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Design and Implementation of an IoT System for Soil Nutrient Monitoring with MQTT Communication and Temporary Data Storage

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ABSTRACT

This study explores the development and evaluation of an internet of things (IoT) system for real-time soil nutrient monitoring, focusing on crucial soil parameters such as nitrogen, phosphorus, potassium (NPK), and pH. By integrating message queuing telemetry transport (MQTT) as the communication protocol, the system ensures low latency, reliable data transmission, and effective management of soil data. The tested NPK and pH sensors showed high accuracy and reliability, with the pH sensor providing highly consistent readings, while the NPK sensor demonstrated variability but reliably tracked nutrient trends. We highly recommend further calibrating the NPK sensor to significantly improve its accuracy across various soil conditions. The IoT system, Soil Station 2.0, effectively assists in decision-making for fertilization and soil management, improving crop yields and soil health. GPS testing of the system revealed high positional accuracy, which is suitable for precision agriculture. MQTT data transmission's testing showed differences in latency, indicating the need for system optimization for large data transmissions. Overall, the system demonstrated good accuracy, reliability, and efficiency in supporting agricultural decision-making and environmental monitoring.

Keywords: soil nutrient, message queuing telemetry transport, internet of things, agriculture.

INTRODUCTION

The agriculture sector has undergone a significant transformation in recent years by adopting modern technologies to enhance productivity, efficiency, and sustainability. One of the most significant advancements in this domain is integrating of internet of things (IoT) systems, enabling real-time monitoring and managing various agricultural parameters. Among these parameters, soil nutrient monitoring has become crucial for optimizing crop yields and reducing environmental impact through precision farming techniques (Pooja et al., 2017). Conventional methods for soil nutrient analysis are often time-consuming, labor-intensive, and need more detail for dynamic field condition management. The development of IoT-based soil monitoring systems aims to address these challenges by providing continuous and real-time data, thereby enabling better decision-making in agricultural practices. One of the most critical aspects of developing this IoT system is the communication protocol to connect devices in the field.

One of the key elements in an IoT system is the communication protocol used to transfer data between devices. Message queuing telemetry transport (MQTT) has emerged as a popular communication protocol in the IoT ecosystem due to its lightweight nature, low bandwidth consumption, and suitability for real-time data exchange between devices (Jain et al., 2023). Initially developed for Machine-to-Machine (M2M) communication, MQTT has been extensively utilized in IoT applications, including smart agriculture, where reliable and low-latency communication is critical (MQTT Protocol Based Smart Greenhouse Environment Monitoring System Using Machine

Learning, 2020). The publish/subscribe model used by MQTT enables efficient data distribution from multiple sensors to a centralized server or cloud, facilitating the integration and scalability of IoT devices in agricultural fields (Mukherji et al., 2019; Syafarinda et al., 2018). In addition to reliable communication capabilities, IoT systems require a temporary data storage solution to ensure that no data is lost during transmission.

In soil nutrient monitoring, transient data storage plays a critical role in managing the large amount of data generated by IoT sensors. This approach not only helps in buffering data during transmission but also ensures that transient connectivity issues do not result in data loss (Has et al., 2023; Tan et al., 2020). By implementing a transient data storage solution, the reliability and robustness of soil monitoring systems can be significantly improved, enabling continuous monitoring even under challenging field conditions (Santos et al., 2021). The accuracy and continuity of soil monitoring data depend heavily on this temporary storage, especially when measuring important parameters such as nitrogen, phosphorus, and moisture levels. This study seeks to address these by incorporating transient data storage solutions, which is a mechanisms to buffer data during connectivity issues, preventing data loss and ensuring continuous monitoring.

Soil nutrient monitoring is a complex process that involves measuring critical parameters such as nitrogen, phosphorus, potassium, and soil moisture levels, all are essential for plant growth. The significant challenges in this process include the accuracy of sensor readings, data transmission reliability, and the monitoring system's power efficiency (Patel et al., 2020). Environmental factors such as weather conditions and soil heterogeneity further complicate the measurement process (Perumal et al., 2021; Aryanto et al., 2020). To address these challenges, adopting advanced IoT systems has brought significant changes to agricultural practices, highlighting the need for continuous innovation in this field.

IoT systems have revolutionized agricultural practices by enabling real-time monitoring and automated management of various parameters, including soil nutrients, weather conditions, and irrigation. By integrating sensors, communication protocols such as MQTT, and data storage solutions, IoT systems provide actionable insights that help farmers optimize input usage, reduce costs, and improve crop yields (Amelia et al., 2020; Eridani et al., 2019). However, as IoT adoption increases, so do concerns regarding the security of transmitted data.

Security is a significant concern in IoT applications, especially agriculture, where data integrity and confidentiality are critical. Despite its many advantages, MQTT has several security challenges, including vulnerability to unauthorized access and data interception. Implementing a secure MQTT with SSL/TLS encryption is essential to protect data transmission in soil nutrient monitoring systems and mitigate associated risks (Alqinsi et al., 2018; Hakam et al., 2022; Has et al., 2023). When designing IoT systems for soil nutrient monitoring, it's crucial to prioritize security. This ensures the protection of sensitive data and maintains the integrity and reliability of the monitoring system.

The purpose of this study is to design and implement a secure IoT-based soil nutrient monitoring systems which can ensure data integrity during transmission, safeguarding against security vulnerabilities and managing transient data storage to prevent data loss doe to conectivity issues. Designing an IoT system for soil nutrient monitoring involves several key considerations, including sensor selection, data transmission method, power management, and user interface design. The system must be designed to operate under various environmental conditions, with sensors capable of providing accurate soil nutrient measurements under varying humidity and temperature conditions (Helmy et al., 2021). The MQTT protocol must also be optimized for low power consumption and efficient data handling to ensure system sustainability and scalability (Wardana et al., 2018). By integrating a secure MQTT protocol with SSL/TLS encryption, incorporating transient data storage solutions, and optimizing sensor and power management, this research aims to enhance the reliability, efficiency, and security of soil nutrient monitoring. This will contribute to precision agriculture practices by providing farmers with accurate, real-time data to make informed decisions, ultimately improving crop yields and promoting sustainable farming. We aim to develop IoT systems which can provide efficient, reliable, and sustainable solutions to improve crop yields while ensuring environmental sustainability.

