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Analysis of Iot-Based Soil Moisture Data Visualization and Network Stability Effects on Precision Irrigation Monitoring

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ABSTRACT: The Internet of Things (IoT) technology has enhanced precision irrigation monitoring by enabling real-time soil moisture measurement. However, the reliability of historical data visualization is strongly influenced by network stability between sensors and data servers. This study analyzes soil moisture trend visualization based on an IoT system and evaluates the effect of network stability on data consistency. Soil moisture data were obtained using a capacitive sensor integrated with an ESP32 microcontroller and transmitted via a Wi-Fi network. Data trends were visualized using time-series graphs, while network performance parameters, including latency, packet loss, and transmission delay, were analyzed. The results indicate that network instability causes data loss and irregular visualization patterns, which may affect irrigation monitoring accuracy. Therefore, improving network reliability is essential for sustainable precision agriculture systems.

Keywords: Internet of Things, Soil Moisture, Data Visualization, Network Stability.

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INTRODUCTION

Soil moisture monitoring is a key component in the implementation of precision irrigation, as soil moisture conditions directly determine crop water requirements and the efficiency of water resource utilization. Proper irrigation management not only contributes to increased crop productivity but also plays a crucial role in reducing water wastage, particularly in agricultural regions that are vulnerable to drought. In the context of modern agriculture, the utilization of Internet of Things (IoT) technology has emerged as an effective solution for acquiring real-time soil condition data through the integration of sensors, microcontrollers, communication networks, and data storage servers (Ariawan, 2024). The continuous availability of data enables more accurate and adaptive data-driven irrigation decision-making.

However, the reliability of IoT data is not solely determined by sensor accuracy but is also strongly influenced by the stability of the network that serves as the medium for data transmission to the server. Historical data visualization, which forms the basis for analyzing daily and weekly soil moisture trends, is highly dependent on the continuity and quality of data transmission. Network instability, such as high latency, jitter, packet loss, or downtime, can potentially cause data loss or disrupt the sequential presentation of data on monitoring dashboards (Nurwarsito & Adaby, 2024). Such conditions may lead to misinterpretation of soil moisture patterns and result in inaccurate irrigation decision-making.

Based on these challenges, this study contributes to examining the relationship between network performance and the quality of historical data visualization in IoT-based soil moisture monitoring systems, a topic that remains relatively underexplored in an integrated manner within the context of smart agriculture. This research focuses on the use of time-series visualization to illustrate soil moisture trends and the evaluation of network stability metrics, such as latency, jitter, and packet loss, to assess their impact on data completeness and consistency on monitoring dashboards. The objectives of this study are to produce informative historical soil moisture data visualizations, analyze the influence of network quality on the reliability of IoT data presentation, and provide insights into the network performance indicators that most significantly affect the effectiveness of irrigation monitoring systems (Vemuri et al., 2023). Thus, this research is expected to support the development of more reliable, efficient, and sustainable smart agriculture systems, while also offering practical benefits in improving water use efficiency through more precise irrigation decision-making (Cinderatama et al., 2025)..

THEORETICAL REVIEW

Various studies have shown that the implementation of the Internet of Things (IoT) has made a significant contribution to improving the effectiveness of precision irrigation systems, particularly through real-time soil moisture monitoring. Most previous studies have focused on the development of automated irrigation systems and the evaluation of hardware performance, such as the integration of soil moisture sensors with microcontrollers in IoT-based irrigation systems (Wahyudi et al., 2025). Other research emphasizes the importance of directly monitoring crop microclimate conditions as a basis for more efficient and responsive irrigation decision-making.

Nevertheless, existing research approaches are still predominantly centered on the functional and technical aspects of devices, resulting in relatively limited attention to data management and presentation, especially historical data visualization. Several studies indicate that data visualization is often treated merely as a supporting component, without in-depth analysis of the factors that influence the quality and continuity of the visualized data. Consequently, the impact of network stability on the consistency, completeness, and reliability of historical data visualization has not been comprehensively examined (Pertiwi et al., 2021). In fact, in IoT-based monitoring systems, successful monitoring is determined not only by sensor accuracy and microcontroller capabilities, but also by network performance as the data transmission medium.

The ESP32 microcontroller has been widely adopted in agricultural monitoring applications due to its robust wireless communication capabilities, energy efficiency, and flexibility in integrating with various sensors (Espinosa-Gavira et al., 2024). However, several studies have also reported that network limitations, such as high latency, packet loss, and unstable internet connectivity, remain major challenges in IoT implementation in agricultural environments, particularly in regions with underdeveloped network infrastructure (Mowla et al., 2023). These network disruptions can potentially lead to data loss, transmission delays, and distortions in historical data visualization, which may ultimately affect data interpretation and the accuracy of irrigation decision-making.

Based on a synthesis of previous studies, a research gap can be identified in the limited number of studies that specifically analyze the relationship between IoT network stability and the quality of soil moisture trend visualization in precision irrigation systems. Therefore, this study is directed toward evaluating the effects of network stability parameters, such as latency and packet loss, on the continuity and reliability of time-series soil moisture data visualization. Accordingly, this research is expected to provide a conceptual contribution to the development of more reliable IoT-based monitoring system models, while also strengthening the foundation for data-driven decision-making in the context of sustainable digital agriculture. To better understand the context and urgency of this research, a discussion of key concepts—such as IoT in digital agriculture, soil moisture sensor characteristics, data visualization techniques, and related studies—will be presented as follows.

Internet of Things for Digital Agriculture

The Internet of Things (IoT) is the concept of integrating physical devices with an internet network, enabling them to automatically collect, process, and transmit data without direct human interaction. In the context of digital agriculture, IoT functions as a monitoring and control system that connects environmental sensors, microcontrollers, communication networks, and data storage servers. Microcontrollers such as the ESP32 are widely used due to their integrated Wi-Fi and Bluetooth features, low power consumption, and sufficient processing capacity for web-based monitoring and control applications. With an

IoT architecture, data on soil conditions, temperature, air humidity, or light intensity can be monitored in real time via a dashboard, allowing for more efficient decision-making in precision irrigation systems (Wahyudi et al., 2025). IoT enables agriculture to shift from conventional systems to data-driven agriculture. The presence of internet-connected sensors and monitoring systems makes agricultural activities not only reactive but also predictive, thus minimizing the potential for land management errors. By utilizing historical and real-time data, farmers can determine the best irrigation patterns based on actual crop needs and environmental conditions.

