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IoT-Based Soil Condition Monitoring System for Supporting Precision and Sustainable Agriculture in West Java

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Abstract

Smallholder horticultural farmers in West Java continue to face challenges related to soil moisture instability, inefficient irrigation practices, and the lack of real-time field monitoring. To address these issues, this study develops an Internet of Things (IoT)-based soil condition monitoring and automatic irrigation system designed to support precision agriculture at the farm level. The system integrates an ESP32 microcontroller with soil moisture, temperature–humidity, and ultrasonic water-level sensors. It also features a web-based dashboard and a Telegram Bot interface for real-time monitoring and remote control. The prototype was evaluated in a representative smallholder farming setup under different network conditions using mobile hotspot and Wi-Fi router connectivity. Quantitative evaluation results indicate that the system operates with high responsiveness, achieving web server loading times of 0.34–0.67 seconds, sensor update intervals of approximately 1.90 seconds, and pump activation delays as low as 0.58 seconds. The sensor performance was stable, with soil moisture fluctuations below 5% and an ultrasonic water-level measurement accuracy of ±0.2 cm. Based on the observed irrigation cycles during system operation, the proposed system indicates a potential improvement in water use efficiency under observed operating conditions compared to conventional manual irrigation practices. These findings demonstrate the feasibility of the proposed system in providing accurate soil condition monitoring, reliable automated irrigation control, and accessible remote interaction through a Telegram Bot interface. The system is presented as a low-cost and practical reference model for supporting precision and sustainable agriculture in smallholder farming environments in West Java.

Keywords: Internet of Things; soil moisture; ESP32; smart irrigation; precision agriculture.

I. Introduction

In recent decades, the agricultural sector in Indonesia has faced increasing challenges in maintaining soil quality due to climate change, declining soil fertility, and improper land management practices. West Java, as one of Indonesia's major horticultural production centers, manages approximately 264,000 hectares of horticultural land and contributes nearly 17% to the province's Gross Regional Domestic Product (GRDP) (BPS, 2023). Despite its strategic role, this subsector is increasingly threatened by prolonged droughts, fluctuating rainfall patterns, and soil degradation. Horticultural crops, such as chili, are particularly sensitive to these environmental stresses, especially soil moisture imbalance, which can reduce nutrient uptake and increase susceptibility to diseases such as root rot and Fusarium wilt [1], [2].

To address these challenges, the West Java Provincial Government, through the Regional Medium-Term Development Plan (RPJMD 2018–2023) and the "Millennial Farmers" program, has emphasized agricultural modernization through the adoption of digital technologies. Precision agriculture has emerged as a promising approach that applies data-driven irrigation and soil management to improve productivity, reduce water wastage, and support sustainable farming practices [3]–[6]. However, at the smallholder farmer level, soil condition monitoring is still predominantly performed manually through visual inspection or periodic field visits. Such practices are time-consuming, prone to human error, and difficult to sustain continuously, particularly in rural farming environments. This situation is evident in Pameungpeuk Subdistrict, Garut Regency, where chili farmers frequently experience yield losses due to poorly timed and inconsistent irrigation [7].

Recent studies have demonstrated the potential of Internet of Things (IoT)-based systems to monitor soil moisture, temperature, pH, and environmental parameters using low-cost microcontrollers such as ESP32 [8]–[14]. These systems enable real-time data acquisition and support automated irrigation control, offering significant advantages over conventional methods. However, most existing implementations have been evaluated in controlled environments, such as greenhouses, hydroponic systems, or laboratory-scale experimental plots. As a result, limited attention has been given to system reliability, responsiveness, and usability when deployed in representative smallholder farming environments characterized by variable soil conditions, outdoor exposure, and unstable internet connectivity.

Furthermore, relatively few studies have investigated IoT-based irrigation systems that combine local processing, offline-capable data storage, and multi-platform user interaction (e.g., local web dashboards and mobile messaging applications) tailored to farmers with

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limited technical literacy. The lack of empirical evaluation focusing on response time, functional reliability, and practical usability under representative farming conditions highlights a critical gap in the current literature.