RESEARCH METHOD

Designing and implementing of an internet of things system for soil nutrient monitoring utilizing message queuing telemetry transport communication and temporary data storage involves several critical components. MQTT is a lightweight, publish/subscribe messaging protocol that is particularly well-suited for resource-constrained environments, making it an ideal choice for agricultural applications where devices may have limited processing power and energy resources (Kodali et al., 2018; Reshma et al., 2020). In soil nutrient monitoring, the lightweight nature of MQTT is especially beneficial, as it aligns well with the specific requirements of agricultural applications.

In soil nutrient monitoring, the IoT system would typically consist of various sensors deployed in the field to collect data on soil parameters such as nitrogen, phosphorus, potassium, moisture levels, and pH, as shown in Figure 1. These sensors would act as publishers in the MQTT framework, sending data to an MQTT broker, which serves as the central hub for message distribution (Pooja et al., 2017). The broker ensures that messages are efficiently routed to subscribers, including cloud-based applications for data analysis and visualization and mobile

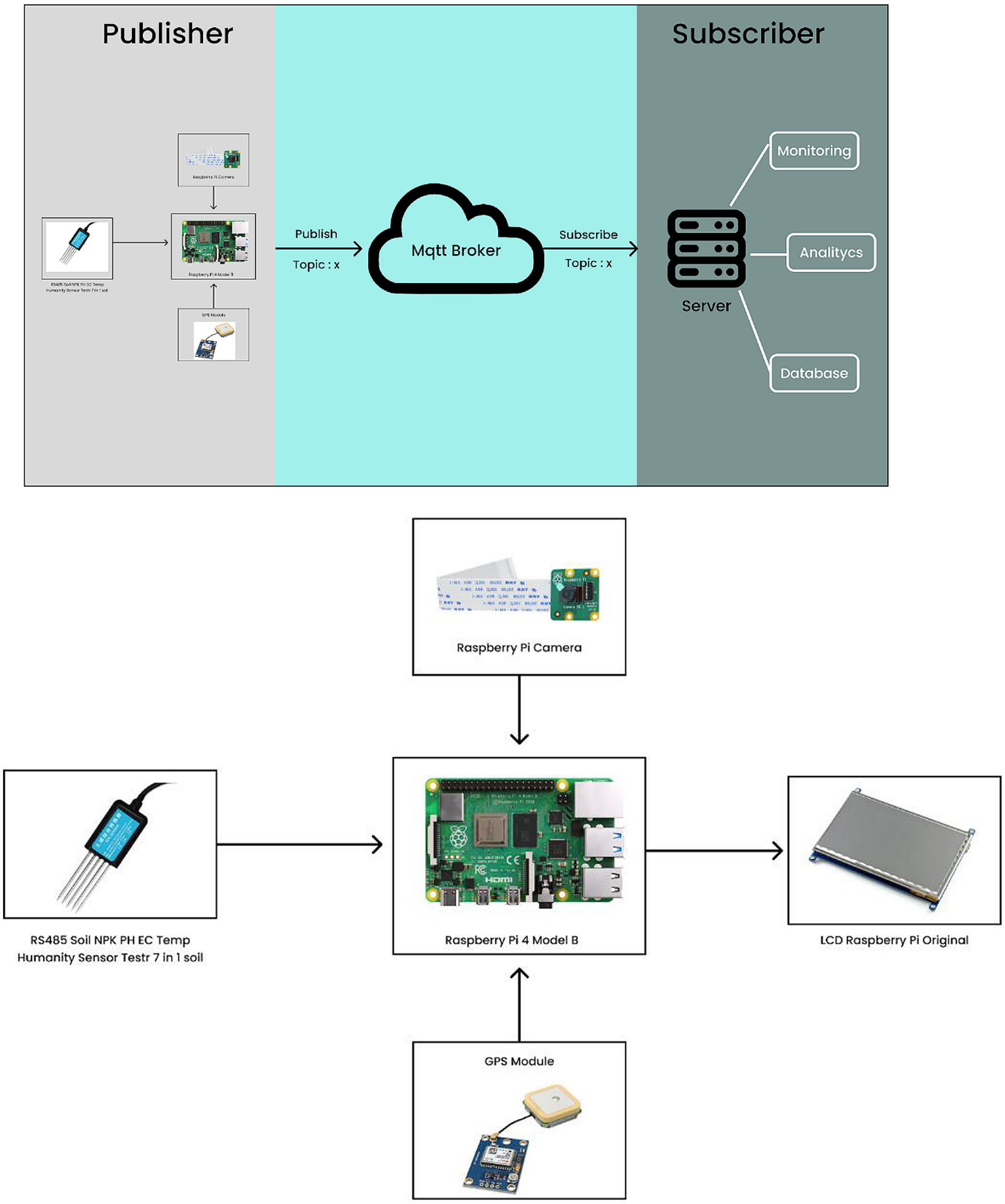

Figure 1. MQTT communication design and hardware design

applications for real-time monitoring by farmers (Mishra et al., 2022; Tan et al., 2020). The efficient distribution of sensor data via the MQTT broker streamlines communication and offers significant advantages in terms of bandwidth optimization and latency reduction.

Implementing MQTT in this system offers several advantages, including low bandwidth usage and reduced latency, which is crucial for real-time monitoring applications (MQTT Protocol Based Smart Greenhouse Environment Monitoring System Using Machine Learning, 2020; Santos et al., 2021). Additionally, MQTT supports different quality of service (QoS) levels, allowing for flexible configurations based on the reliability needs of the data transmission (Tholhappiyan et al., 2023). Beyond its low latency and bandwidth efficiency, MQTT also provides different quality of service (QoS) levels, allowing for adaptable configurations based on data reliability needs.

