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Energy-Autonomous IoT Precision Irrigation with Soil Moisture Telemetry for Paddy Fields

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Abstract

The adoption of IoT-based smart agriculture in Indonesia remains limited among farmers because of high costs, low digital literacy, and the absence of an easy-to-replicate system. This study develops and evaluates an IoT-based monitoring and control system for rice-field irrigation, built on a WiFi-bridge and solar-powered architecture. The system uses an ESP32 microcontroller, a capacitive soil moisture sensor, a DC water pump, a 50 Wp solar panel, and a TP-Link wireless transmitter for long-distance connectivity. A human-in-the-loop approach is implemented through a web dashboard that lets farmers control irrigation manually, avoiding the failure risk of fully automated systems. System performance was evaluated through experimental testing, including sensor validation against an Intelligent Soil Tester, network-performance testing at distances up to 1000 meters, and pump-efficiency measurements. The calibrated soil moisture sensor achieved 99.0% accuracy with an error of only 1%. The WiFi bridge maintained a stable connection up to 700 meters with an average response time of 2.08 seconds. The system reduced irrigation-control time by 99.0% (from 15.5 minutes to 9 seconds per cycle), saving about 92 minutes per day. The pump delivered an average discharge of 22.2 L/min with a power consumption of 180.1 W. This modular system offers an easy-to-replicate solution that bridges the gap between IoT research and farmers' needs, while supporting the inclusive and sustainable digital transformation of Indonesia's food sector.

Keywords—Internet of Things; smart irrigation; WiFi bridge; soil moisture sensor; solar-powered system

1. Introduction

The digitalization of Indonesia's food sector has not yet advanced comprehensively or evenly, particularly at the farmer level, where farmers still dominate the national agricultural production structure (Ardiana & Purnomo, 2025). In practice, most farmers still rely on traditional production-management approaches, including land irrigation, carried out manually without support from real-time environmental data. This reliance on subjective experience leads to low efficiency in water and electrical-energy use, and makes it difficult for farmers to adapt to weather changes and resource availability. This situation reflects a fundamental problem in the digital transformation of the food sector: the limited use of IoT technology and field sensors at the primary production stage (Winarno & Lestari, 2025). IoT technology has strong potential as a gateway to agricultural digitalization because it can continuously provide real-time data on land conditions, microclimate, and crop water needs (Mowla et al., 2023; Qazi et al., 2022). However, low digital literacy and the lack of a simple, easily replicated smart-farming model (Sukriadi et al., 2026) have kept the adoption of this technology very limited among farmers. IoT has also been applied outside agriculture, such as in systems that detect moisture content and tank levels

at refueling stations, demonstrating the technology's potential for real-time automatic monitoring and control (Hidayat et al., 2023).

Various studies have developed intelligent irrigation systems based on the Internet of Things (IoT) and renewable energy. One study developed an IoT system for smart agriculture in Indonesia that integrated electronic modules—solar panels, a weather station, soil-quality sensors, an ESP32, 3G/4G communication modules, and relay actuators—to operate water pumps automatically based on soil moisture levels (Westari & Ilman, 2024). Another study designed a solar-powered IoT water-supply robot to support sustainable tourism and integrated fish farming; the results showed that the solar–IoT system could reduce water use by more than 30% and increase plant growth by about 30% in chili and rice production (Santoso et al., 2025). A further study developed a real-time agricultural monitoring system using an ESP32 and LoRa communication to transmit soil-moisture, temperature, and air-humidity data over long distances with low power consumption (Abdelli et al., 2025). Related work developed a smart-farming system based on IoT and Long Range (LoRa) technology to automate drip irrigation for mustard greens; the system integrated several sensors with an ESP32 microcontroller and a LoRa module, enabling remote monitoring and irrigation control through an IoT platform, and was shown to support automatic irrigation and effective land monitoring (Anshori et al., 2025).

Another study proposed a LoRa-based IoT communication model for smart farming that emphasized power efficiency and long range for monitoring farms in remote areas (Rahmansyah et al., 2025). Other research developed an edge-intelligence-based smart-farming system with LoRa and IoT that enables decision-making at the network edge to reduce latency and bandwidth consumption (Elbasi et al., 2025). Related work designed an IoT-powered smart-farming system that used LoRa technology for sustainable agriculture, integrated with soil and weather sensors (Elhattab & Abouelmehdi, 2024). Research on an IoT-integrated, modular intelligent water-pump system using the ESP-NOW protocol demonstrated an alternative device-to-device communication approach that does not require WiFi infrastructure (Siyam et al., 2025).