Based on these gaps, this study aims to develop and evaluate an IoT-based soil condition monitoring and automatic irrigation system tailored for smallholder chili farming in Pameungpeuk, West Java. The proposed system integrates an ESP32 microcontroller, soil moisture and temperature sensors, a water pump actuator, a local web server with onboard data storage, and a Telegram Bot interface to support real-time monitoring, automated irrigation, and remote user interaction. Rather than relying solely on cloud-based infrastructure, the system is designed to operate reliably under varying network conditions commonly encountered in rural agricultural settings.

To guide the investigation, two research questions (RQs) are formulated;

RQ1: How can an IoT-based monitoring system improve the accuracy and timeliness of soil moisture information compared to manual observation?

RQ2: How reliable and responsive is the ESP32-based automatic irrigation system when implemented in representative smallholder farming conditions?

By addressing these research questions, this study contributes to the application of IoT technologies in precision agriculture by providing empirical evidence on system performance, responsiveness, and usability in a smallholder farming context. The findings of this study are expected to support regional agricultural modernization initiatives and offer a practical, low-cost technological reference for improving irrigation management in rural horticultural environments.

II. Methods

A. Research Flow

This study employed a Research and Development (R&D) approach aimed at developing and evaluating a prototype of an IoT-based soil condition monitoring and automatic irrigation system to support precision and sustainable agriculture. The R&D stages adopted in this study follow a systematic prototype-oriented development model, ranging from needs analysis to system evaluation [15]. Unlike studies that focus purely on technical implementation, this approach emphasizes system development and the empirical evaluation of system performance, reliability, and usability in representative smallholder farming environments.

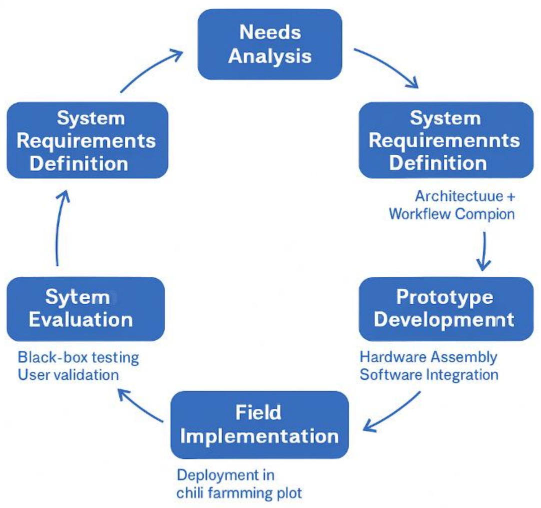

Figure 1. Research Flow

Figure 1 illustrates the research flow adopted in this study, which consists of seven sequential stages designed to ensure that the developed system meets both functional and user requirements.

1) Needs Analysis

This stage focused on identifying irrigation-related challenges faced by smallholder chili farmers in Pameungpeuk Subdistrict, Garut Regency. Field observations were conducted to understand current irrigation practices, soil moisture monitoring methods, and operational constraints. The analysis revealed that soil moisture assessment is predominantly conducted manually, leading to delayed irrigation decisions and increased risk of crop stress due to inconsistent watering.

2) System Requirements Definition

Based on the identified problems, both functional and non-functional system requirements were formulated. The functional requirements included real-time soil moisture monitoring, automatic pump activation based on predefined thresholds, and remote user interaction. The non-functional requirements emphasized system reliability, ease of use, low cost, and the ability to operate under intermittent network connectivity through local data storage using SPIFFS. Multi-platform access via a web dashboard and Telegram Bot was also defined as a key requirement to accommodate users with limited technical literacy.

3) System Design

In this stage, the overall system architecture, workflow, sensor integration logic, and communication mechanisms were designed. This included defining irrigation decision rules based on soil moisture thresholds and water tank availability, designing user interface mockups, and arranging hardware components to support precision irrigation principles.

4) Prototype Development

The system prototype was developed using an ESP32 microcontroller integrated with soil moisture sensors, environmental sensors, a relay module, and a water pump. Software modules were implemented to process sensor data, execute irrigation control logic, store data locally, and communicate with the web server and Telegram Bot API. This integration enabled automated irrigation as well as manual override functionality.