Capacitive Soil Moisture Sensor

Capacitive soil moisture sensors operate based on changes in the dielectric constant of the soil medium. When the water content in the soil changes, the sensor's capacitance value also changes, allowing the microcontroller to translate it into an analog or digital value. Compared to resistive sensors, which are more susceptible to corrosion, capacitive sensors offer better durability, more consistent reading stability, and are more suitable for long-term use in agricultural environments (Schwamback et al., 2023) (Mardiyati et al., 2023). However, the accuracy of this type of sensor reading is still affected by external factors such as temperature, soil composition, and electrical interference. The main challenge in using capacitive sensors is sensor calibration so that moisture readings match actual conditions. Furthermore, data transmission from the sensor to the server must be stable so that visualization graphs can accurately reflect soil conditions. Therefore, soil moisture sensors require not only good hardware quality but also a reliable network communication system.

Time-Series Data Visualization

Time-series data visualization is a technique for presenting data based on a time sequence to analyze changes in values over a specific period. In the context of precision irrigation monitoring, historical data visualizations such as line charts, area charts, or heatmaps are used to observe patterns of soil moisture changes on a daily, weekly, or monthly basis. This technique makes it easier for users to identify soil drying trends, critical moisture points, and required watering frequencies. Time-series data visualization is necessary to support accurate, data-driven irrigation decisions, especially when moisture changes cannot be observed solely through real-time data. Interpreting data visualizations allows users to identify patterns such as daily cycles, reading anomalies, or missing data due to network disruptions (Htun et al., 2022). Therefore, the quality of visualization is greatly influenced by the continuity of data received by the server. If there is packet loss or delays in data transmission, the graph may show false spikes or gaps, resulting in inaccurate data interpretation.

IoT Network Stability

Network stability is a crucial aspect of successful IoT implementation. Network stability parameters include latency, jitter, packet loss, throughput, and downtime. Latency refers to the delay in sending data from an IoT device to a server, while jitter refers to the variation in delay between data packets. Packet loss occurs when some data packets are lost during transmission, which can result in incomplete data being received by the server. Packet loss is a major cause of irregularity in monitoring graphs in agricultural IoT systems. Throughput, on the other hand, describes the data capacity that can be transmitted in a given time unit. Network instability can cause sensor data to fail or be sent with significant delays, resulting in inaccurate data visualization. This condition is critical in precision irrigation applications because watering decisions are highly dependent on data presented on the dashboard (Baraka et al., 2025). Therefore, research on the impact of network stability is crucial to support the sustainability of IoT-based monitoring systems.

METHODOLOGY

Research Type and Design

This study employs a quantitative approach with a descriptive-analytic research design, aiming to analyze the relationship between Internet of Things (IoT) network stability and the quality of soil moisture data visualization in precision irrigation systems. The quantitative approach is selected because the study relies on numerical data obtained from sensor measurements and network performance parameters, allowing for objective, measurable, and reproducible analysis. The descriptive-analytic design is used to describe the operational conditions of the IoT system factually based on time-series data, while simultaneously evaluating the relationships among the research variables.

Through this design, the study not only describes the observed phenomena but also analyzes how variations in network stability affect the continuity and accuracy of data visualization displayed on a web-based irrigation monitoring dashboard. The overall conceptual research workflow is illustrated in Figure 1, which represents the stages of data collection, data transmission through the network, historical data storage, and the processes of data analysis and visualization.

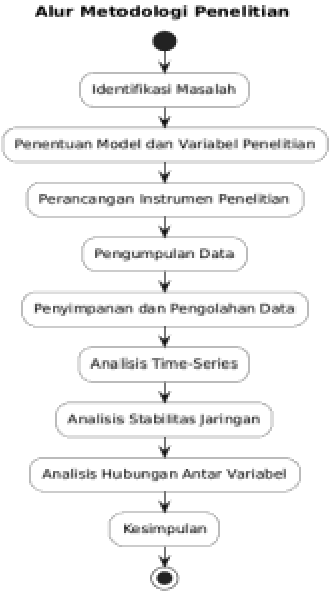

Figure 1. Research Workflow

Based on the workflow shown in Figure 1, the research was conducted through several interrelated and systematically arranged stages. The initial stage involved problem identification to determine the research focus and scope. This was followed by the determination of the research model and variables to ensure a clear and measurable analytical direction. Subsequently, research instruments were designed as the basis for data collection, including system preparation and data recording mechanisms.

The data collection stage was carried out periodically according to the system's operational conditions. The collected data were then stored and processed to ensure data readiness prior to further analysis. The analysis process included observing data characteristics over time and evaluating the relationships among the research variables. The final stage involved drawing conclusions based on the analysis results, which were used to address the research objectives and provide an overall interpretation of the findings.

Research Model and Variables

This study is structured based on a quantitative research model that positions IoT network stability as the independent variable (X) and the quality of soil moisture data visualization as the dependent variable (Y). The model is developed to explain the causal relationship between network performance and the reliability of historical data presentation in precision irrigation monitoring systems.

Network stability is measured using several quantitative indicators, namely latency, packet loss, data transmission delay intervals, and connection downtime. Meanwhile, data visualization quality is measured based on data continuity, time-series graph consistency, and the accuracy of soil moisture trend representation. The selection of these indicators is grounded in the literature on IoT network performance and time-series data visualization, which emphasizes the importance of data continuity and accuracy in supporting data-driven decision-making.

