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System Testing and Performance Evaluation of an MQTT-Based IoT Monitoring System for Crop Cultivation

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Abstract – **Agriculture is a crucial component of Indonesia's economy and food security. However, farmers have been using conventional techniques, such as planting according to a fixed timetable that is unaffected by weather or temperature. This will negative effect on the quality and yields of crops. Thus, a device is needed that can provide information about the weather or temperature. The message queuing telemetry transport (MQTT) is very helpful because it send data from the microcontroller to the display. This research aims to develop a prototype that displays measurement data utilizing MQTT and Node-RED, along with performance evaluations including latency, packet loss, and energy efficiency. This study employs an experimental approach that starts with a schematic design, followed by the installation and evaluation of a monitoring system. The outcome of this research indicates that the prototype ~~worked~~ performed well in an open farming field. System performance was assessed in terms of latency, packet loss, and energy efficiency. The results demonstrate stable operation during a 10-day field deployment, with an average latency of approximately 1.3 s, a packet loss rate of 1.38% and average power consumption of 1.25 W over 24 hours of continuous operation. These findings indicate that the proposed system is suitable for real-time agricultural monitoring under open-field conditions. The study emphasizes deployment feasibility and system-level performance rather than detailed agronomic analysis providing insights into the use of MQTT-based IoT solutions for open-field precision agriculture.**

Keywords: agriculture, latency, monitoring, MQTT, packet loss

I. INTRODUCTION

Agriculture is an essential sector for achieving food security and economic sustainability in Indonesia. Agriculture in Indonesia has employed conventional techniques, namely planting according to a calendar system that is not yet adapted to climate and weather changes. Climate and weather changes result from an imbalance between the rainy and dry seasons, disrupting agriculture[1]. The Internet of Things (IoT) in agriculture presents considerable opportunities to enhance production and resource management. Interconnected sensors and communication protocols enable the continuous real-time monitoring and analysis of environmental factors, including soil moisture, temperature, humidity, wind speed, wind direction, and rainfall. Agriculture is significantly vulnerable to climatic variability, prompting concerns about sustainability[2][3]. The effects of climate change, including elevated temperatures, altered precipitation patterns, and increased extreme weather events such as floods and droughts, present a substantial danger[4]. According to BMKG, during August 2024, several regions in Indonesia experienced extreme rainfall (>150 mm/day), including West Kalimantan. For predictions in October-December 2024, the West Kalimantan region is classified as a high monthly rainfall status (300-400mm/month)[5].

Consequently, significant rainfall in the West Kalimantan region would lead to flooding, interrupting the agricultural planting season. Environmental conditions, including climate and weather, significantly influence plant growth. Weather and climatic factors include the duration of sunlight, atmospheric humidity, wind direction, temperature, air pressure, wind velocity, and precipitation[6]. These data can be immediately acquired from BMKG (Meteorology, Climatology, and Geophysics), including air temperature, wind speed, wind direction, and air humidity. Conversely, other variables, including air pressure and precipitation, are challenging to obtain. Furthermore, the data acquired from BMKG has shortcomings, including the measurement range at the sub-district level, the lack of daily rainfall measurements, and the presentation of data hourly rather than per minute.

Agriculture requires data, including ambient temperature, humidity, atmospheric pressure, wind velocity, and precipitation levels. Consequently, real-time identification of the data needed concerning agricultural land is essential and readily accessible. Traditional agriculture practices, including non-adaptive planting cycles, have evolved in precision agriculture to ensure food security in response to climate and weather changes. Precision agriculture is a technology-driven methodology for agricultural management that begins with the observation, measurement, and analysis of the specific requirements of land and plants [7]. This method employs IoT (Internet of Things) and filtering to enhance agricultural productivity. The Internet of Things refers to the ability of diverse devices to connect and transmit data over the Internet. IoT technology enables control,

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communication, and collaboration across diverse hardware and data over the internet. Nonetheless, IoT encompasses more than merely the capability of devices to remotely control and share data, extending to the representation of all tangible entities within the internet framework[8], [9], [10], [11]. Enhancing knowledge pertinent to the primary needs to augment agricultural productivity, including nitrogen, phosphorus, and potassium, is essential for accelerated plant growth. This nutrient is ideal for promoting plant growth [12].