This is particularly important in agricultural settings where timely data can significantly impact decision-making processes regarding fertilization (Gomathi et al., 2022). Ensuring appropriate QoS levels is crucial in agricultural settings, where the timely transmission of data can significantly impact critical decisions related to fertilization.

The operational environment of this project comprises hardware and software that support the development and implementation of the system. The hardware setup features a Lenovo ThinkPad Yoga 370, equipped with a 7th generation Intel Core i5 processor, 16 GB of RAM, a 64-bit system type, and Windows 10 as the operating system. On the software side, Visual Studio Code serves as the integrated development environment (IDE) for writing, testing, and managing code, as well as supporting multiple programming languages and offering extensive extensions. We utilize Fritzing for designing schematics, PCB layouts, and creating circuit diagrams for Soil Station 2.0. Python is the primary programming language, especially for developing applications on the Raspberry Pi. We use Figma as the design tool for creating the user interface for the soil software for the desktop application. Additionally, Node-Red is crucial in subscribing to MQTT and allocating data to MongoDB, facilitating data management and integration within the system. These hardware and software components form the system's backbone, supporting the design and implementation of the Soil Station 2.0, which is focused on reading and integrating soil nutrient data.

This section provides an overview of the circuit design for Soil Station 2.0. As shown in Figure 2, which is being implemented. Soil Station 2.0 is engineered to read and integrate soil nutrient data using various components connected to a Raspberry Pi 4 Model B.

Figure 2 illustrates the circuit schematic for the data reading hardware of Soil Station 2.0, which is based on Raspberry Pi. The Raspberry Pi 4 Model B is the control and data processing center, interfacing with several external components to collect and display data. A 3.5-inch TFT GPIO screen displays information from the sensors and GPS module, connected directly to the GPIO of the Raspberry Pi. The Neo 6M GPS module gathers location data. The 7-in-1 Soil Sensor (JXBS-3001-NPK-RS), capable of measuring various soil parameters such as moisture and temperature, is connected to the Raspberry Pi through a USB-to-RS485 converter. The RS485 connector converts the signals to a format readable by the Raspberry Pi. These components work together to form a system designed to collect environmental soil data, process it using the Raspberry Pi, and display the measurement results. This system is designed to collect environmental soil data, process it using the Raspberry Pi, and display the measurement results on the TFT screen, while the GPS module provides location data for tracking the soil monitoring station's position. This system is highly suitable for applications in precision agriculture and environmental research. Table 1 shows the details of the pin connection of the soil station 2.0.

Figure 3 shows the flowchart of the data collection and storage process of the Soil Station 2.0. The flowchart outlines the process for measuring data related to soil nutrients (N, P, K) and pH levels. A QR code identifies the specific land or crop to be measured. After scanning the QR code, the system measures the relevant parameter and saves the data locally. It checks for a connection to the server to upload the collected data. The connection is checked by sending a ping command to the server through the connectivity hardware on the Raspberry Pi 4 Model B, ensuring the device is connected to the server before proceeding with the next tasks. The system proceeds with the next task once the device is connected to the server.. The system continues measuring soil nutrients using the soil sensor, which assesses parameters such as NPK, pH, and others. The measurement results are displayed on the LCD and stored in the system for further analysis.