Research Instruments and System Architecture

The system design is illustrated in Figure 2, which enables the analysis of periodically recorded soil moisture patterns as well as the evaluation of network performance to assess the reliability of the IoT system in transmitting data in both real-time and historical contexts. Time-series analysis is applied to understand soil moisture patterns over time, while network performance evaluation is used to assess data transmission stability throughout the research period. The integration of these two approaches provides a comprehensive overview of the relationship between network quality and data visualization accuracy.

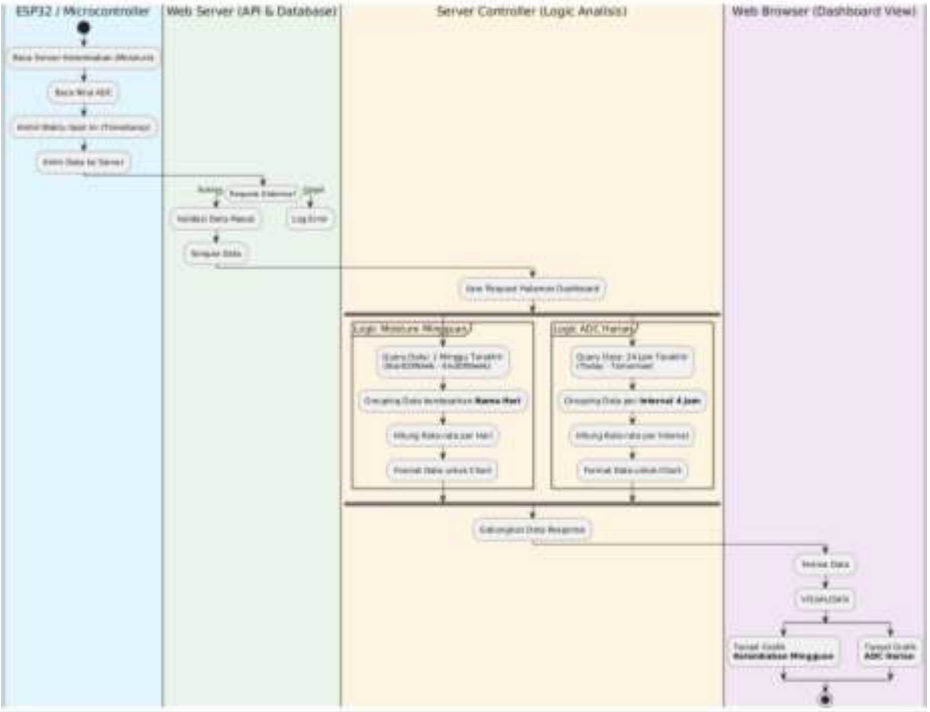

Figure 2. System Design Workflow

The system process begins with the hardware, an ESP32 microcontroller, which is responsible for reading environmental conditions in real time, including soil moisture sensor data, ADC values, and the time of data collection (timestamp). After the data is collected, the ESP32 sends the information to the web server. The server then validates the data before storing it in the database. Data processing is carried out when the user accesses the dashboard page. The Server Controller runs two analysis logics in parallel. The first logic takes data from the last week, groups it by day, and calculates the average daily soil moisture. The second logic takes data from the last 24 hours, divides it into 4-hour time intervals, and calculates the average ADC value for each interval. The results of the two analysis processes are combined and sent to the web browser to be visualized in the form of a weekly humidity graph and a daily ADC value movement graph.

Data Collection Scheme

The research instrument consists of a web-based IoT monitoring system comprising a capacitive soil moisture sensor and an ESP32 microcontroller. This system is used as a tool for automated and continuous data collection. The soil moisture sensor records ADC values and soil moisture levels at fixed time intervals of 30 seconds to obtain time-series data with sufficient resolution.

Data collection is performed automatically using a capacitive sensor that measures ADC values and soil moisture levels at fixed 30-second intervals. This interval is selected to capture soil moisture changes with adequate granularity without overburdening the network and server with excessive data volume. The capacitive sensor generates analog signals that are converted into digital values by the ADC module of the ESP32 microcontroller. These ADC values represent raw, uncalibrated soil moisture conditions, consistent with findings by Sudarmaji et al. (2024), who reported that capacitive sensors exhibit high stability in dielectric-based measurements.

After data acquisition, the ESP32 transmits the data to the server using the HTTP/REST API communication protocol. Each request contains the measurement timestamp, ADC value, and calibrated soil moisture value. This REST API-based transmission mechanism aligns with findings by Ahmad et al. (2021), which indicate that request–response approaches in IoT systems enable real-time data reception with consistent structure. However, this transmission process is highly dependent on Wi-Fi network quality. High latency, packet loss, or connectivity disruptions may result in delayed, failed, or lost data transmissions.

Upon arrival at the server, the received data are stored in a historical database, such as MySQL or a cloud-based database system. Historical data storage enables long-term analysis of soil moisture trends, including soil drying patterns, irrigation effectiveness, and the relationship between network conditions and data completeness. This is supported by Sudarmaji et al. (2024), who emphasize that historical data storage is a critical component of agricultural IoT systems for trend analysis and data-driven prediction. Furthermore, structured data storage serves as the foundation for data visualization, enabling the generation of daily, weekly, and monthly graphs.

Overall, this data collection scheme reflects the continuous and real-time nature of IoT systems, where monitoring quality is strongly influenced by network stability and sensor reliability. Thus, data collection functions not only as the primary source of analytical information but also as a key parameter in evaluating overall IoT system performance. This approach aligns with the descriptive quantitative research framework described by Yulianto and Sumarno (2022), which emphasizes systematic and measurable numerical data in describing observed phenomena.

Data Analysis Techniques

Data analysis in this study is conducted in a staged and systematic manner in accordance with the predefined research model. The analysis process is designed to provide a comprehensive understanding of soil moisture data characteristics and their relationship with IoT network stability in a web-based precision irrigation system. The analytical approach is quantitative and descriptive-analytic, utilizing numerical data derived from sensor measurements and network performance parameters collected during the observation period.