NPK is a macronutrient essential for plant growth. Despite the widespread adoption of IoT technologies, numerous systems lack adequate performance validation. Their efficacy in practical situations, including network stability, data transmission delay, sensor precision, and system availability, is seldom scrutinized comprehensively. Numerous research studies have investigated the applicability of IoT in agriculture. [13] examines the performance of the MQTT protocol in agricultural IoT systems, emphasizing data compression and secure transmission with AES and TLS. The findings indicate MQTT's efficacy in low-power sensor networks and unpredictable wireless environments, underscoring its appropriateness for real-time agricultural applications. The constraint of this study is its applicability solely inside laboratory or controlled settings. Nonetheless, these do not accurately reflect the genuine operational issues, such as variable connectivity, power instability, and environmental interference, in real agricultural fields.

A separate study [14] introduces a comprehensive IoT system engineered for the real-time monitoring of soil nutrients utilizing sensors and MQTT. The report encompasses comprehensive latency and message delivery assessments, demonstrating dependable system performance in practical implementation. The research highlights MQTT's low overhead and rapid reactivity. The limitation of this study is its exclusive focus on soil, neglecting the influence of climate on agriculture. [15] concentrated on Node-RED and MQTT for environmental surveillance and automation in greenhouses. The evaluation encompasses message consistency and performance within a regulated agricultural setting. [16] introduces a real-time monitoring system utilizing soil sensors and LoRaWAN (Long Range Wide Area Network) / MQTT communication protocols. It examines the system's transmission range (up to 3.4 km), data dependability, and low-power functionality in outdoor agricultural environments. The study’s limitations include the incomplete characterization of MQTT testing inside agricultural network constraints.

In [17], contemporary trends in IoT sensor integration for agricultural monitoring were examined, emphasizing sensor classifications, data acquisition methodologies, wireless communication protocols such as MQTT, and problems associated with system deployment. MQTT is extensively utilized in wireless applications owing to its superior performance, minimal bandwidth requirements, and reduced power consumption, with a significant advantage being energy efficiency, particularly when employing a cloud-based broker, as numerous experiments continue to rely on physical brokers for data transmission[18]. Node-RED is a flow-based development platform that facilitates the integration of hardware, APIs, and web services[19]. A primary feature of Node-RED is its ability to integrate multiple protocols and services, including Message Queuing Telemetry Transport (MQTT), HTTP (Hypertext Transfer Protocol), and WebSockets, enabling seamless communication among diverse devices and applications [20].

Although past research has proved the usefulness of MQTT-based IoT systems for agricultural monitoring, present assessments remain scattered. Some studies focus solely on soil monitoring without considering environmental dynamics, while others examine communication under controlled or greenhouse conditions. Moreover, system-level testing concurrently investigates communication reliability, latency, energy efficiency and deployment resilience under actual field settings is still restricted. Consequently, there is a lack of comprehensive studies that assess MQTT-based agricultural IoT systems as integrated deployments rather than discrete components. To solve these constraints, this work proposes a system testing and performance assessment of an MQTT-based IoT monitoring system for agricultural cultivation.

The suggested technique stresses deployment-oriented evaluation by rigorously measuring latency, packet loss, network resilience, and energy efficiency in a solar-powered agricultural context. Unlike past sensor-centric or laboratory-focused research, this study provides practical insights into real-world IoT deployment issues and presents a scalable and cost-effective framework for precision agricultural applications. The novelty of this research compared to previous research lies in the deployment and performance evaluation of an MQTT-based IoT monitoring system for crop cultivation. This study focuses on the systematic assessment of communication performance, including latency, packet loss and energy efficiency under real-world deployment conditions powered by solar energy. The proposed approach provides practical insights into IoT monitoring systems in dynamic agricultural environments and offers a cost-effective scalable solution for precision agriculture. The integrated soil and environmental sensors serve as supporting components for comprehensive system testing, not as a primary source of novelty.