5) Laboratory / Miniature Testing

Prior to outdoor deployment, a miniature testbed representing chili plant growth conditions was developed to verify basic system functionality under controlled scenarios. This stage focused on validating sensor readings, control logic execution, pump activation rules, and user interface responsiveness. The miniature testing stage was intended solely to ensure functional correctness and system readiness and was not designed to represent real-world farming conditions.

6) Field Implementation

Following laboratory testing, the validated prototype was deployed in an outdoor smallholder chili farming plot in Pameungpeuk Subdistrict. This field implementation exposed the system to natural soil moisture variation, ambient environmental conditions, and unstable internet connectivity commonly encountered in rural farming environments. The deployment aimed to assess system reliability and responsiveness under representative smallholder farming conditions rather than full-season crop production cycles.

7) System Evaluation

The system was evaluated through black-box testing, response time measurements, and user validation. These evaluation activities were designed to address the research questions by assessing the accuracy and timeliness of soil moisture monitoring (RQ1), as well as the reliability and responsiveness of the automatic irrigation system under representative farming conditions (RQ2). This structured research flow ensures that the developed system not only functions technically but is also practical, reliable, and suitable for use in rural agricultural environments.

B. System Architecture

The system architecture developed in this study consists of three main layers: input, processing, and output, as illustrated in Figure 2. This layered architecture ensures that environmental data are captured, processed, and translated into automated irrigation actions while maintaining continuous two-way communication between the system and the user.

The input layer comprises sensors responsible for monitoring real-time environmental conditions around the chili plants, including:

(1) A soil moisture sensor (YL-38 + YL-69) for measuring soil moisture levels;
(2) A DHT11 sensor for detecting ambient temperature and humidity;
(3) An ultrasonic sensor (HC-SR04) for monitoring water levels in the irrigation tank.

A water tank serves as the primary irrigation resource, while a regulated power supply provides electrical support for system operation.

The processing layer is centered on the ESP32 microcontroller, which functions as the system's control unit. Sensor readings are continuously collected and processed using predefined rule-based decision logic. Irrigation decisions are made based on soil moisture thresholds and water tank availability. Sensor data are temporarily stored using the SPIFFS file system, allowing the system to maintain core monitoring and control functions even during intermittent network disruptions. In addition, the ESP32 hosts a local web server that enables real-time data access through a browser interface without reliance on cloud-based infrastructure.

The output layer consists of two primary components:

(1) A water pump, which is automatically controlled via a relay module when soil moisture levels fall below the defined threshold;
(2) User interaction interfaces, including a web-based dashboard and a Telegram Bot notification system.

The dashboard visualizes soil moisture, temperature, humidity, water tank level, and pump status, while the Telegram Bot provides event-driven notifications (e.g., dry soil, pump activation, empty tank) and supports manual control commands.

Through this architecture, the system facilitates reliable irrigation automation and interactive monitoring, enabling farmers to receive timely information and take corrective actions to improve irrigation efficiency. The