The first stage of analysis involves time-series data analysis, which aims to identify patterns of soil moisture variation over time. Sensor-derived soil moisture data are collected periodically and organized into time-based historical datasets. For analytical convenience, the data are grouped into daily and weekly intervals to observe short-term and medium-term trends and to reduce random data fluctuations.

For each interval, average soil moisture values are calculated to represent soil conditions during the respective periods. In addition to mean values, visualization patterns are examined to assess consistency in data presentation over time. The results of the time-series analysis are used to evaluate data continuity on the monitoring dashboard, including update regularity and visualization stability. This analysis also facilitates the identification of anomalies, such as abnormal spikes or drops, as well as missing data that may affect visualization accuracy and interpretation (Althoubi et al., 2021).

The second stage involves IoT network stability analysis, which evaluates network performance during data transmission from field devices to the server and monitoring dashboard. The analyzed network performance parameters include latency, packet loss, data transmission delay intervals, and downtime duration during the observation period. These parameters are selected due to their direct influence on the system's ability to transmit data continuously and in real time (Althoubi et al., 2021; Pratama et al., 2023).

Network stability analysis is conducted using a descriptive quantitative approach by calculating average values, ranges, and trends for each network parameter. The results are used to assess network reliability in supporting IoT-based precision irrigation operations. A stable network is expected to maintain continuous sensor data transmission, ensuring that the data visualized on the monitoring dashboard remain accurate and up to date (Pratama et al., 2023).

The subsequent stage involves linking network stability analysis results with time-series soil moisture data analysis. This stage evaluates the relationship between network disturbances and data visualization quality, particularly regarding delayed updates, irregular graph patterns, and incomplete data. The purpose of this analysis is to identify the extent to which variations in network performance affect the quality of historical data presentation in the monitoring system.

Analysis of Intervariable Relationships

To scientifically address the research questions, the analysis is conducted based on a quantitative research model that explicitly relates IoT network stability as the independent variable to soil moisture data visualization quality as the dependent variable. Network stability is represented by quantitative parameters including latency, packet loss, delay intervals, and downtime, while data visualization quality is represented by data continuity, time-series graph consistency, and trend representation accuracy.

Intervariable relationship analysis is performed by comparing variations in network stability parameters with changes in data visualization quality indicators during the observation period. Network performance data and sensor data are analyzed using a descriptive quantitative approach to identify trends linking network disturbances with missing data occurrences, irregular visualization patterns, and time-series distortion. This approach enables empirical assessment of how network performance variations directly affect the reliability of historical data presentation on the monitoring dashboard.

The results of this analysis are used to evaluate the extent to which network stability contributes to maintaining data continuity and visualization accuracy in IoT-based precision irrigation monitoring systems. Consequently, research questions are addressed through systematic numerical data analysis rather than qualitative observation alone. This ensures that the conclusions drawn are supported by quantitative evidence consistent with the formulated research model.

Through a methodology designed around a clear conceptual framework, this study goes beyond describing system construction and operation by explicitly demonstrating how data are analyzed to answer the research questions in accordance with quantitative research principles. By integrating the research model, measurable variables, and intervariable analysis, this methodology provides a strong scientific foundation for assessing the impact of network stability on the reliability of IoT-based precision irrigation monitoring systems, thereby enhancing the rigor, clarity, and scientific validity of the overall study.

RESULTS

Overview of Data and Scope of Analysis

This section presents the empirical results obtained from the implementation of an Internet of Things (IoT)-based soil moisture monitoring system, as well as the quantitative analysis conducted based on the previously formulated research model. The monitoring system was designed to continuously collect soil moisture data using a capacitive sensor integrated with an ESP32 microcontroller. Sensor data were transmitted periodically at 30-second intervals via a Wi-Fi network to a web-based server for data storage, processing, and visualization. The selection of this sampling interval was intended to provide sufficiently high data resolution to represent changes in soil moisture conditions, while also considering network efficiency and server storage capacity.

Simultaneously with sensor data collection, network stability parameters (including latency, packet loss, delay intervals, and downtime) were systematically recorded throughout the observation period. The recording of these network parameters aimed to evaluate the reliability of the connectivity used in the system and to identify potential transmission disruptions that could affect the continuity and accuracy of the data received by the server. Accordingly, the collected dataset represents not only the physical condition of the soil but also the performance of the network as a critical component of the IoT monitoring system.

The presentation of the research results is structured and systematic, distinguishing three main aspects of analysis: (1) descriptive statistical analysis results that characterize the general properties of soil moisture data and network parameters; (2) time-series-based data visualizations that illustrate patterns and trends in soil moisture variations over specific time periods; and (3) empirical findings regarding the relationship between network stability and the quality of data visualization produced by the monitoring system. This presentation structure is designed to ensure a clear linkage between the collected data, the applied analytical methods, and the formulated research questions.

Through this presentation approach, the research results are expected not only to provide a factual overview of the performance of the IoT-based monitoring system but also to establish a strong analytical foundation for subsequent discussion. The discussion will focus on testing the research hypotheses and interpreting the findings within the context of the research model and previous studies, thereby clearly and systematically conveying the scientific contribution of this study.

Data Analysis

The data analysis in this study was conducted through a series of systematic steps to ensure that the data interpretation reflects actual field conditions. The first step was identifying trend patterns, which was performed by analyzing time-series graphs to observe fluctuations in moisture and ADC values. This analysis helped identify soil drying patterns, irrigation effectiveness, and potential sensor reading anomalies.

The second stage is gap and missing data analysis, which is crucial in IoT-based research. Missing data can occur due to network disruptions, packet loss, or device downtime. This data loss can affect visualization accuracy and result in incomplete graphs. Therefore, any gaps that appear are analyzed to determine their occurrence time, duration, and potential causes.

The third step is a correlation analysis between network disruption indicators and graph instability patterns. For example, increased latency or packet loss can be associated with a decrease in the amount of data received by the server, causing unusual fluctuations or stagnant values on the graph. By conducting this analysis, the researcher can identify the extent to which network performance impacts the integrity of the monitoring data.