II. METHODOLOGY

This research employs an experimental design. It uses the MQTT protocol because of its ability to transmit messages ranging from 0 to 256 MB while utilizing little network resources, in contrast to the HTTP protocol [21]. MQTT offers the highest data transfer rate, with an average transmission time of 0.0197 seconds, compared with 0.169 seconds for HTTP and 2.211 seconds for HTTPS [22]. Consequently, MQTT was selected for real-time data transfer, proving more appropriate for a monitoring system than HTTP.

A. System Architecture

This section outlines the whole architecture of the proposed IoT-based monitoring system for agricultural production. The system utilized a layered architecture consisting of sensor nodes, communication modules, a gateway, and a cloud-based or local server. The sensor layer collects real-time environmental and soil data, encompassing soil temperature, soil moisture, electrical conductivity, pH, nitrogen, phosphorus, potassium, and salinity, along with climate temperature, humidity, air pressure, rainfall, wind direction, and wind speed, which is transmitted via the MQTT protocol to a microcontroller ESP32.

A cloud-based Node-RED server processes the incoming data and visualizes the results via a web interface. The architecture is engineered to support modular expansion, enabling the incorporation of additional sensors or actuators as required. The real-time monitoring system was developed with Fritzing software, as illustrated in Figure 1.

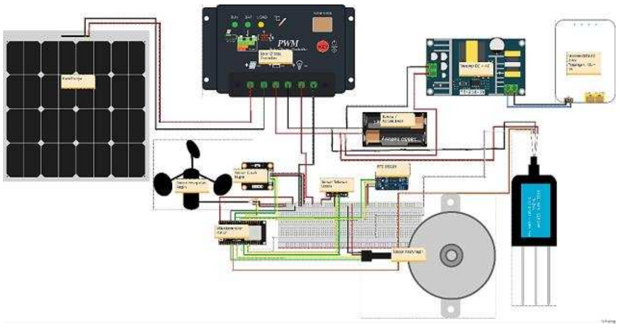

Figure 1. Schematic diagram designed in Fritzing

Figure 1 illustrates the framework for real-time surveillance of agricultural conditions. It integrates several ambient and soil sensors with wireless data transmission and is controlled and powered by solar energy. A photovoltaic (PV) solar panel charges a 12V battery with a PWM solar charge controller. This battery provides electricity to the microcontroller and the GSM modem. A DC-to-AC inverter converts the 12V DC output into 220V AC, enabling the operation of higher-voltage components such as the GSM modem. The ESP32 microcontroller is the fundamental component of the sensor unit. The ESP32 connects with multiple analog and digital sensors to gather data from the agricultural environment. The aggregated data is transmitted to a Node-RED dashboard, which displays it in real time to facilitate analysis and decision-making. Node-RED is a flow-based programming interface that enables seamless integration of data logging, alert generation, and connections to external APIs or databases. The system architecture is structured to assess communication reliability, energy efficiency and deployment viability in real-world agricultural settings.

B. Hardware and Sensors

This section delineates the hardware components used in the proposed real-time monitoring system. The sensing layer utilizes a commercially available 8-in-1 integrated soil sensor from Hondetec. The specifications of the sensors used are shown in Table 1.

Table 1. The specifications of the sensors used

Component	Parameter	Specification
Soil Sensor	Type	8 in 1 soil sensor integrated
	Vendor	Hondetec
	Measured parameters	Temperature, moisture, pH, EC, salinity and NPK
	Interface	RS485
	Supply voltage	5-12 V
	Output format	Digital (Modbus RTU)
MCU	Type	ESP32
Env Sensor	DHT22/AHT10	Temperature and Humidity
Pressure sensor	BMP280	Pressure and Temperature

The hardware components and sensor requirements listed in Table 1 aim to ensure transparency and repeatability of the system. The integrated soil sensor functions as a realistic, field-deployable sensing instrument, facilitating multi-parameter data collection for system testing. This research does not prioritize laboratory-grade calibration or chemical accuracy validation of soil nutrients, namely NPK readings, since its main contribution is on system integration, communication performance, and energy-efficiency assessment under open-field conditions. Some of the tools and materials, including sensors, used in this study are shown in Figure 2.