Although these studies make significant contributions, several limitations still need to be addressed. Research on IoT-based precision irrigation shows that integrating soil moisture sensors, ESP32 microcontrollers, and web- or mobile-connected automatic pumps can create smart-farming solutions that minimize water and energy waste while improving food security and farmer productivity amid climate change (Djamen & Kamasi, 2025). In addition, many existing prototypes rely heavily on the state electricity grid (PLN) or on hybrid systems, which limits their use in remote rural areas (Yunus & Hasnawati, 2025). Research on real-time monitoring and predictive maintenance of PV-fed BLDC irrigation-pump systems emphasizes the importance of real-time monitoring for identifying failures and triggering alerts to improve reliability and operational efficiency (Kumar & Naik, 2026). Although IoT-based automated systems have improved irrigation-management efficiency, some approaches remain limited in adapting decisions to actual field conditions. There is therefore a need to develop a system that integrates real-time monitoring, flexible control, and clear information presentation to help users make more optimal decisions.

The novelty of this research lies in three main aspects. First, the web-based human-in-the-loop approach gives farmers the flexibility to control irrigation manually as an additional safety layer, in contrast to fully automated systems that are prone to failure from sensor errors. Second, a WiFi-bridge communication architecture that uses a TP-Link unit as a transmitter at the farmer's house and an ESP32 as a receiver in the rice field enables long-distance connectivity without a 4G modem or a separate data plan in the field, thereby reducing operational costs. Third, this study reports soil moisture sensor validation obtained by calibrating against an Intelligent Soil Tester as a reference on paddy soil, providing transparency of data accuracy that is often not reported in the development of agricultural IoT systems. The scientific contribution of this research is therefore a modular, cost-effective, and easily replicable IoT irrigation-system model that bridges the gap between technology research and the real needs of farmers, accelerating the digital transformation of Indonesia's food sector.

2. Methods

This research uses a quantitative approach with the Research and Development (R&D) method. The quantitative approach was chosen to objectively measure and analyze system-performance parameters (sensor accuracy, network delay, cost efficiency, and pump discharge) through experimental testing (Prihartanto et al., 2026). The R&D method was chosen because it aims to produce a product—an IoT-based irrigation monitoring and control system—and to test the effectiveness of that product in the field. The research comprises three main stages: (1) identification of system needs and system design, (2) implementation and integration of hardware and software, and (3) system-performance testing and analysis.

2.1 Research Flow Diagram

The stages are organised around four research objectives (RO): **RO1** – to design and implement a low-cost, solar-powered IoT irrigation monitoring and control system that uses a WiFi-bridge link and web-based human-in-the-loop control; **RO2** – to ensure the accuracy of soil-moisture data by calibrating and validating the capacitive sensor against an Intelligent Soil Tester on paddy soil (target accuracy ≥ 95%, error < 5%); **RO3** – to determine the effective range and responsiveness of the WiFi-bridge link between the farmer's house and the field (target response time < 5 s); and **RO4** – to quantify the operational benefits of the system in terms of irrigation-control time, operational cost, pump discharge (target > 20 L/min), and power consumption.

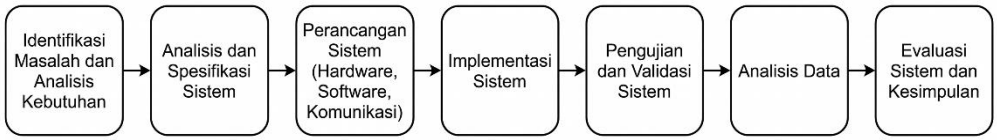


Figure 1. Research flow diagram.

The research methodology consists of seven stages, beginning with problem identification and needs analysis, followed by system analysis and specification, hardware and software design, system implementation, testing and validation, data analysis, and system evaluation. Each stage has defined inputs, activities, and outputs to ensure a systematic and reproducible development process. The implementation includes soil-moisture sensor calibration, ESP32-based monitoring and pump control, and web-dashboard development. System performance is then evaluated through sensor accuracy, WiFi communication range and response time, irrigation-control efficiency, pump discharge, and operational costs. Finally, the results are compared with predefined performance indicators and previous studies to assess the system's effectiveness and identify its contributions.