The final step is the application of descriptive statistics, including the calculation of the mean, median, minimum and maximum values, and variance. These descriptive statistics provide a quantitative overview of the general soil moisture condition and assist in comparing changes in values between periods. They also support the evaluation of sensor and network performance in transmitting data consistently.

Daily ADC values are calculated to obtain a more stable representation of values compared to raw data sent every 30 seconds. Daily averaging is necessary because sensor readings can be affected by noise, electrical interference, soil quality, or network instability. Therefore, averaging the data provides the basis for long-term trend analysis. The equation used to calculate daily ADC values is:

$$ADC_{harian} = \frac{\sum_{i=1}^{n} ADC_i}{n} \quad ....(1)$$

Information:

ADC_{harian} : Average ADC value per day
ADC_i : ADC value on the i-th measurement
n : Number of measurements in one day

This calculation allows for the generation of smoother and more stable ADC trend graphs, making it easier to interpret soil moisture changes over a daily timeframe. Furthermore, the daily average ADC is used as a benchmark to detect sensor anomalies, such as sudden spikes or stagnation in ADC values due to technical issues.

Converting ADC values to soil moisture percentages is a crucial step in interpreting sensor data. Capacitive sensors output ADC values that don't directly indicate moisture levels, so a calibration formula is required to produce more meaningful and understandable values. The formula used in this study is:

$$Moisture(\%) = 100 \times \frac{ADC_{max} - ADC_{read}}{ADC_{max} - ADC_{min}} \text{............}(2)$$

Information:
$Moisture(\%)$: Soil moisture value in percent
ADC_{read} : ADC value of sensor reading result
ADC_{max} : Upper limit of sensor calibration
ADC_{min} : Lower limit of sensor calibration

This formula assumes that the sensor operates linearly within a specific range of ADC values. After the conversion, the daily humidity value is calculated using the following average formula:

$$Moisture_{harian} = \frac{\sum_{i=1}^{n} Moisture_i}{n} \text{ ....}(3)$$

Information:
$Moisture_{harian}$: Average soil moisture per day
$Moisture_i$: Soil moisture value at the i-th measurement
n : Number of measurements in one day

This calculation produces stable and informative daily moisture values for trend analysis. These values are also used to compare moisture change patterns between days and to detect abnormal conditions such as prolonged soil dryness or prolonged moisture recovery after irrigation.

Soil Moisture Trend Visualization

This section presents the visualization of soil moisture data obtained from the IoT-based monitoring system. As a first step in understanding the overall monitoring flow, Figure 3 displays the web dashboard interface used in the study. The dashboard provides real-time soil moisture information, historical time-series graphs, and network connection stability indicators, which play a crucial role in ensuring the completeness of the monitoring data.

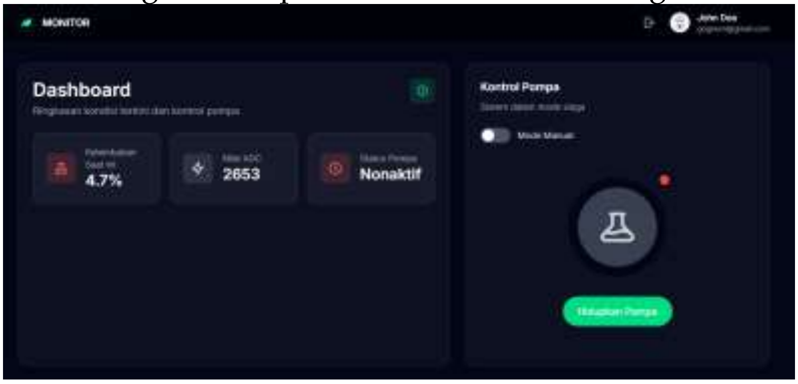

Figure 3. IoT System Monitoring Web Dashboard View

The weekly soil moisture graph is one of the key visualization components of the IoT-based precision irrigation monitoring system. This visualization is designed to present a summary of soil moisture conditions over a seven-day period, from Monday to Sunday, based on data collected every 30 seconds and averaged daily. Figure 4 shows how the system organizes historical data into a weekly time-series graph, allowing users to observe soil moisture dynamics over a longer, more structured timeframe.

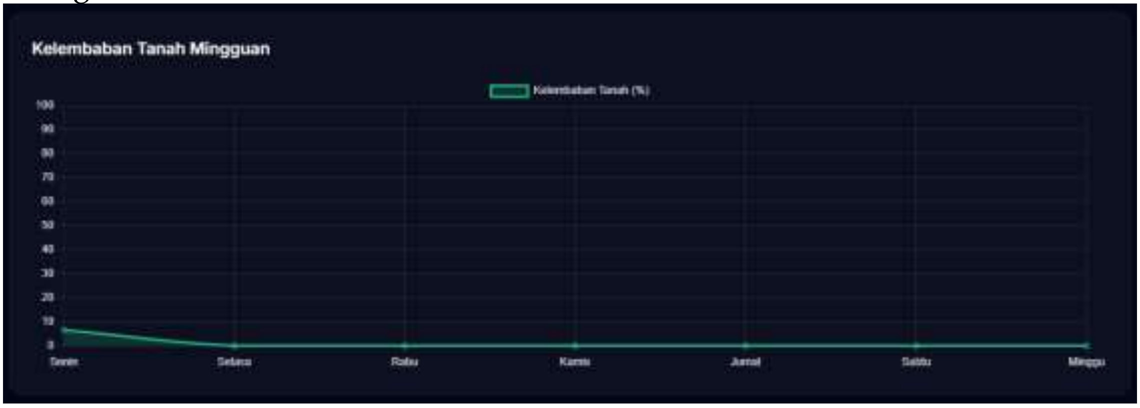

Figure 4. Weekly Soil Moisture Time-Series Graph

Functionally, this weekly chart serves as an evaluation tool for assessing macroscale moisture patterns, including soil stability, sensor response consistency, and irrigation effectiveness over a one-week period. Unlike daily charts, which highlight short-term variations, the weekly chart focuses on general patterns and mid-term trends. This allows users to gain a more comprehensive understanding of soil conditions, such as whether soil moisture has been stable, declining, or fluctuating over the week.