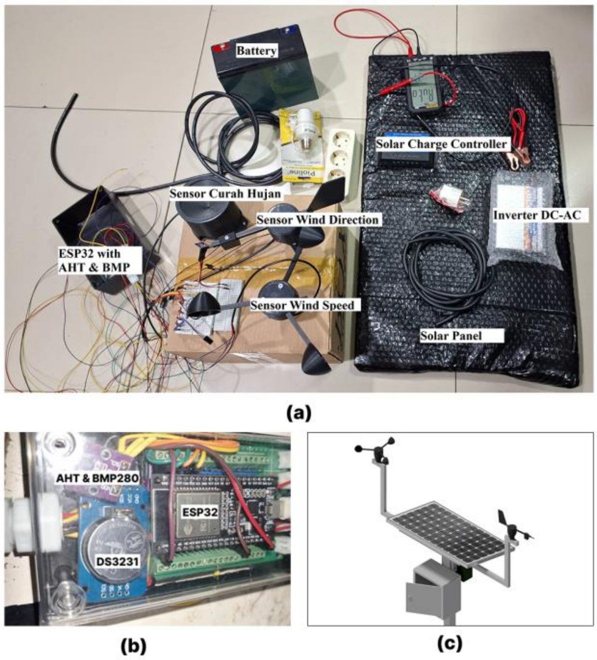

Figure 2. (a) Material and sensor, (b) Microcontroller ESP32 with AHT and BMP sensor, (c) Design of prototype

The soil and environmental sensors were used mostly for system-level performance assessment rather than comprehensive agronomic analysis. The integrated soil sensor, which measures temperature, moisture, pH, electrical conductivity (EC), salinity, and macronutrient indicators (NPK), was used with the manufacturer's calibration settings, and no further laboratory recalibration was conducted before field deployment. Thus, nutrition-related data are regarded as relative trend indicators for evaluating system responsiveness and communication efficacy, rather than as absolute or laboratory-validated nutrient concentrations.

C. Communication Protocols

The system utilizes the MQTT (Message Queuing Telemetry Transport) protocol for efficient, low-bandwidth communication between sensor nodes and the gateway. MQTT is optimal for agricultural IoT because it facilitates a publish/subscribe architecture, enabling scalable data dissemination and energy-efficient operation. The ESP32 publishes sensor data to designated MQTT topics, which are accessed by an MQTT broker on a cloud or ~~a~~ local server. In this case, the MQTT broker is hosted on a cloud server.

D. Node-RED Dashboard

The user interface for monitoring and interacting with the real-time sensing system is built with Node-RED, a low-code, flow-based programming language commonly utilized in Internet of Things (IoT) applications. Node-RED offers a graphical interface enabling developers to connect hardware devices, APIs, and web services using a browser-based flow editor. It is particularly effective for swift prototyping and integration inside edge and fog computing infrastructure [19]. The dashboard has numerous widgets, including gauges, status indicators, and charts that depict data such as soil moisture, temperature, humidity, pH, EC, NPK, rainfall, and wind conditions.

E. System Testing Parameters

This section delineates the performance assessment criteria used to analyze the proposed MQTT-based IoT monitoring system in actual open-field deployment scenarios. The system testing emphasizes communication and operational performance metrics, such as latency, packet loss, and energy consumption, to accurately reflect authentic system behavior beyond laboratory or simulation-based trials. Field testing was performed continuously over many days to assess system resilience, network dependability, and power efficiency under varying environmental conditions. This assessment focuses on system-level performance and excludes sensor accuracy and agronomic data validation from its scope.

