, exploring adaptive, self-healing network topologies and cost-reduction strategies can make WSN solutions more viable for diverse agricultural environments, from smallholder farms to large-scale operations.

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