From a technical functional standpoint, this graph also serves as a supporting indicator of IoT system performance. Any irregularities or deviations in the weekly graph pattern could indicate potential issues with the sensors, data transmission, or network stability. Thus, this visualization not only illustrates ground conditions but also helps verify the overall reliability of the system. The weekly graph can show whether daily data is being recorded consistently, whether there are any days where data is not fully received, or whether errors are affecting the daily data accumulation.

Additionally, the weekly graph serves as a reference for mid-term irrigation decision-making. By observing weekly trends, users can determine whether adjustments to the watering schedule are necessary, evaluate weekly water consumption, or plan corrective actions if soil conditions show signs of drying out or otherwise. The clarity of the graph and the timeframes displayed make it easy for users to compare moisture conditions between days and identify whether emerging patterns align with land management plans.

Therefore, even though the weekly graph in the figure doesn't show significant fluctuations, its core functionality remains intact. The graph provides a structural overview of weekly moisture data, supports system evaluation, and serves as a decision-making tool for precision irrigation management.

In addition to humidity, the daily ADC values calculated using the formula in the previous section are also visualized to assess the stability of the sensor readings. As shown in Figure 5, the daily average ADC graph shows a more significant and smoother pattern than the raw data.

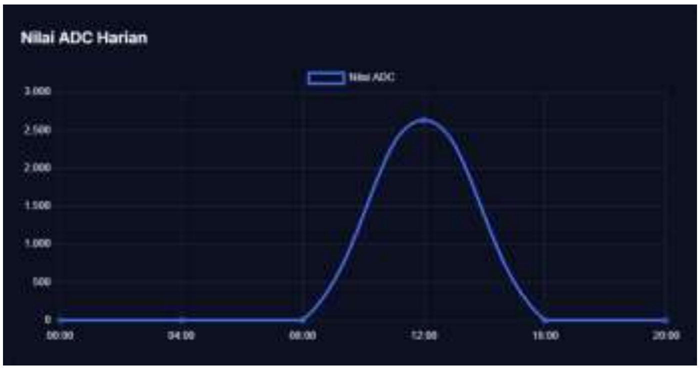

Figure 5. Daily ADC Average Chart

The figure above shows that the daily averaging process is effective in reducing sensor interference, noise, and irregularities caused by network instability. Therefore, daily ADC values can be used as diagnostic parameters to identify potential sensor anomalies and changes in soil characteristics.

Network Stability Analysis

The reliability of an IoT monitoring system is greatly influenced by the stability of the network that mediates data transmission from the ESP32 to the server. Therefore, this study also visualizes several network performance indicators to evaluate their impact on data continuity, as shown in Table 1 below.

Table 1. Network Performance Indicators

Indicator	Average	Maximum Value	Minimum Value	Notes
Latency (ms)	226	1320	211	There was a latency spike of up to 1320 ms and 2 request time outs.
Packet Loss (%)	0.24	0.24	0	Losing 2 packets out of 840 packets (~0.24%) causes potential missing data.
Delay Interval (seconds)	33	75	30	Delay increases as the network signal weakens
Downtime (minutes)	12	5 minutes/incident	1	There were 3 downtimes during the observation.

Based on the test results presented in the table above, it can be seen that network quality has a significant impact on the reliability of the IoT monitoring system. The latency indicator shows an average value of 226 ms, with a maximum value reaching 1320 ms. This latency spike indicates a delay in network response at certain times, potentially causing sensor data to enter the system with a longer delay. Furthermore, two request timed out events were detected, indicating a temporary communication disruption between the ESP32 device and the server.

The packet loss indicator was recorded at 0.24%, meaning two packets were lost out of a total of 840 data packets sent during the test. Although the packet loss percentage is relatively small, this condition still has the potential to cause missing data in the system, especially in graphical visualizations that rely on data continuity. This indicates that even though the network is generally stable, minor disruptions can still affect the completeness of received data.

Furthermore, the delay interval measurement results showed an average value of 33 seconds, with a minimum value of 30 seconds and a maximum of 75 seconds. This increase in delay interval occurs when network signal quality decreases, resulting in inconsistent sensor data transmission intervals. This condition results in a graph that appears less smooth due to the uneven spacing between data points.

The downtime indicator recorded three downtime events during the observation period, with an average total duration of approximately 12 minutes, a minimum duration of 1 minute, and a maximum duration of approximately 5 minutes per event. During the downtime, the system received no sensor data, resulting in a temporary halt in dashboard visualizations. However, the system was able to resume normal operation after the network connection was restored without requiring manual intervention.

These test results indicate that although the developed IoT monitoring system performed well and displayed data in real time, network quality remains a crucial factor affecting data continuity and accuracy. Therefore, mitigation strategies such as improving network connection quality, implementing local buffering mechanisms, or implementing data retry mechanisms are needed to improve system reliability going forward.

Network Impact on Monitoring

To assess the direct impact of network disruptions on monitoring data quality, an analysis of the soil moisture graphs during the network disruption period was performed. Table 2 below shows examples of missing data, which appear as gaps in the time-series graphs. These gaps appear when packet loss increases or when server downtime prevents data from being received for a specific period. This data loss has the potential to obscure the true soil drying pattern.