III. RESULTS AND DISCUSSION

A. The Development of the Prototype

This section clarifies the design and implementation of a real-time monitoring system via integrating the Internet of Things. The hardware architecture used in this study is shown in Figures 2(a) and 2(b), with the preliminary schematic design shown in Figure 1. The system's development and implementation employed the Arduino Integrated Development Environment (IDE) as the principal platform for programming and interfacing with the ESP32 microcontroller. The system's core consists of an extensive sensor suite, featuring soil from Hondetec. These sensors can concurrently measure eight essential soil parameters: soil temperature, soil moisture, electrical conductivity (EC), pH, nitrogen (N), phosphorus (P), potassium (K), and salinity. The system incorporates environmental sensors to measure essential atmospheric factors, such as precipitation, wind velocity, wind orientation, humidity, temperature, barometric pressure, and soil properties. All sensors are interconnected and configured according to the specified schematic, ensuring full compatibility with the ESP32 microcontroller.

After successfully assembling and wiring the hardware according to the schematic design, the system was coded and uploaded using the Arduino IDE. Following successful code compilation and deployment, the system advanced to the functional testing phase, during which each sensor module was assessed for precision and reliability in real-time data collection. The ESP32 conveys sensor data to a central server via the MQTT (Message Queuing Telemetry Transport) protocol. The protocol is a lightweight messaging system based on a publish-subscribe model, optimized for low-bandwidth, high-latency networks, particularly in rural agricultural settings. MQTT guarantees the efficient and dependable transfer of real-time sensor data. The Node-RED platform serves as the foundation for data-flow orchestration and the server-side dashboard interface.

Node-RED facilitates the visual development of data pipelines, MQTT topic subscriptions, and database storage. Moreover, it offers a dynamic, customizable interface that displays real-time sensor data, charts, and historical patterns for users, including farmers and agronomists. The use of MQTT and Node-RED in this system facilitates an uninterrupted connection between field equipment and the user interface, ensuring near real-time data accessibility, system scalability, and ease of maintenance. The Node-RED library developed the user interface, streamlining the configuration process. Figure 3 displays the dashboard which contains gauges for various soil parameters.

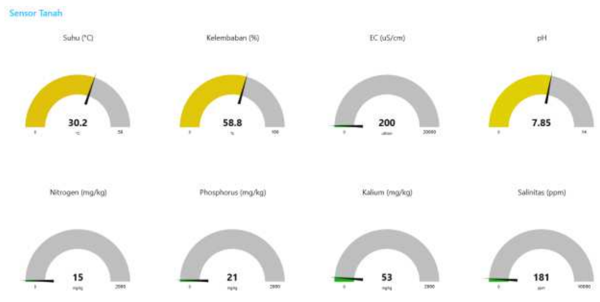

Figure 3. Dashboard result featuring a gauge

To view historical data on the measurement of various parameters in the soil sensor, as illustrated in the time series presented in Figure 4.

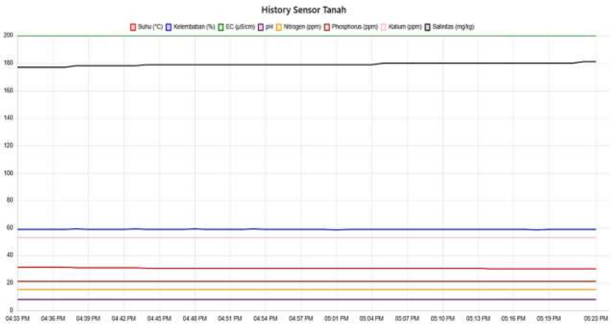

Figure 4. History of soil sensor with time series

In addition, a dashboard is available to display environmental measurements using sensors such as AHT10, BMP280, rainfall, wind direction and wind speed, as illustrated in Figure 5.

Figure 5. Dashboard environmental section

To view historical data on environmental measurements in the form of a time series as shown in Figure 6.

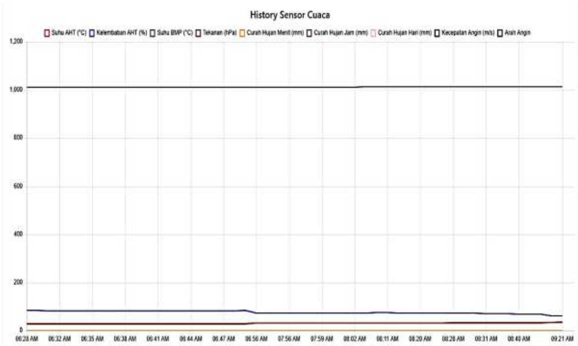

Figure 6. Historical data of the environmental measurements

As illustrated in Figure 7, the developed prototype was situated on agricultural land comprising peat soil in Rasau Jaya village, Kubu Raya Regency, West Kalimantan province, over the previous month.