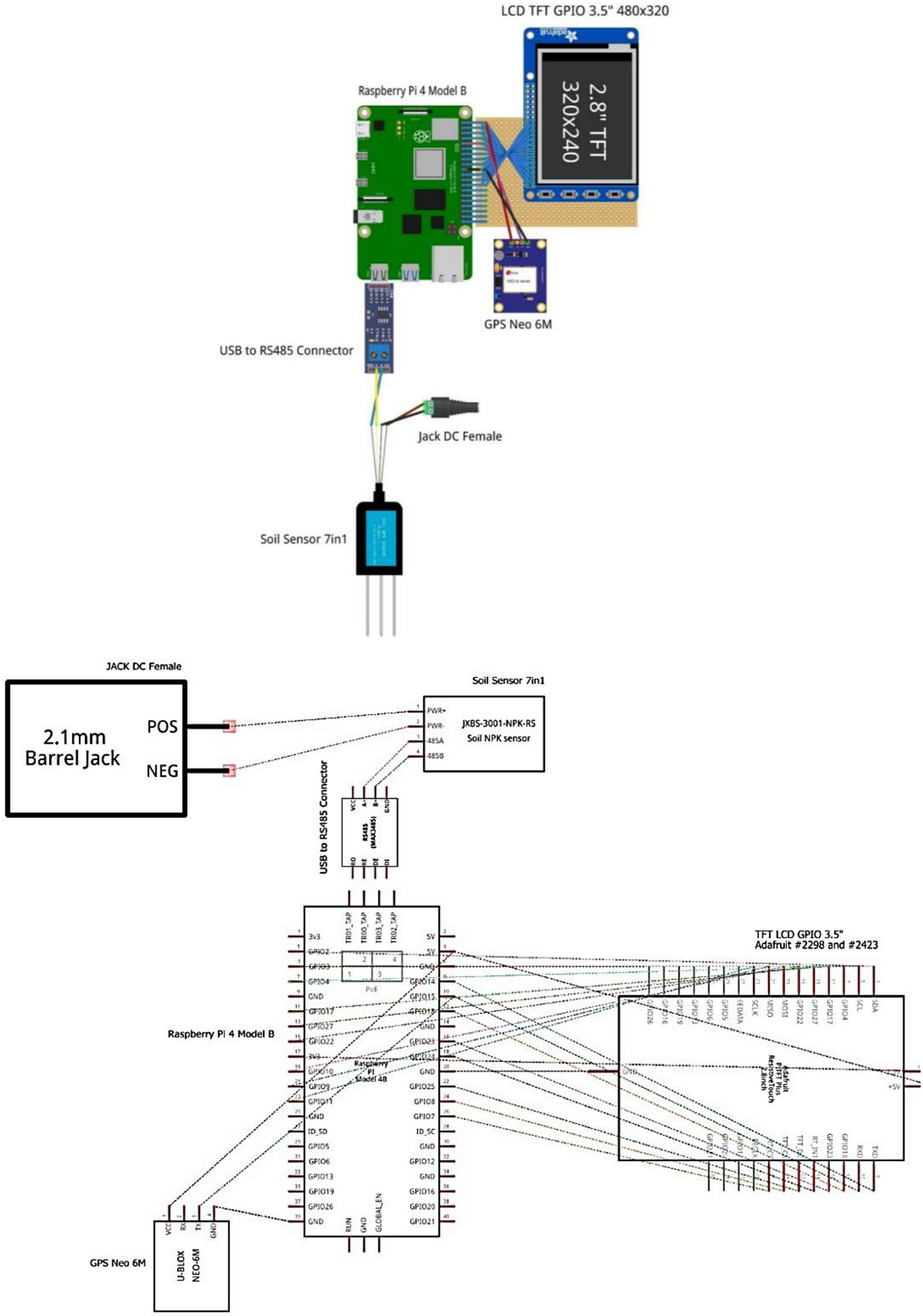

Figure 2. Schematic design for the soil station 2.0

Table 1. Pin connection

Component	Pin	Connect to Raspberry Pi Pins
LCD TFT GPIO 3.5” 480×320	VCC	2 (5V)
	GND	6 (GND)
	CS	24 (SPI0_CE0_N)
	RESET	18 (GPIO 24)
	DC	16 (GPIO 23)
	SDI (MOSI)	19 (GPIO 10 / SPI0_MOSI)
	SCK	23 (GPIO 11 / SPI0_SCLK)
	LED	4 (5V)
	SDO (MISO)	21 (GPIO 9 / SPI0_MISO)
GPS Neo 6M	VCC	3.3V
	GND	GND
	RX	GPIO 15 / UART TX
	TX	GPIO 14 / UART RX
USB ke RS485 connector	VCC	Connected via USB
	GND	Connected via USB
	A+	A+ pada Soil Sensor
	B-	B- pada Soil Sensor
Soil sensor 7in1	VCC	5V
	GND	GND
	A+	A+ on USB ke RS485 connector
	B-	B- on USB ke RS485 Connector
Jack DC Female	VCC	VCC
	GND	GND

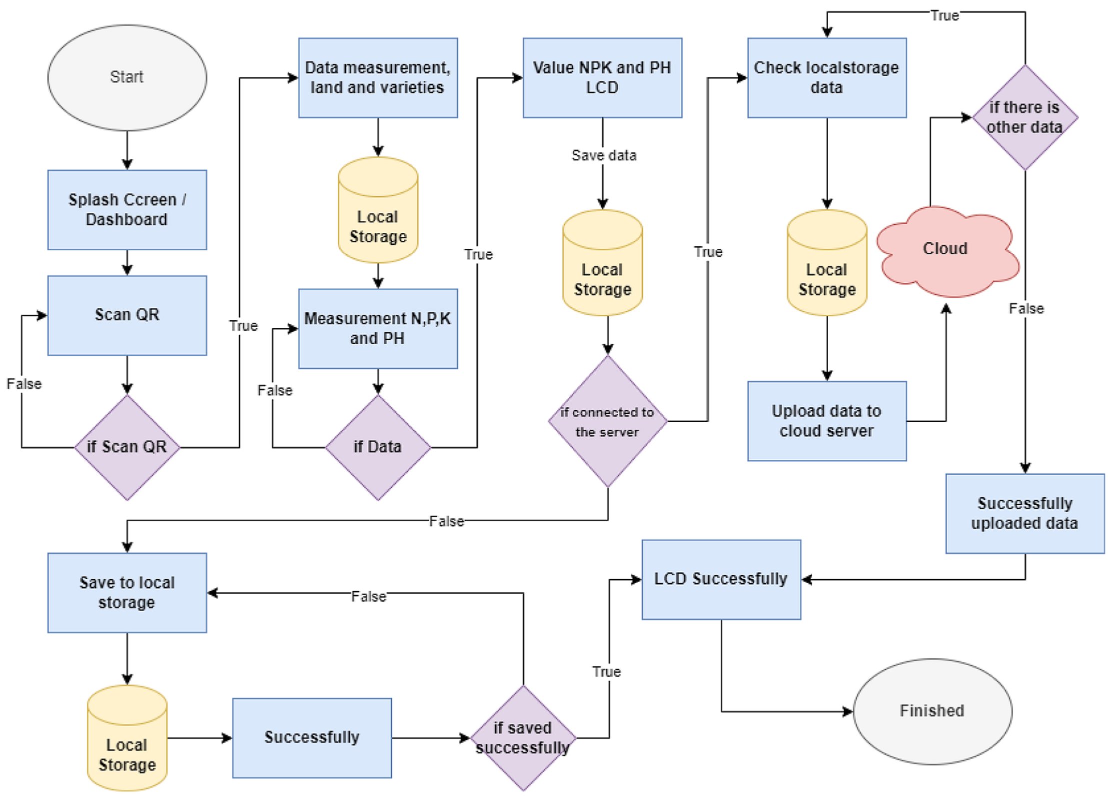

Figure 3. The workflow of the Soil Station 2.0

The data storage and upload process includes checking the connection to the server. New data is added to the local database and uploaded to the server if connected. If not connected, data is temporarily stored in the local database until a connection is available. Previously stored data in the local database is also uploaded to the server and deleted after successful transmission. Data uploads utilize the MQTT protocol, which ensures efficient machine-to-machine communication. If the device is offline, it pauses the upload and waits for the connection to be restored. Throughout the flow, the system ensures data integrity by checking whether it has successfully saved measurements and whether it needs to upload any additional data, ultimately facilitating efficient data management for agricultural monitoring.