Table 2. Impact of Indicators on Data Visualization

Time of Incident	Network Problem	Impact on Graphics	Impact on Data	Information
1st and 2nd minutes	Normal	Stable Graph	Login Normal	The system is running normally and the network is stable.
3rd and 4th minutes	High Latency (ms)	Temporary stagnant graph	Late data entry	Latency spikes occurred during testing

5th and 6th minutes	Packet Loss (0.24%)	There is a small GAP on the chart	Missing data	Lost 2 packets out of 840 data packets
7th and 8th minutes	Downtime	Disconnected graph	No data received	The system does not accept data
9th and 10th minutes	Delay Interval	Graphics are not smooth	Data is unstable over time	Late data delivery interval

Table 2 above shows the direct impact of network disruption on the quality of soil moisture data visualization on the monitoring dashboard, which was conducted over a 10-minute period. From minutes 1 to 2, the system was in normal condition, so the soil moisture graph appeared stable and data was received consistently by the server. Entering minutes 3 to 4, a spike in latency occurred, causing delays in data transmission from the ESP32 device to the server. This condition caused the graph on the dashboard to appear temporarily stagnant because new data was not received in a timely manner, although the data was ultimately entered into the system. From minutes 5 to 6, a packet loss of 0.24% was detected, resulting in the loss of a small portion of sensor data. This data loss is visible on the graph as a small gap in the time-series visualization. Although not significant in quantity, this missing data has the potential to obscure the actual pattern of soil moisture changes. Furthermore, from minutes 7 to 8, the system experienced downtime, so the server received no sensor data at all. This condition caused the soil moisture graph to be interrupted and not display data updates during that period. Downtime is the most critical condition because it completely halts the monitoring process. In the 9th to 10th minute, there was an increase in the delay in data transmission intervals, resulting in inconsistent intervals between data points. As a result, the displayed graph appeared less smooth and the soil moisture data became unstable between observations.

The analysis results show that network disruptions, including high latency, packet loss, downtime, and delay intervals, significantly impact the continuity and quality of data visualizations displayed on the irrigation system website. Therefore, network stability is a critical factor in ensuring the IoT monitoring system operates optimally and produces accurate data.

DISCUSSION

Discussion Based on the Research Model

The discussion of the research findings is structured based on the research model that positions IoT network stability as the independent variable and data visualization quality as the dependent variable. This model is designed to explain the causal relationship between communication network performance and the reliability of soil moisture data presentation in precision irrigation monitoring systems. Within this framework, the empirical results are not only described from a technical perspective but are also analyzed in the context of testing the proposed research hypotheses.

The results indicate that when network parameters operate under stable conditions—characterized by relatively low latency, minimal packet loss, consistent data transmission intervals, and the absence of downtime—sensor data can be transmitted completely and in a timely manner to the server. Under these conditions, the resulting time-series data visualization is continuous, coherent, and capable of accurately representing soil moisture variations. These findings directly support the research hypothesis that IoT network stability has a positive influence on data visualization quality in precision irrigation monitoring systems.

Conversely, the analysis also reveals that network disturbances, identified through increased latency, packet loss, variable transmission delays, and downtime, have a significant negative impact on data visualization quality. Latency spikes cause delays in dashboard updates, resulting in temporarily stagnant graphs. Packet loss leads to missing data, which appear as gaps in time-series graphs, while downtime completely halts the monitoring process during certain periods. These findings demonstrate that variations in network performance directly affect the integrity, continuity, and readability of the visualized data.

Accordingly, this discussion confirms that data visualization quality cannot be separated from communication network performance. IoT monitoring systems equipped with reliable sensors and hardware may still produce unreliable visualizations if network stability is not maintained. This reinforces the validity of the proposed research model and demonstrates that hypothesis testing is supported by measurable empirical evidence.

Comparison with Previous Studies

The findings of this study are consistent with the results reported by Althoubi et al. (2021), who stated that network parameters such as latency and packet loss significantly affect data quality in IoT systems. However, this study not only confirms these effects conceptually but also extends existing knowledge by demonstrating how such network disturbances manifest visually in time-series graphs that serve as the basis for irrigation decision-making.

Furthermore, the results support the findings of Pratama et al. (2023), which emphasized that downtime and irregular data transmission intervals reduce the reliability of real-time monitoring systems. This study enriches those findings by providing empirical evidence of the impact of downtime on historical data visualization, particularly in the form of graph discontinuities and the loss of critical information during specific periods.

The primary distinction between this study and previous research lies in its analytical focus. Most IoT studies in the agricultural domain emphasize irrigation automation, sensor performance, or hardware efficiency. In contrast, this study explicitly positions historical data visualization as the main object of analysis and examines its relationship with network stability. As such, this research contributes to the agricultural IoT literature by highlighting the role of data visualization as a critical bridge between raw data and data-driven decision-making.

CONCLUSION

Based on the quantitative analysis and discussion conducted, it can be concluded that this study successfully demonstrates the relationship between Internet of Things (IoT) network stability and the quality of soil moisture data visualization in precision irrigation monitoring systems. The time-series visualizations show that soil moisture data transmitted continuously and in a timely manner are able to consistently represent soil moisture variation patterns at both daily and weekly scales. These patterns provide valuable information regarding soil drying processes, soil responses to irrigation, and the potential determination of more optimal irrigation schedules.

However, the results also empirically indicate that network stability is a critical factor influencing the continuity and accuracy of data visualization. Network performance measurements—including an average latency of 226 ms with peaks up to 1320 ms, packet loss of 0.24%, delay interval variations of up to 75 seconds, and several downtime events—were shown to have a direct impact on dashboard visualization quality. These impacts manifested as missing data, stagnant values, irregular graphs, and visualization interruptions during certain periods.

These findings consistently support the research hypothesis that IoT network instability negatively affects soil moisture data visualization quality. Network disturbances not only reduce the integrity of historical data but also have the potential to cause misinterpretation by users. In the context of precision irrigation, such misinterpretation may lead to suboptimal irrigation decisions, including delayed irrigation or excessive water usage. Therefore, this study confirms that the success of IoT-based monitoring systems is determined not only by sensor accuracy and hardware performance but also heavily depends on the quality and reliability of the communication network.