2.2 System Needs Identification and Design

2.2.1 Literature Study and Needs Analysis

A literature review was conducted to examine previous research on IoT-based irrigation systems, long-range WiFi technology, soil moisture sensors, and solar-power systems for agriculture. The literature was drawn from SINTA-accredited national journals and reputable international sources (IEEE, Scopus) (Hammouch et al., 2024). A needs analysis was then carried out to identify:

1. System functional requirements (soil moisture monitoring, remote pump control, real-time data display)
2. Non-functional requirements (system reliability, ease of use, low operational costs)
3. System limitations (limited internet access in rice fields, limited electrical power)

2.2.2 Field Surveys and System Specifications

Field surveys were carried out in rice fields to observe the irrigation practices used by farmers. Interviews were conducted to gather information on irrigation methods, operational time and cost,

obstacles faced, and the availability of internet and electricity access (Kgopa & Monchusi, n.d.). Based on the literature review and field surveys, the system-requirement specifications were compiled in Table 2.

Table 2. System Requirements Specifications

No.	Requirements	Description
1	Soil Moisture Monitoring	Reads and displays soil moisture data in real-time
2	Remote Control	Farmers control the pump via the web (human-in-the-loop)
3	Energy self-sufficiency	50 Wp solar panel and 12V battery
4	Remote Connectivity	TP-Link 2.4 GHz transmits WiFi from the house to the field
5	Reliability	Auto-reconnect when WiFi connection drops
6	Sensor Accuracy	At least 95% accuracy against reference tools

2.3 System Implementation and Integration

2.3.1 System Architecture Design

The system was designed with a client–server architecture consisting of three layers: (1) the sensor and actuator layer, (2) the communication layer, and (3) the user-interface layer. The system architecture is shown in Figure 2.

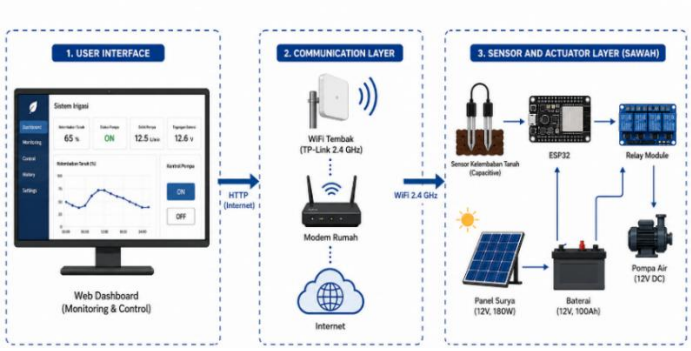


Figure 2. System Architecture

2.3.2 Hardware Assembly

The hardware was assembled by integrating all system components according to the predetermined specifications. The components used and their functions are listed in Table 3.

Table 3. Hardware Component Specifications

No.	Components	Specification	Function
1	ESP32	ESP32-WROOM-32	Microcontroller, WiFi receiver, relay control
2	Soil Moisture Sensor	Capacitive YL-69/HL-69	Soil moisture reading (ADC 0–4095)
3	Solar Panels	50 Wp	Main power source
4	Battery/Accu	12V	Energy storage
5	Relay	1 Channel DC 5V	Pump control ON/OFF
6	Water Pump	DC 12V 125W	Pumping/discharging water
7	TP-Link	2.4 GHz TL-WA901ND	Remote WiFi transmitter
8	WiFi Modem	4G/LTE	Source of internet connection at home
9	Intelligent Soil Tester	Digital	Sensor validation reference measuring tool
10	Digital Multimeter	Digital	Measuring voltage and current

2.3.3 Software Development

Software development consisted of two main components: (1) the ESP32 firmware and (2) the web dashboard.