RESULTS AND DISCUSSION

The experiments show that while various measurement devices provide valuable data for soil management, their accuracy levels can differ significantly. Devices with a strong correlation to established benchmarks were found to be both accurate and reliable. These devices specifically measure key soil parameters such as NPK (nitrogen, phosphorus, potassium) and pH, offering precise and consistent readings. This methods ensures that the collected data is dependable for real-time decision-making in the field.

NPK and PH sensor testing

The reliability of these devices plays a crucial role in helping farmers make informed decisions about fertilization and soil amendments. Farmers can optimize their crop yields and improve soil health more effectively with accurate measurements. The precision demonstrated by these tools supports agricultural interventions that are both efficient and impactful, contributing to the advancement of sustainable farming practices. Figure 4 shows the measurement data from the Soil Station 2.0.

The box plot of soil parameters (pH, nitrogen, phosphorus, and potassium) highlights significant patterns in the data distribution. The tight clustering of pH values indicates consistent and precise measurements across all samples, with most readings concentrating around the median. This suggests that the pH sensor is stable and highly reliable in capturing soil acidity or alkalinity levels. The consistency of pH measurements provides confidence in the accuracy of the data, making the sensor suitable for

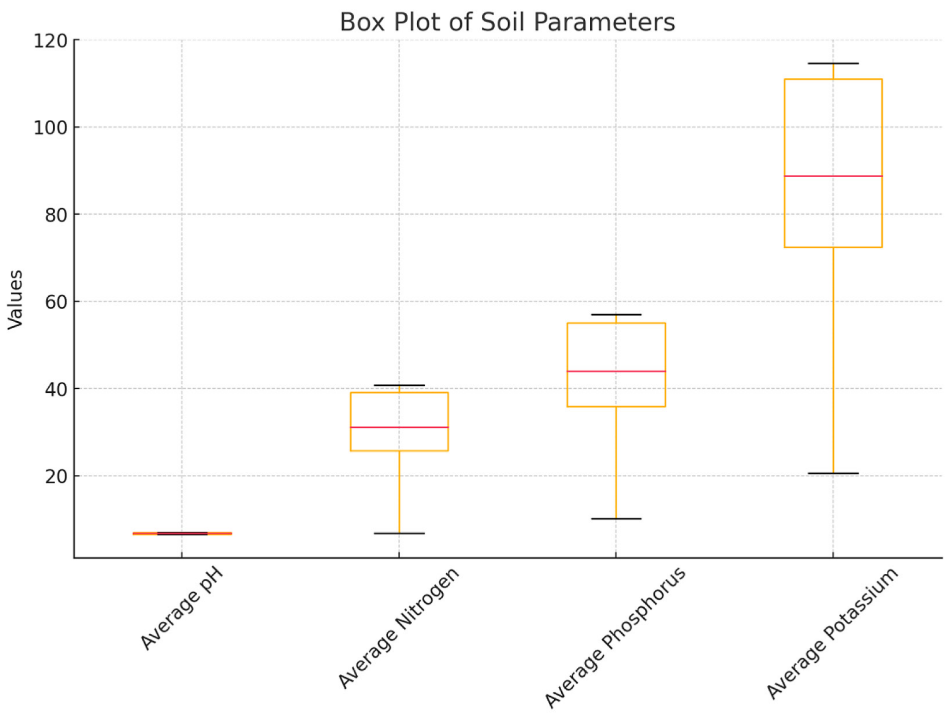

Figure 4. The measurement NPK and PH

informed decision-making regarding soil treatment and management strategies.

In contrast, nitrogen, phosphorus, and potassium (NPK) display broader distributions, reflecting more significant variability in nutrient levels across different samples. This broader range may indicate the device's sensitivity to fluctuations in soil composition. Despite this variability, the strong correlations between these nutrients suggest the device reliably tracks trends in nutrient concentrations. However, due to the spread of values, further calibration or cross-validation against standard reference data may be required to confirm the precise accuracy of the NPK measurements, ensuring optimal performance in diverse soil conditions. Figure 5 shows the distribution of pH and soil parameters.

From the histogram visualizations in Figure 5, we can observe several key characteristics regarding the distribution of pH and nutrient content in the samples. First, the pH values tend to concentrate around 7, indicating neutral conditions with minimal variation. This suggests that the environment from which the samples were taken has either stable pH conditions or that the sampling process was consistently conducted. For nutrients, both nitrogen and phosphorus exhibit relatively normal distributions centered around their average values, indicating stable availability of these nutrients in the samples. This information is crucial in ecological or agricultural contexts, as both nutrients are essential for plant growth and biological functions.

Conversely, potassium shows a broader distribution but remains concentrated near the median value, indicating more significant variability in potassium content. This variability could be influenced by factors such as soil type, moisture levels, or different land management practices. Overall, the nutrient and pH distributions reveal no extreme values or outliers, affirming no conspicuous anomalies in the data and that the samples were likely taken from areas with relatively homogeneous conditions or under similar management. This information can be used for nutrient balance evaluation, fertilization adjustment, or further environmental condition analysis. Figure 6 shows the image of the tool and data transmission.