RECOMMENDATIONS

Based on the research findings, several recommendations are proposed to improve the reliability of IoT-based precision irrigation monitoring systems in future implementations. First, the use of more efficient and network-tolerant communication protocols, such as MQTT, is highly recommended. MQTT offers publish–subscribe mechanisms and improved Quality of Service (QoS) management compared to HTTP, making it more suitable for unstable network environments.

Second, the implementation of local buffering mechanisms on microcontroller devices should be considered. This mechanism allows sensor data to be stored locally during network disruptions and retransmitted once the connection is restored. Through this approach, the risk of data loss (missing data) can be minimized, thereby preserving the continuity of historical data visualization.

Third, for agricultural regions with limited network infrastructure or challenging geographical conditions, the development of hybrid communication systems should be explored. Combining Wi-Fi with low-power long-range communication technologies such as LoRa can be an effective solution, as LoRa supports long-distance data transmission with low power consumption, despite its limited data rate.

Overall, the implementation of these recommendations is expected to enhance data transmission reliability, improve data visualization quality, and support more accurate and sustainable irrigation decision-making. Furthermore, the results of this study can serve as a foundation for future research focusing on the evaluation of alternative networking technologies and the application of inferential statistical analysis to strengthen the generalizability of findings in IoT-based digital agriculture systems.

FURTHER STUDY

This study is limited by its testing scale and observation duration, making it incapable of fully representing long-term field conditions and larger land scales. Furthermore, this study focused solely on the impact of network quality on data visualization, without examining aspects of energy consumption, sensor robustness, and integration with automated irrigation systems. Therefore, further research is recommended to conduct long-term testing under various environmental and network conditions, as well as develop systems with more reliable integration of automated decision-making and communication technology to optimally support precision irrigation.

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REFERENCES

Ariawan, A. (2024). Smart Sprout: Irigasi Cerdas Berbasis AIoT untuk Pertanian Modern dan Ramah Lingkungan. bit-Tech, 7(2), 434-444. DOI: https://doi.org/10.32877/bt.v7i2.1841.

Nurwarsito, H., & Adaby, R. W. (2024). Pengembangan Internet Of Things (IOT) Dalam Perekaman Data Iklim Mikro Dengan Platform Thingsboard. Jurnal Teknologi Informasi dan Ilmu Komputer, 11(6), 1385-1398. DOI: https://doi.org/10.25126/jtiik.2024118987.

Vemuri, N., Thaneeru, N., & Tatikonda, V. M. (2023). Smart farming revolution: Harnessing IoT for enhanced agricultural yield and sustainability. Journal of Knowledge Learning and Science Technology ISSN: 2959-6386 (online), 2(2), 143-148. DOI: https://doi.org/10.60087/jklst.vol2.n2.p148.

Cinderatama, T. A., Alhamri, R. Z., Yunhasnawa, Y., Efendi, F. S., & Ariyanto, R. (2025). Sistem Monitoring Irigasi dan Prediksi Debit Air Berbasis IoT Dan Support Vector Machine (SVM). Jurnal Informatika Polinema, 11(2), 171-184. DOI: https://doi.org/10.33795/jip.v11i2.6812.

Pertiwi, A., Kristianti, V. E., Jatnita, I., & Daryanto, A. (2021). Sistem otomatisasi drip irigasi dan monitoring pertumbuhan tanaman cabai berbasis Internet of Things. Sebatik, 25(2), 739-747.DOI:

https://doi.org/10.46984/sebatik.v25i2.1623.

Mowla, M. N., Mowla, N., Shah, A. S., Rabie, K. M., & Shongwe, T. (2023). Internet of Things and wireless sensor networks for smart agriculture applications: A survey. IEEe Access, 11, 145813-145852. DOI: 10.1109/ACCESS.2023.3346299.

Htun, N. N., Rojo, D., Ooge, J., De Croon, R., Kasimati, A., & Verbert, K. (2022). Developing visual-assisted decision support systems across diverse agricultural use cases. Agriculture, 12(7), 1027. https://doi.org/10.3390/agriculture12071027.

Baraka, K., Ezzahar, J., Madiafi, M., Erraji, H., Vivaldi, G. A., & Tallou, A. (2025). AgriLink: an innovative real-time data monitoring and connectivity platform for an orange orchard in Morocco. Frontiers in Sustainable Food Systems, 9, 1542166.

Sudarmaji, A., Gunawan, B., Nugraha, F., Arini, N., & Mulyani, S. (2024). Smart Soil Moisture Control Based on IoT ESP-32 for Horticulture Cultivation in Coastal Area. In BIO Web of Conferences (Vol. 96, p. 04001). EDP Sciences. https://doi.org/10.1051/bioconf/20249604001.

Ahmad, I., Suwarni, E., Borman, R. I., Rossi, F., & Jusman, Y. (2021, October). Implementation of restful api web services architecture in takeaway application development. In 2021 1st International Conference on Electronic and Electrical Engineering and Intelligent System (ICE3IS) (pp. 132-137). DOI: 10.1109/ICE3IS54102.2021.9649679.

Althoubi, A., Alshahrani, R., & Peyravi, H. (2021). Delay analysis in iot sensor networks. Sensors, 21(11), 3876. https://doi.org/10.3390/s21113876.

Pratama, D. B., Santoso, D. B., & Rahmadewi, R. (2023). Analisis Quality Of Service Dan Implementasi Sistem Monitoring Menggunakan Internet Of Things (IoT) Pada Pembangkit Listrik Tenaga Angin. Power Elektronik: Jurnal Orang Elektro, 12(1), 17-28. DOI: https://doi.org/10.30591/polektro.v12i1.4309.

Huere-Peña, J. L., Castrejon-Valdez, M., Castañeda-Campos, C., Leon-Gomez, R., Mateu-Mateo, W. A., Bautista-Gómez, R., ... & YAULILAHUA-HUACHO, R. (2024). Innovations in soil health monitoring: Role of advanced sensor technologies and remote sensing. JEBAS, 12(5), 653-667.DOI: http://dx.doi.org/10.18006/2024.12(5).653.667.