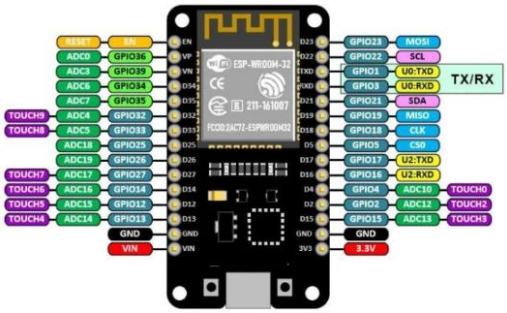


Figure 3. ESP32 Pinout Diagram

The ESP32 pinout is shown in Figure 3. In the designed system, the ESP32 acts as a control center that reads data from four soil moisture sensors through its Analog-to-Digital Converter (ADC) pins, converts the readings into soil moisture percentages (%), and displays the raw ADC values (0–4095) on the web page. The ESP32 also transmits the manually controlled pump status via the ON/OFF button on the web interface, records system activity logs (time, status, and events) during operation, and displays network information such as the ESP32's IP address and WiFi connection status, so that users can monitor the device and control the pump remotely through a browser.

The web dashboard was developed using HTML, CSS, and JavaScript as a user interface for monitoring and controlling the system (Ardhi et al., 2025). It displays soil moisture levels from four sensors, pump status (ON/OFF), raw ADC values (0–4095), system activity logs, and network information, including the ESP32 IP address and connection status. It also provides manual pump control. Using a client–server architecture, data are transmitted from the ESP32 to the server via HTTP POST, stored in a database, and displayed on the dashboard in real time.

2.3.4 Soil Moisture Sensor Calibration

The soil moisture sensors were calibrated to ensure measurement accuracy (Mane et al., 2025). The IoT sensors and Intelligent Soil Tester were placed at the same locations in the rice field, with simultaneous measurements taken at 10 points with moisture levels ranging from 30% to 80%. The raw ADC values (0–4095) were then converted into moisture percentages (0–100%) using a linear regression equation. Finally, the IoT sensor readings were compared with the Intelligent Soil Tester measurements to calculate the average error and accuracy.

2.4 System Testing and Analysis

2.4.1 Test Plan

System testing was designed to evaluate five key aspects: (1) sensor validation, (2) WiFi-bridge network performance, (3) control-time efficiency, (4) operational-cost efficiency, and (5) pump discharge and power consumption. The test matrix is presented in Table 4.

Table 4. System Testing Matrix

No.	Testing Aspects	Parameters	Method	Success Indicators
1	Sensor Validation	Error (%), Accuracy (%)	Compare with Intelligent Soil Tester (10 samples)	Error < 5%

2	Network Performance	Response time (sec), Success (%)	Test at 7 distances (100-1000m)	5 seconds < delay
3	Time Efficiency	Control time (sec/minute)	Compare IoT vs manual (5 samples)	Faster than manual
4	Cost Efficiency	Operational costs (Rp/day)	Compare PLN grid vs solar	Cost-effective
5	Discharge & Pump Power	Discharge (L/min), Power (Watts)	Measure volume, voltage, current (10 minutes)	Discharge > 20 L/min

2.4.2 Testing Procedure

a. Sensor Validation Testing
The IoT sensor and the Intelligent Soil Tester were placed at the same point in the rice field. Measurements were taken simultaneously at 10 points with varying moisture levels (30–80%). Data were recorded for error and accuracy calculation.

b. WiFi-Bridge Network Performance Testing
Network-performance testing measured connection quality and response time at various distances (100–1000 meters) between the TP-Link transmitter at the house and the ESP32 receiver in the field. An ON/OFF command was sent from the web interface to the ESP32, and the time from command transmission to relay response was recorded. Each distance was tested five times and averaged. Tests were conducted under line-of-sight (LOS) conditions without significant obstruction (Kafrashi et al., 2025).

c. Control Time Efficiency Testing
Control-time efficiency was tested by comparing two irrigation-control methods: (1) control through the IoT application using a smartphone, and (2) control by going directly to the field. Time was measured from the moment the decision was made until the pump was successfully switched on or off. Testing was performed five times (three for the IoT method and two for the manual method) and averaged (Mohamed et al., 2026).