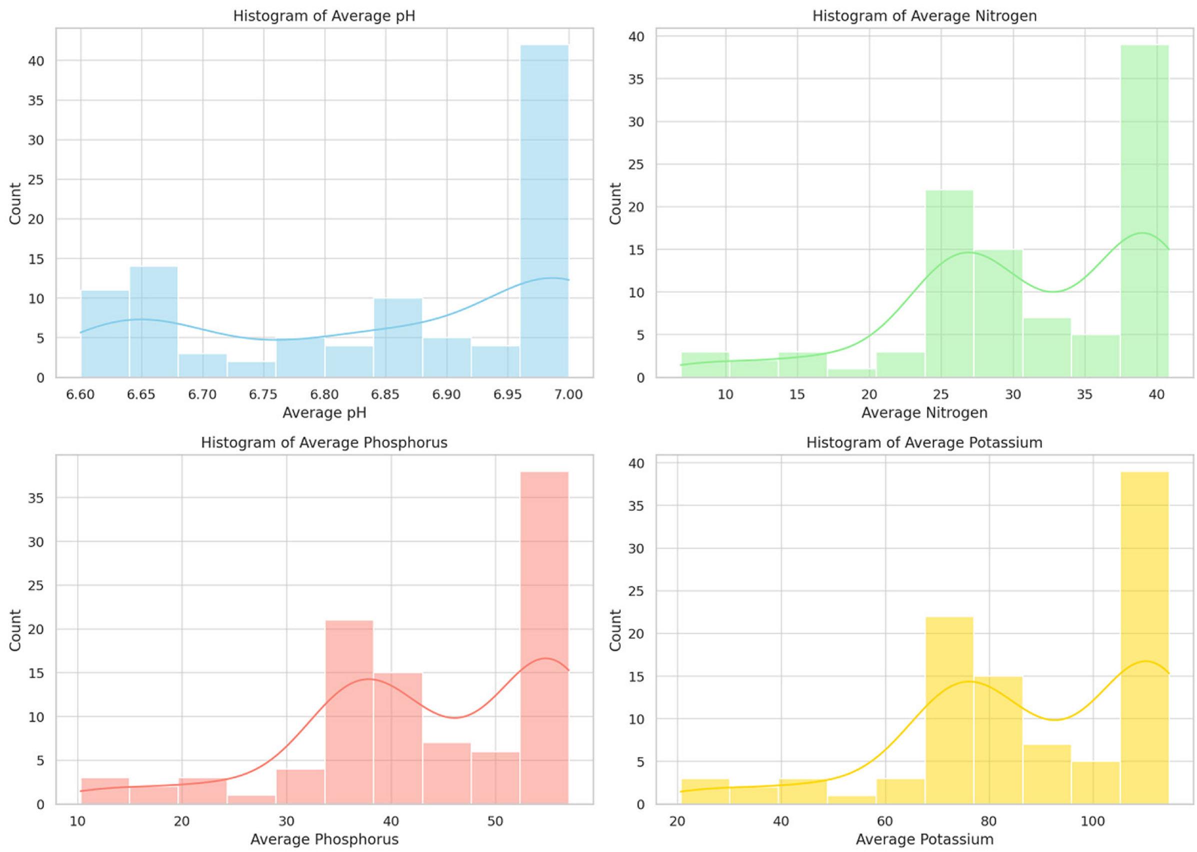

Figure 5. Distribution of NPK and PH measurement data

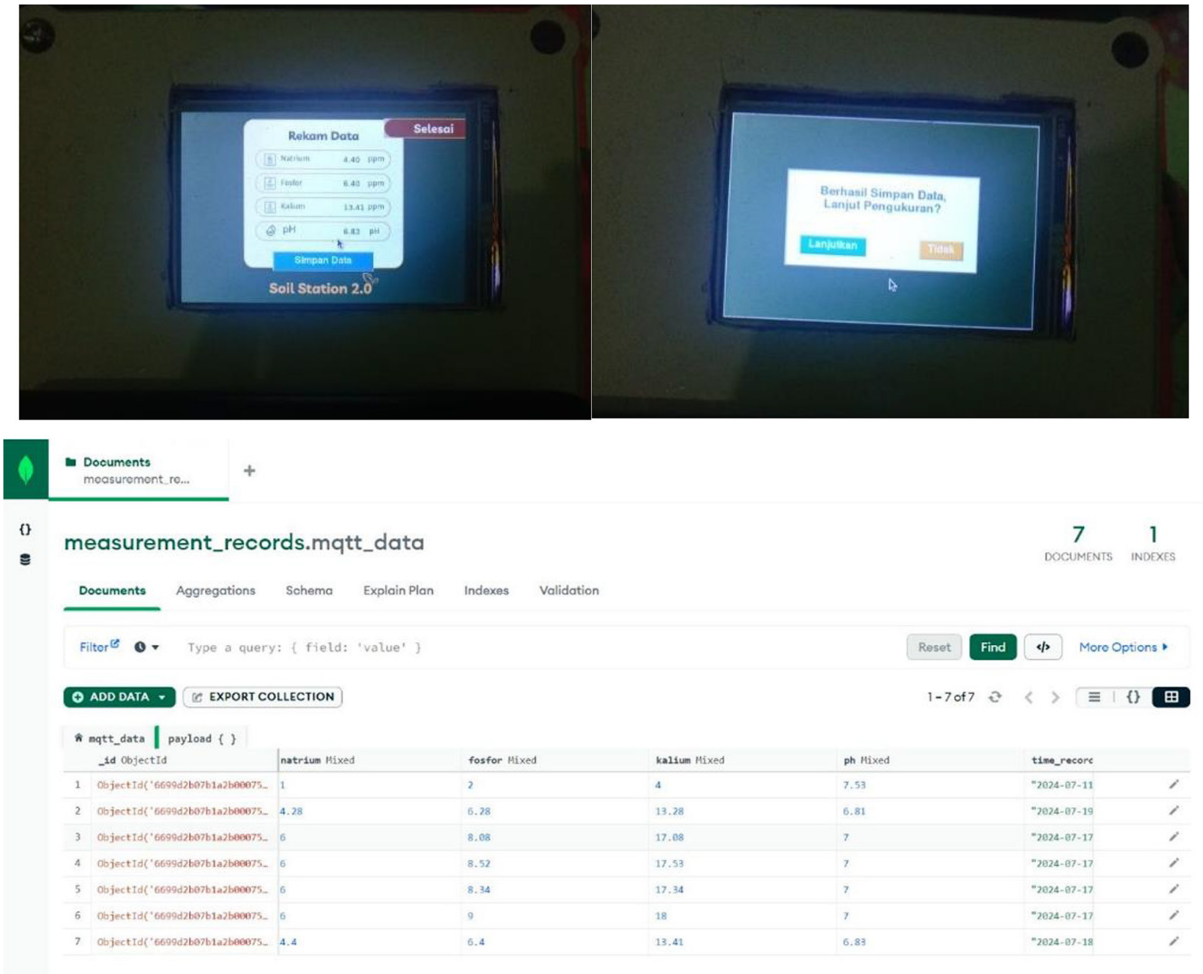

Figure 6. Soil Station 2.0 of MQTT MonggoDB

GPS testing with three location points

Based on the analysis of GPS, data collected from three measurement points (location 1, location 2, and location 3), the device used demonstrates a high level of accuracy in capturing geographical positions.