Figure 7. Prototype implemented at Rasau Jaya

B. *System Performance Evaluation*

The system was assessed according to latency, packet loss rate, and scalability. Latency was quantified as the interval between data transmission from the ESP32 node and its display on the Node-RED dashboard. The calculation is based on the temporal disparity between data transmission from the sensor and its reception at the dashboard. Table 2 illustrates the latency measurements conducted over 10 days.

Table 2. Latency over 10 days

Day	Timestamp Sent	Timestamp Received	Latency (ms)
1	08:00:320	08:01:550	1230
2	09:05:400	09:06:640	1240
3	10:07:170	10:08:320	1150
4	08:05:120	08:07:060	1940
5	08:15:510	08:16:210	700
6	08:20:150	08:22:010	1860
7	08:00:190	08:01:780	1590
8	14:08:140	14:09:100	960
9	17:11:540	17:12:650	1110
10	20:14:603	20:15:780	1177
Average			1295.7

Table 2 indicates that the latency fluctuates between 700 ms and 1940 ms throughout 10 days. This results from varying signal-strength conditions influenced by weather and network congestion, since this study used a cellular access point and retransmissions due to packet loss. The average delay is 1295.7 ms (1.3 s), which is satisfactory for real-time agricultural monitoring. The assessment of packet loss rate utilized data transmitted over 24 hours on July 25, 2025, with transmissions every minute, as illustrated in Table 3.

Table 3. Packet loss rate over 24 hours

Hour	Packet Sent	Packet Received	Loss
00-01	60	60	0
01-02	60	60	0
02-03	60	59	1
03-04	60	57	3
04-05	60	60	0
05-06	60	60	0
06-07	60	60	0
07-08	60	59	1
08-09	60	57	3
09-10	60	59	1
…	…	...	...
23-24	60	60	0
Total	1440	1420	20

The packet loss rate calculation is shown in Equation (1).

$$Packet\ Loss\ Rate = \left(1 - \frac{N_{received}}{N_{sent}}\right) x100\% \quad \ldots\ldots\ldots\ldots\ldots (1)$$

From Table 2, the total packets received and packets sent are calculated using Equation (1).

$$= \left(1 - \frac{1420}{1440}\right) x100 = 1.38\ \%$$

The computed packet loss rate of 1.38% is considered low and acceptable for MQTT use in open-field conditions. However, if it exceeds 5-10%, concerns may be related to MQTT interference, range, or congestion. A prototype's energy-efficiency measurement utilizes a 12V battery with a capacity of 20 Ah, yielding 240 Wh. The projected power consumption derived from the sensor parameters is presented in Table 4.

Table 4. Power consumption regarding sensors

Component	Estimated Power Consumption	Quantity
ESP32	80-240 mA (active WiFi)	1
Soil Sensor (RS485)	40-60 mA	1
Wind Direction (analogue/PWM)	5-20 mA	1
Wind Speed (Reed Switch)	~5 mA (pulsed)	1
Rainfall (Tipping Bucket)	~5 mA (pulsed)	1
BMP280	0.5-1.5 mA	1
AHT10	0.5-1.5 mA	1
RTC DS3231	< 1 mA	1
Total	~150-300 mA @5V	

Battery voltage range: 12.6 - 11.1V corresponds to 1.5V with a total energy capacity of 240 Wh. Energy consumption may be calculated as mentioned in Equation 2.

$$Energy\ used = \frac{V_{full} - V_{used}}{V_{cell}} x\ C \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

The energy consumption is determined from the battery voltage decline according to the following Equation (2).

$$Energy\ consumption = \left(\frac{(12.60 - 11.10\ )}{12} x240\right)$$

$$= \frac{1.5 * 240}{12}$$

$$= 30\ Wh$$

The average energy consumption per day is around 1.25 W. This estimate indicates that enabling deep sleep on the ESP32 and using a buck regulator are viable strategies. Energy efficiency was assessed by documenting the battery voltage before and following a 24-hour operation. The 12V battery exhibited a voltage drop of 1.25V, corresponding to an approximate energy consumption of 30 Wh. The overall average power usage of the system was 1.25 W, encompassing the ESP32, soil sensor, wind direction sensor, anemometer, tipping bucket, BMP280, AHT10, and DS3231 modules.