2.5 Data Analysis Methods

The data obtained from testing were analyzed using descriptive and inferential statistical methods (Wibisonya, 2024):

a. Sensor Validation Analysis
Error (%) = IoT Sensor Value - Intelligent Soil Tester Value (1)
Accuracy (%) = 100% - Average Error (2)

b. Network Performance Analysis
The average response time is calculated for each distance. Linear regression analysis is used to determine the relationship between distance and response time with equations:

$$y = a + bx \quad (3)$$

where y is the response time, x is the distance, and a and b are the regression constants.

c. Control Time Efficiency Analysis
Time Efficiency (%) = ((Manual Time - IoT Time) / Manual Time) × 100% (4)

d. Operational Cost Efficiency Analysis
Cost Efficiency (%) = ((PLN Cost - Solar Cost) / PLN Cost) × 100% (5)

e. Discharge and Pump Power Analysis
Pump Discharge (L/min) = Water Volume (Liters) / Time (min) (6)
Power (watts) = voltage (volts) × current (amperes) (7)

The Pearson correlation coefficient is used to analyze the relationship between battery voltage and pump discharge (Fintoro et al., 2025):

$$r = \Sigma((xi - \bar{x})(yi - \bar{y})) / \sqrt{(\Sigma(xi - \bar{x})^2 \times \Sigma(yi - \bar{y})^2)} \quad (8)$$

The solar panel does not supply the pump directly; instead, it charges the battery, which acts as an energy store.

3. Results and Discussion

3.1 Soil Moisture Sensor Validation

Sensor-validation testing evaluated the accuracy of the developed soil moisture sensor against the Intelligent Soil Tester as a reference. The results are presented in Table 5.

Table 5. IoT Sensor Validation Results Against the Intelligent Soil Tester

Sample No.	Intelligent Soil Tester (%)	IoT Sensor (%)	Error (%)
1	30	29	1
2	35	34	1
3	40	39	1
4	46	45	1
5	51	50	1
6	56	55	1
7	62	61	1
8	68	67	1
9	74	73	1
10	80	79	1
Average	54.20%	53.20%	1.00%
Accuracy	-	-	99.00%

Based on Table 5, the developed IoT sensor has an average error of only 1% relative to the Intelligent Soil Tester, corresponding to an accuracy of 99.0%. The consistent 1% error across the entire measurement range indicates excellent linearity relative to the reference device. These results show that the soil moisture sensor used in this study is highly precise and reliable for soil-moisture monitoring in rice fields. This high accuracy results from the calibration performed specifically for the soil type at the test site, consistent with prior recommendations that capacitive sensors require calibration to ensure accuracy (Djamen & Kamasi, 2025).

3.2 WiFi-Bridge Network Performance

Network-performance testing evaluated the system's ability to maintain a connection and the response time at various distances between the TP-Link transmitter at the house and the ESP32 receiver in the field. The results are presented in Table 6.

Table 6. WiFi-Bridge Network Performance at Various Distances

No.	Distance (m)	Connection Status	Response Time (sec)
1	100	Excellent	1.2
2	250	Good	1.5
3	400	Good	1.8
4	550	Stable	2.1
5	700	Stable	2.5
6	850	Less Stable	3.4
7	1000	Unstable	-
Average (100–700 m)	-	-	2.08

Based on Table 6, the system maintained a stable connection up to 700 meters, with an average response time of 2.08 seconds. At 850 meters the connection became less stable and the response time increased to 3.4 seconds. At 1000 meters the system could not maintain the connection. This

indicates an effective range of up to 700 meters for very stable operation and up to 850 meters for marginal operation.

Linear-regression analysis over 100–700 meters showed a very strong relationship between distance and response time ($y = 0.0022x + 0.98$, $R^2 = 0.99$). The developed system also has an auto-reconnect mechanism that successfully handled connection drops; system logs recorded a disconnect at 08:16 that was restored in less than one minute.

3.3 Irrigation Control Time Efficiency

Control-time efficiency was tested by comparing two irrigation-control methods: control through the IoT web application using a smartphone, and control by going directly to the field. The results are presented in Table 7.

Table 7. Irrigation Control Time Comparison

Experiment No.	Control via IoT (smartphone)	Manual Control (on-site)
1	8 seconds	15 minutes (900 seconds)
2	10 seconds	16 minutes (960 seconds)
3	9 seconds	-
Average	9 seconds	930 seconds (15.5 minutes)

Based on Table 7, control through the IoT application took an average of only 9 seconds, whereas control by going directly to the field took an average of 15.5 minutes (930 seconds). The IoT system therefore saves up to 99.0% of the time—about 921 seconds (15.3 minutes) per control action making it approximately 103 times faster than the conventional method.