Each measurement point consistently recorded latitude and longitude values over time, with only minimal variation. This indicates that the device can precisely measures without significant positional shifts, making it highly reliable for applications requiring stable and accurate location data.

The device's accuracy is further evidenced by its ability to maintain consistent readings across different points, according to Figure 7 and Table 2. The stability of the positional data for each point highlights that this GPS is well-suited for environmental monitoring, location tracking, or any application that demands high precision in determining positions.

As a result, the device provides robust reliability in capturing accurate geographical measurements, which is essential for various fields of research and industry.

MQTT testing to send data

Figure 8 shows the results of the MQTT latency time of the Test 1 and Test 2. There is a significant difference in latency times between Test 1 and Test 2 for each round of data transmission, according to the Figure 8. Test 1 exhibits a more stable increase in latency, starting below 1 ms and gradually rising to approximately 11 ms by the fifth round. In contrast, Test 2 shows a sharper and more consistent increase in latency, beginning at around 3 ms and reaching 20 ms by the fifth round. This results indicates that Test 2 experiences higher latency overall compared to Test 1 at each data point.

The noticeable difference between the two tests suggests variations in the performance of the

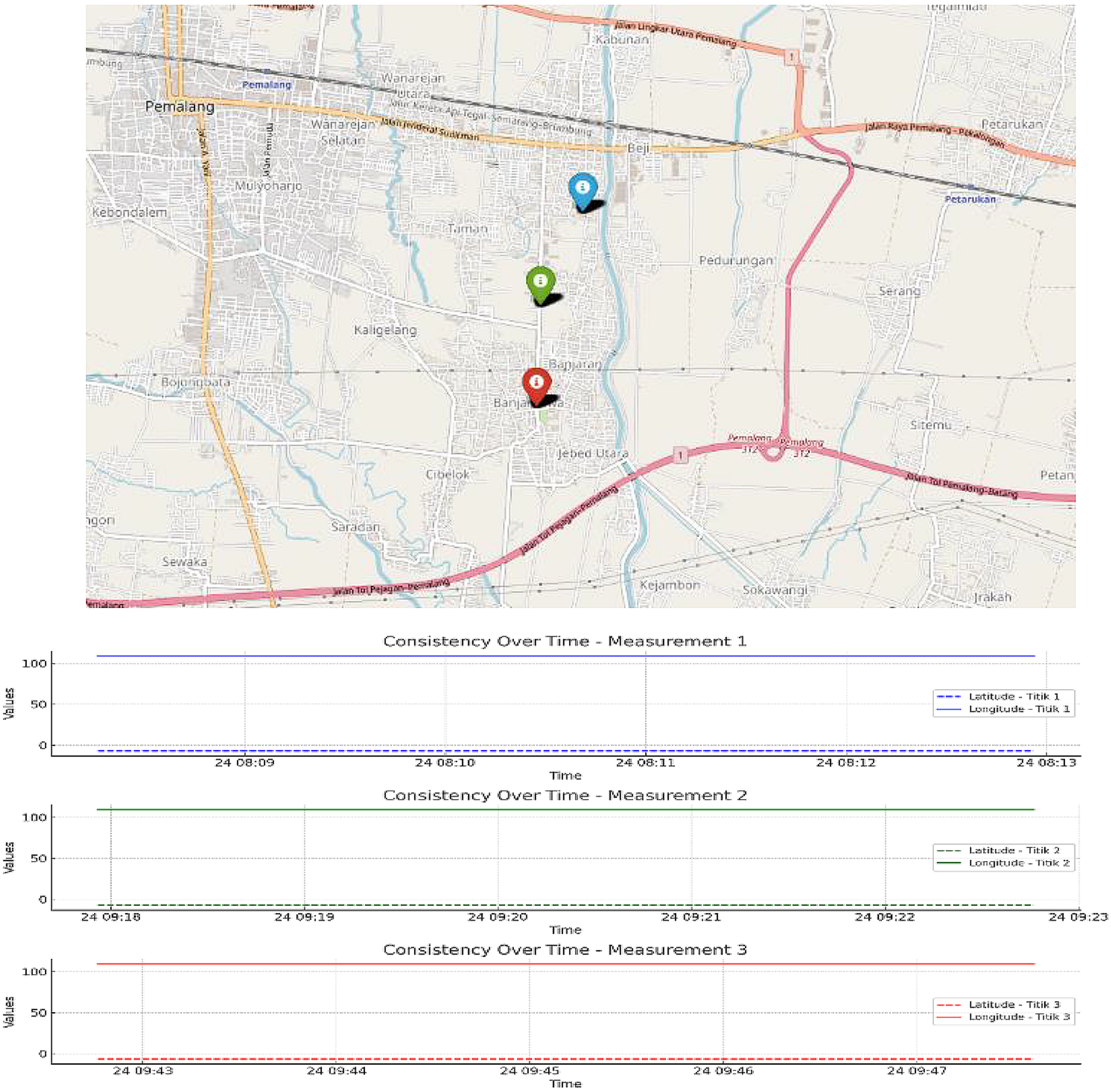

Figure 7. Measurement location and results

network or system under evaluation. Factors such as hardware configurations, network conditions, or differing testing methodologies could contribute to these results. Overall, this data can help identify potential bottlenecks or inefficiencies in the data transmission system, providing a basis for further optimization to reduce latency, particularly in scenarios involving larger data loads.