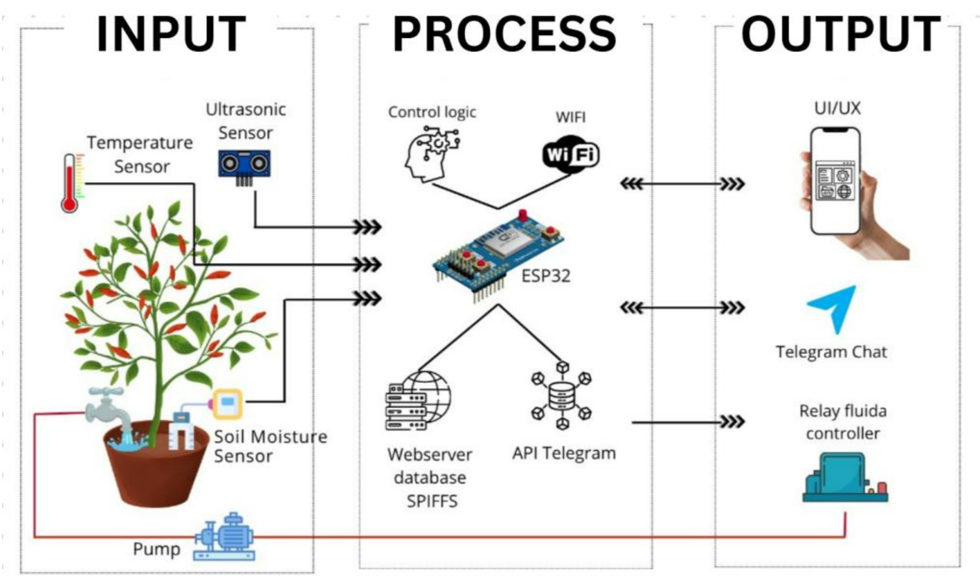

Figure 2. System Architecture

proposed IoT-based soil monitoring system integrates multiple hardware and software components to enable real-time data acquisition and automated irrigation control. The selection of components, such as the ESP32 WROOM-32 and various environmental sensors, is based on their capability to support wireless communication and efficient data processing in IoT applications. The complete list of components and their functions is presented in Table 1.

III. Results and Discussion

The results of this study are presented and discussed in relation to the research questions formulated in Section I. The evaluation focuses on system functionality, monitoring accuracy, responsiveness, and reliability under representative smallholder farming conditions. The discussion is organized to explicitly address RQ1 and RQ2 to ensure consistency between the research objectives, methodology, and obtained results.

A. Accuracy and Timeliness of Soil Moisture Monitoring

To address RQ1, a comparison was conducted between conventional manual soil moisture observation and the proposed IoT-based monitoring system. Manual observation commonly relies on visual inspection or periodic checking of soil conditions, which may result in delayed irrigation decisions and inconsistent monitoring frequency. Table 2 presents a qualitative and functional comparison between the two approaches.

The results demonstrate that the IoT-based system significantly improves both the timeliness and continuity of soil moisture information. Real-time sensor readings allow immediate detection of dry soil conditions and prompt irrigation activation, which is not feasible through manual observation. This improvement directly addresses RQ1 by showing how automated sensing and monitoring enhance irrigation decision accuracy.

TABLE 1. Hardware and Software Components of the IoT-Based Soil Monitoring System

No	Comp.	Spec. / Model	Function in System
1	**ESP32 WROOM-32**	Dual-core MCU, Wi-Fi, SPIFFS support	Main controller for data processing, decision-making, server hosting, and communication
2	**Soil Moisture Sensor (YL-38 + YL-69)**	Analog resistive sensor	Measures soil moisture level and triggers irrigation logic
3	**DHT11**	Temperature–humidity sensor	Reads ambient temperature and humidity around the plant
4	**Ultrasonic Sensor (HC-SR04)**	2–400 cm measuring range	Detects water tank level to prevent pump operation during empty-tank condition
5	**Relay Module (1-channel)**	5V control	Controls the activation/deactivation of the water pump based on ESP32 logic
6	**Water Pump**	DC pump 5–12V	Irrigation actuator controlled automatically or via manual override
7	**I2C LCD Display (16×2)**	I2C interface	Displays real-time sensor readings and pump status locally
8	**Power Supply**	5V/2A	Provides power for ESP32 and sensors
9	**Local Web Server (ESP32)**	HTML, CSS, JS (AJAX)	Provides real-time dashboard access via browser
10	**Telegram Bot API**	HTTPS API	Sends notifications and handles remote commands (/status, /pump_on, /pump_off)

B. System Reliability and Responsiveness under Representative Farming Conditions

1) Field Deployment and System Operation

The system was deployed in an outdoor smallholder chili farming setup using soil-based potted plants. This deployment exposed the system to natural variations in soil moisture and network stability, which are commonly encountered in rural agricultural environments. It should be noted that the evaluation was conducted under representative small-scale farming conditions, rather than a full planting-to-harvest cultivation cycle.

During deployment, the system successfully monitored soil moisture, ambient temperature, humidity, and water tank levels while performing automatic irrigation based on predefined control rules. Manual override functionality through the web dashboard and Telegram Bot was also consistently operational.

2) Black-Box Testing Results

To evaluate functional reliability, black-box testing was performed by observing system responses to various input conditions without examining internal program logic. The test scenarios included sensor-based triggers, network conditions, and user commands.