In this study, with an average of 6 irrigation cycles per day (based on operational data), the total time saved reached about 92 minutes per day (15.3 minutes × 6 cycles), which can be reallocated to other productive activities. This time efficiency is one of the main advantages of the IoT system and is consistent with the research goal of improving farmers' efficiency in irrigation management.

3.4 Pump Discharge and Power Consumption

Pump discharge was measured by collecting the water delivered over 10 minutes in a measuring container. The results are presented in Table 8.

Table 8. Pump Discharge and Power Consumption Test Results

Minute No.	Voltage (V)	Current (A)	Power (W)	Volume (L)	Flow (L/min)
1	12.8	13.9	177.9	24	24
2	12.7	14	177.8	47.6	23.8
3	12.7	14.1	179.1	70.8	23.6
4	12.6	14.2	178.9	93.6	23.4
5	12.6	14.3	180.2	116	23.2
6	12.5	14.4	180	138	23
7	12.5	14.5	181.3	159.6	22.8
8	12.4	14.6	181	180.8	22.6
9	12.4	14.7	182.3	201.6	22.4
10	12.3	14.8	182	222	22.2
Average	12.55	14.35	180.1	-	22.2

Based on Table 8, the average pump discharge is 22.2 L/min, decreasing gradually from 24.0 L/min to 22.2 L/min over 10 minutes of operation. This 1.8 L/min decrease (7.5%) correlates with

a drop in battery voltage from 12.8 V to 12.3 V (0.5 V, or 3.9%). Correlation analysis showed a very strong positive relationship between battery voltage and pump discharge (r = 0.99), meaning that a decrease in battery voltage directly affects pump performance. The measured average pump power is 180.1 W, higher than the 125 W specification. Nonetheless, the 50 Wp solar panel can still meet this demand because the system uses a battery as an energy buffer. With an average discharge of 22.2 L/min and an average irrigation duration of 9 minutes per cycle, the system delivers about 199.8 liters per cycle. With 6 cycles per day, the total volume reaches about 1,199 liters per day. This is sufficient for irrigating rice fields of limited area and shows that the system can provide an adequate, sustainable water supply.

3.5 Summary of Research Results

Table 9. Summary of All Test Parameters

No.	Parameters	Results	Target	Remarks
1	Sensor Accuracy	99.00%	> 95%	Achieved
2	Average Sensor Error	1.00%	< 5%	Achieved
3	Network Response Time (100-700m)	2.08 seconds	< 5 seconds	Achieved
4	Effective Reach	850 m (stable up to 700 m)	-	Achieved
5	Control Time Efficiency	99.00%	> 50%	Achieved
6	Average Pump Discharge	22.2 L/min	> 20 L/min	Achieved
7	Average Pump Power	180.1 W	-	Scalable
8	Total Irrigation per Day	6 cycles	-	-
9	Total Water Volume per Day	1,199 liters	-	-
10	Auto-Reconnect	Works	Works	Achieved

3.6 Discussion

3.6.1 Interpretation of Findings

The sensor-validation result matters less for its headline accuracy than for the structure of the error. The deviation from the Intelligent Soil Tester was a constant offset of about 1 percentage point across the whole 30–80% range (Table 5). The deviation did not grow with moisture level, which indicates that a single linear ADC-to-moisture mapping, calibrated on the paddy soil at the site, captures the sensor response adequately and that the residual bias is systematic rather than random. A systematic offset of this kind can be removed by a simple correction term. This is consistent with the view that capacitive sensors require site- and soil-specific calibration (Djamen & Kamasi, 2025; Mane et al., 2025). However, the validation covered ten points at one site, and readings above 80%, which are typical of flooded paddy and appear on the dashboard (Figure 6), lie outside the validated range.