CONCLUSIONS

This study successfully developed an effective and significant IoT-based soil nutrient monitoring system called "Soil Station 2.0". The system demonstrates satisfactory performance in monitoring soil nutrients with high accuracy. The pH sensor recorded measurement consistency of over 95%, while the NPK sensor detected nutrient trends with an accuracy range of 85% to 90%, depending on soil conditions and the environment. Regarding data transmission, the MQTT communication protocol proved reliable, with an average low latency of around 5–7 ms during initial testing, increasing to 20 ms under higher data load scenarios but maintaining a data transmission success rate of over 98%. The integration of GPS in the system also showed high accuracy, with an error margin of less than 2 meters, supporting precision agriculture applications that require stable location mapping. Overall, the system offers a more accurate and reliable soil nutrient monitoring solution and opens up opportunities for further development, such as improved NPK sensor calibration and MQTT protocol optimization to

Table. 2 GPS test data

No	Lattitude 1	Longitude 1	Lattitude 2	Longitude 2	Lattitude 3	Longitude 3
1	-6,8997035	109,4157805	-6,9080473	109,4120937	-6,9170853	109,4117659
2	-6,8997035	109,4157811	-6,9080467	109,4120937	-6,9170859	109,4117665
3	-6,8997029	109,4157805	-6,9080473	109,4120943	-6,9170859	109,4117665
4	-6,8997029	109,4157805	-6,9080467	109,4120943	-6,9170853	109,4117659
5	-6,8997029	109,4157811	-6,9080467	109,4120937	-6,9170859	109,4117665
6	-6,8997029	109,4157805	-6,9080473	109,4120943	-6,9170859	109,4117659
7	-6,8997035	109,4157805	-6,9080467	109,4120943	-6,9170853	109,4117665
8	-6,8997035	109,4157811	-6,9080473	109,4120937	-6,9170853	109,4117659
9	-6,8997029	109,4157811	-6,9080473	109,4120937	-6,9170853	109,4117659
10	-6,8997029	109,4157811	-6,9080467	109,4120943	-6,9170859	109,4117665
11	-6,8997035	109,4157811	-6,9080473	109,4120937	-6,9170853	109,4117665
12	-6,8997029	109,4157805	-6,9080473	109,4120943	-6,9170859	109,4117659
13	-6,8997035	109,4157805	-6,9080467	109,4120937	-6,9170853	109,4117659
14	-6,8997029	109,4157811	-6,9080473	109,4120937	-6,9170853	109,4117659
15	-6,8997035	109,4157811	-6,9080467	109,4120937	-6,9170853	109,4117665
16	-6,8997035	109,4157805	-6,9080473	109,4120943	-6,9170859	109,4117659
17	-6,8997029	109,4157811	-6,9080473	109,4120943	-6,9170853	109,4117665
18	-6,8997029	109,4157811	-6,9080467	109,4120943	-6,9170859	109,4117659
19	-6,8997035	109,4157811	-6,9080467	109,4120937	-6,9170859	109,4117659
20	-6,8997029	109,4157805	-6,9080467	109,4120943	-6,9170859	109,4117659
21	-6,8997029	109,4157811	-6,9080467	109,4120943	-6,9170859	109,4117665
22	-6,8997029	109,4157811	-6,9080467	109,4120943	-6,9170853	109,4117659
23	-6,8997035	109,4157805	-6,9080473	109,4120943	-6,9170853	109,4117659
24	-6,8997029	109,4157805	-6,9080473	109,4120943	-6,9170853	109,4117659
25	-6,8997029	109,4157805	-6,9080467	109,4120943	-6,9170853	109,4117659
26	-6,8997029	109,4157805	-6,9080467	109,4120943	-6,9170859	109,4117665
27	-6,8997035	109,4157811	-6,9080467	109,4120937	-6,9170853	109,4117665
28	-6,8997029	109,4157811	-6,9080467	109,4120943	-6,9170859	109,4117665
29	-6,8997035	109,4157805	-6,9080473	109,4120943	-6,9170853	109,4117659
30	-6,8997035	109,4157805	-6,9080467	109,4120943	-6,9170859	109,4117665

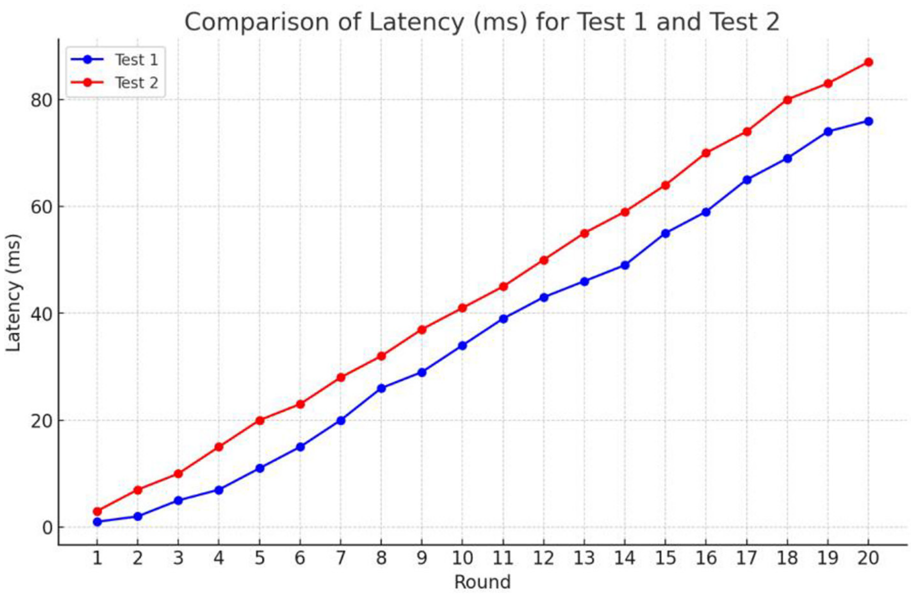

Figure 8. MQTT testing

reduce latency in larger data transmission scenarios. The qualitative contributions of this study include enhanced efficiency and effectiveness of the monitoring system, supporting productivity and sustainability in precision agriculture.

Acknowledgments

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