The black-box testing results as shown in Table 4 confirm that all core system functionalities operated correctly under different scenarios. The system reliably executed irrigation decisions, prevented pump activation under unsafe conditions, and accurately responded to user commands.

3) System Responsiveness under Different Network Conditions

System responsiveness was quantitatively evaluated by measuring response times under two network

TABLE 2. Comparison between Manual Observation and IoT-Based Soil Monitoring

Aspect	Manual Observation	Proposed IoT System
Monitoring frequency	Periodic (1–2 times per day)	Real-time (≈1.9 s update interval)
Response time	Delayed (minutes to hours)	< 1 second (pump activation)
Data continuity	Discrete and subjective	Continuous and sensor-based
Human error	High	Low
Remote access	Not available	Web dashboard and Telegram Bot

TABLE 3. SYSTEM RESPONSE TIME UNDER DIFFERENT NETWORK CONDITIONS

Operation	Mobile Hotspot	Wi-Fi Router
Web server load time	0.67 s	0.34 s
AJAX sensor update	2.57 s	1.90 s
Pump ON	3.50 s	0.58 s
Pump OFF	4.46 s	0.27 s
Telegram /status	1.97 s	2.60 s
Telegram /pump_on	2.44 s	3.38 s
Telegram /pump_off	2.45 s	3.66 s

configurations: mobile hotspot and Wi-Fi router connectivity. The results are summarized in Table 3.

The results indicate that the system performed most reliably under Wi-Fi router connectivity, achieving significantly faster response times for dashboard-based monitoring and pump control. The pump activation delays were as low as 0.58 seconds, demonstrating high system responsiveness. Although Telegram command execution exhibited longer delays (2–3 seconds) due to internet latency, command execution remained reliable and consistent.

These findings directly address RQ2, confirming that the ESP32-based irrigation system maintains high responsiveness and functional reliability under representative farming and network conditions.

4) Sensor Stability and Automation Accuracy

In addition to responsiveness, the sensor stability and automation accuracy were evaluated. The soil moisture sensor exhibited stable readings with fluctuations below 5%, while the ultrasonic water-level sensor achieved an accuracy of approximately ±0.2 cm. Irrigation actions were executed correctly in all evaluated scenarios, including dry soil detection, pump activation, pump deactivation, and safety blocking during empty-tank conditions.

C. User Validation Results

User validation was conducted through functional interaction with the system during field deployment. The validation focused on usability, clarity of system feedback, and effectiveness of control interfaces.

The user validation results as shown in Table 5 indicate that the system interfaces were easy to use and provided clear feedback, supporting practical adoption by smallholder farmers with limited technical experience.

TABLE 4. BLACK-BOX TESTING RESULTS

Test Scenario	Input Condition	Expected Output	Result
Dry soil detected	Soil moisture < 30%	Pump ON	Pass
Moist soil detected	Soil moisture ≥ 30%	Pump OFF	Pass
Empty water tank	Tank level > threshold	Pump blocked	Pass
Telegram /pump_on	Command sent	Pump activated	Pass
Telegram /pump_off	Command sent	Pump deactivated	Pass
Network disruption	Wi-Fi disconnected	Local operation maintained	Pass

TABLE 5. USER VALIDATION RESULTS

Validation Aspect	Method	Outcome
Ease of monitoring	Web dashboard usage	Successfully accessed
Manual pump control	Telegram commands	100% executed
Notification clarity	Automatic alerts	Clearly received
Overall usability	Field interaction	System usable

D. Discussion

The results demonstrate that the proposed IoT-based soil condition monitoring and irrigation system successfully fulfills its functional and operational objectives. By providing real-time soil moisture monitoring and automated irrigation control, the system effectively addresses the limitations of manual irrigation practices identified in the needs analysis stage.

The integration of Telegram Bot functionality enhanced system accessibility and flexibility, enabling remote monitoring and control with simple text-based commands. This finding aligns with previous studies highlighting the effectiveness of lightweight communication platforms in improving the adoption of IoT among non-technical users. Similarly, the AJAX-based web dashboard improved interactivity and responsiveness by allowing real-time updates without page reloads, consistent with prior IoT monitoring research.