The network results reveal a clear operating envelope rather than gradual degradation. Response time increased almost linearly with distance up to 700 m ($y = 0.0022x + 0.98$, $R^2 = 0.99$), which means that each additional 100 m adds only about 0.2 s. Beyond that point the link degraded abruptly (marginal at 850 m, lost at 1000 m). In practice, therefore, the WiFi bridge offers a predictable response inside its envelope and should not be relied on near its edge. Because the tests were performed under line-of-sight conditions (Kafrashi et al., 2025), vegetation, buildings, and rain would be expected to shorten the usable range. The auto-reconnect mechanism, which restored a dropped connection within one minute, is what makes the link usable in a human-in-the-loop setting, where a farmer waiting for a pump command cannot tolerate a link that does not recover by itself.

The dashboard (Figure 6) shows how the human-in-the-loop design works in practice. Besides moisture percentages and status warnings, it exposes the raw 12-bit ADC values and an event log that records disconnections and reconnection attempts. In the captured state, two sensors report

"TOO WET" while the pump remains OFF, and the unconnected channels are clearly marked. A farmer can therefore distinguish a genuinely wet field from a faulty or disconnected sensor before acting. A threshold-driven automatic controller cannot make this distinction. In this design, the sensor informs the decision and the farmer makes it.

The 99% reduction in control time comes mainly from removing the trip to the field, not from faster pump switching. Its absolute value therefore depends on the distance between the farmer's house and the plot, and the result should be read as indicative because it is based on a small number of trials. The practical meaning is that irrigation decisions can be made as often as field conditions require, instead of being limited by travel. Previous IoT irrigation studies mostly report benefits in water use (Mohamed et al., 2026; Santoso et al., 2025). The benefit demonstrated here is in labour and responsiveness; water savings were not measured in this study.

The pump results show that the battery, not the solar panel, is the effective performance bottleneck. The measured power (180.1 W) exceeded the 125 W rating, and discharge fell in step with battery voltage ($r = 0.99$). For the reported duty cycle (6 cycles × 9 min), this implies a daily pump demand of roughly 160 Wh. Assuming typical tropical insolation of about 4–5 peak-sun hours, a 50 Wp panel yields on the order of 200–250 Wh/day before conversion losses, so the energy margin is narrow on cloudy days. For longer irrigation cycles, battery state-of-charge monitoring, a larger battery, or a larger panel should be treated as design requirements rather than optional extensions.

3.6.2 Critical Distinction and Trade-offs: WiFi Bridge vs LoRa

Three features together set the current study apart. First, the web-based human-in-the-loop design is a deliberate safety layer, not a missing automation feature. In the automatic systems in Table 10, a single drifting, saturated, or disconnected capacitive sensor can trigger over- or under-irrigation without anyone noticing. Here, raw ADC values and event logs let the farmer detect such failures before acting. Second, the WiFi-bridge architecture reuses the internet connection that already exists at the farmer's house: a TP-Link transmitter relays it to the ESP32 in the field. No 4G modem, SIM card, or separate data plan is needed at the field node (unlike the 3G/4G configuration of Westari & Ilman, 2024), and no LoRa gateway is required, which lowers recurring operational cost. Third, the study reports a transparent, point-by-point validation of the soil-moisture sensor against an Intelligent Soil Tester on paddy soil, whereas soil-moisture validation is absent or partial in most of the compared work (Rahmansyah et al., 2025).

The WiFi bridge offers far higher bandwidth than LoRa. This allows a native HTTP web dashboard that shows live values, raw ADC data, and event logs in an ordinary smartphone browser, with no intermediate cloud platform. It uses inexpensive commodity hardware (a consumer access point and the ESP32's built-in radio) and requires no subscription beyond the household connection. These benefits come with clear costs. The usable range is limited to about 700 m (stable) to 850 m (marginal) under line-of-sight conditions. The link depends on the household internet connection and power supply at the transmitter. The 2.4 GHz signal is sensitive to obstruction, and the WiFi radio draws more power than a LoRa radio.

LoRa provides kilometre-scale links, for example 2 km at a packet delivery ratio above 95% (Abdelli et al., 2025), and low power consumption that suits battery-powered and solar-powered sensor nodes (Elhattab & Abouelmehdi, 2024; Rahmansyah et al., 2025). However, its low data rate limits the richness of the data that can be transmitted. Each node requires a dedicated LoRa module. A gateway or master node is also needed, and a web dashboard cannot be provided natively without additional infrastructure such as MQTT brokers, Node-RED, or cloud services (Elhattab & Abouelmehdi, 2024; Rahmansyah et al., 2025). This increases system complexity and the skills required for maintenance. Device-to-device protocols such as ESP-NOW (Siyam et al., 2025) remove the need for infrastructure, but they offer short range and no internet access on their own.