C. Discussion

The real-time monitoring system developed in this study ilustrates the practical feasibility of using an Internet of Things (IoT) based approach for precision agriculture. The proposed system prioritizes open-field, multi-day deployment above controlled laboratory or greenhouse assessments, in contrast to previous MQTT-based agricultural monitoring systems. The amalgamation of soil-integrated sensors and environmental sensors enables extensive environmental data collection while ensuring consistent communication efficacy.

1) System reliability and latency

The latency evaluation performed during a 10-day open field deployment indicated values between 700 ms to 1940 ms, with an average latency of 1295.7 ms (~1.3 seconds). Compared with prior MQTT-based agricultural monitoring studies, latency reported here is higher than the values reported under controlled conditions. For instance, research [14] reported latency ranging from 5-7 ms during initial testing, increasing to 20 ms under higher data load scenarios. However, such measurements were obtained in controlled environments with stable network configurations. In contrast, study [15] conducted in a greenhouse setting reported an average delay of around 1.9 seconds, which is closer to the latency observed in the current study. Considering the deployment in ~~a~~ rural areas where signal attenuation, environmental interference and various networks are more prominent, the average latency of 1.3 seconds remains within an acceptable range for real-time agricultural monitoring applications. These results prove that MQTT retain reliable communication under realistic field conditions, although latency is affected by the deployment environment and network infrastructure.

2) Packet loss

The packet loss rate recorded over a 24-hour observation period was 1.38%, well below the critical threshold of 5%, indicating reliable data transmission. This low packet loss indicates stable and dependable communication performance despite the challenges associated with open-field deployment, such as environmental interference and variable network conditions. Previous studies on IoT-based agricultural monitoring systems often focus on latency, throughput, or system responsiveness, while detailed packet-loss metrics are rarely reported, particularly for MQTT-based deployment in outdoor environments. Consequently, the result presented in this study provides additional insight into the reliability of MQTT under open-field conditions.

3) Energy efficiency

Power efficiency is a critical factor in off-grid, remote agricultural systems. The proposed system demonstrated an average power consumption of 1.25 W, demonstrating a moderate energy profile facilitated by the low-power attributes of the ESP32 microcontroller and the associated sensor suite. During continuous 24-hour operation, a 12 V, 20 Ah battery exhibited a voltage drop of around 1.5 V, corresponding to an estimated energy use of 30 Wh. Compared with other ESP32-based agricultural monitoring systems reported in recent studies, the measured power consumption is within a comparable range for continuous operation. This indicates that the system is suitable for deployment in areas with limited power infrastructure, particularly when combined with renewable energy such as solar panels. Further optimization could be achieved by implementing ESP32 deep sleep modes and duty-cycled sensor activation strategies to reduce idle power consumption.

IV. Conclusion

The proposed MQTT-based IoT monitoring system demonstrated reliable performance in open-field precision agriculture through multi-day deployment. The evaluation of latency, packet loss, and energy efficiency under realistic environmental conditions suggests that the system can support continuous monitoring with stable communication and moderate energy demands. While the energy profile of the low-power components indicates potential for cost efficiency in off-grid contexts, a formal economic evaluation was not performed in this research. Similarly, although the architecture supports expansion of sensor nodes, scalability was not empirically tested across larger deployment scales. Moreover, limitations such as the lack of laboratory calibration for agronomic measurements should be addressed in future work. Therefore, future research should focus on cost analysis, scalability assessment, and systematic validation of sensor accuracy to further enhance the system's practical applicability.

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