From a networking perspective, the superior performance observed under Wi-Fi router connectivity confirms the importance of stable network infrastructure for real-time agricultural IoT systems. However, the system's ability to maintain core functionality during temporary network disruptions demonstrates its suitability for intermittent connectivity in rural environments.

Compared to cloud-dependent irrigation systems reported in previous studies, the proposed system achieves faster local response times due to its local processing and server architecture. The pump activation latency of 0.58 seconds compares favorably with reported response times of 1–2 seconds in cloud-based systems, highlighting the effectiveness of the lightweight system design.

Although the evaluation was limited to small-scale deployment and did not encompass a full planting-to-harvest cycle, the results provide strong empirical evidence of system reliability, responsiveness, and usability. These findings indicate that the proposed system is feasible as a low-cost, practical reference model for supporting precision irrigation in smallholder farming environments.

IV. CONCLUSION

This study successfully developed and implemented an IoT-based soil condition monitoring and irrigation system in a representative smallholder farming environment. The system integrates soil moisture sensors, air temperature and humidity sensors, and a water tank level sensor with an ESP32 microcontroller to enable real-time condition detection and automated pump control based on predefined thresholds. The integration of a web-based dashboard and a Telegram Bot enhances system accessibility by supporting remote monitoring and manual override functionalities.

Experimental evaluation demonstrated that the system operated reliably under various usage scenarios, both through the web dashboard and Telegram Bot interface. Performance was more stable when using a Wi-Fi router compared to a mobile hotspot, resulting in faster response times. The pump protection mechanism for empty-tank conditions functioned effectively, ensuring safe system operation. Black-box testing confirmed that all core features—monitoring, irrigation automation, manual control, and notification delivery—operated as expected.

Quantitative results indicate strong real-time system performance, with web server loading times ranging from 0.34 to 0.67 seconds, pump activation delays as low as 0.58 seconds, and average sensor update intervals of approximately 1.90 seconds. Sensor evaluation showed stable soil moisture readings with fluctuations below 5%, while the ultrasonic water-level sensor achieved an accuracy of ± 0.2 cm. Based on the observed irrigation cycles during system operation, the proposed system indicates a potential water use efficiency improvement of approximately 30–40% compared to manual irrigation practices.

Compared with previous IoT-based smart irrigation studies, the proposed system demonstrates advantages in its lightweight local processing and two-way communication design, particularly through the implementation of a simple yet responsive Telegram Bot interface. The use of representative small-scale soil-based validation further supports the practical relevance of the system, distinguishing this work from simulation-based approaches. Therefore, the system is considered feasible as a low-cost and practical reference model for precision irrigation support in smallholder agricultural settings, particularly in rural environments such as Pameungpeuk, Garut Regency.

Despite these promising results, several limitations remain. The system was evaluated only in a small-scale chili farming setup, and the resistive soil moisture sensor (YL-69) used in this prototype is susceptible to corrosion, which may affect its long-term accuracy. Additionally, the system relies on Wi-Fi connectivity and does not yet incorporate solar power or long-range communication technologies. Future work should include long-term multi-location field deployment, the integration of more durable capacitive soil moisture sensors, incorporation of cloud-based analytics, and evaluation across different crop types to enhance system scalability and robustness.

DECLARATIONS

Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

CRediT Authorship Contribution

Ayu Latifah: Conceptualization, Methodology, Funding Acquisition, Supervision, Validation, Writing – Original Draft, Writing – Review and Editing. Dendi Ardimansah: Software, Hardware, Investigation, Data Curation, Visualization, Validation, and Writing – Original Draft.

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Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this manuscript, the authors used AI-assisted language tools (ChatGPT) to support proofreading and improve the clarity and quality of the English language. The original manuscript was written in Indonesian, and the AI tool was used solely for language editing and wording improvement. The AI system was not used to generate research ideas, methodology, experimental results, analysis, or conclusions.
After using this tool, the authors carefully reviewed and edited the manuscript to ensure the accuracy and integrity of the scientific content. The authors take full responsibility for the final content of the publication.

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