A WiFi bridge is preferable when the plot lies within about 700 m line-of-sight of a house that has electricity and internet access, when the budget for hardware and subscriptions is minimal,

and when farmers are comfortable with a smartphone browser but not with configuring gateways or cloud platforms. These conditions are typical of smallholder rice fields near village settlements. LoRa is preferable when fields are beyond 1 km, scattered, or obstructed; when many low-data sensor nodes must be aggregated; when no powered, connected building is nearby; and when an institution can install and maintain the gateway infrastructure. A hybrid design is also possible, with LoRa or ESP-NOW aggregating sensor nodes inside a large field and a WiFi bridge providing the backhaul to the house.

Within this trade-off space, the current study deliberately gives up kilometre-scale range in exchange for zero recurring field connectivity cost, a native web interface, and full transparency of the sensor data on which the farmer bases decisions. It does not claim to replace LoRa systems. Instead, it shows quantitatively that, within a tested envelope of about 700 m, a simpler and cheaper link combined with human oversight is sufficient for practical smallholder irrigation.

3.6.3 Implications, Limitations, and Future Work

For practitioners, the results suggest that a smallholder near a connected house can obtain remote irrigation control without paying for field connectivity, provided that the sensor is calibrated on the local soil and the battery is sized for the pump's actual (rather than rated) power demand. The study has several limitations. Testing was performed at a single site, under line-of-sight conditions, and with small numbers of trials for control time. Sensor validation did not extend to saturated paddy conditions above 80%. Water savings and crop-yield effects were not measured. Future work should therefore (i) test the link under vegetation and seasonal conditions; (ii) extend calibration to saturated paddy soil and repeat it across soil types and seasons; (iii) add battery state-of-charge monitoring and low-voltage alerts; (iv) provide optional decision support (e.g., threshold notifications) while keeping the farmer as the final decision-maker; (v) evaluate a hybrid LoRa/ESP-NOW field network with a WiFi-bridge backhaul for larger plots; and (vi) measure water use and yield over complete growing seasons.

3.6.4 Scientific Standing of the Study

This study fills a specific gap in agricultural IoT research. Prior systems tend either to maximise range and automation or to remain monitoring-only, and they rarely report soil-sensor validation or measured link envelopes together with actuator control. The novelty of this work lies in combining a human-in-the-loop safety layer, a subscription-free WiFi-bridge architecture whose operating range has been measured, and a transparently validated soil-moisture sensor on paddy soil in one low-cost, solar-powered system. Several elements are transferable to other researchers and farmers: the component list and wiring (Table 3, Figures 2–4), the ten-point calibration procedure, the test matrix with its distance set and repetition counts (Table 4), and the explicit acceptance thresholds (Table 9). Together they make the system a replicable reference design that narrows the gap between agricultural IoT research and farmers' real needs and supports the inclusive and sustainable digital transformation of Indonesia's food sector.

4. Conclusions

This research successfully developed an IoT-based rice-field irrigation monitoring and control system built on a WiFi-bridge and solar-powered architecture, which proved effective in optimizing agricultural irrigation and improving farmer efficiency.

Across all tests, the system performed well: sensor accuracy reached 99.0% after calibration against the Intelligent Soil Tester, and the system maintained a stable WiFi connection up to 700 meters with an average response time of 2.08 seconds. It reduced irrigation-control time by up to 99.0% (about 103 times faster than the conventional method). All research objectives were thus satisfactorily achieved.

The human-in-the-loop approach proved effective in avoiding the risk of failure in fully automated systems due to sensor errors, with a mechanism that keeps farmers as the main

decision-makers in irrigation management. The average pump discharge of 22.2 L/min, with a total volume of about 1,199 liters per day, shows that the system can provide an adequate water supply for rice-field irrigation. This research addresses the slow adoption of technology and digital transformation in the food ecosystem at the farmer level through a modular, easily replicated solution suited to field conditions. This system can therefore serve as a foundation for the digitalization of an inclusive and sustainable food sector in Indonesia.

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