

Internet of Things System Implementation for Post-Landfill Soil Rehabilitation Based on pH and Moisture Monitoring

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Abstract

Post-landfill land is characterized by extreme soil conditions, such as low acidity (pH) and poor water retention, which impede rehabilitation and revegetation processes. Conventional manual watering and fertilization methods have proven inefficient in responding to these dynamic and degraded soil conditions. This study aims to design and implement an Internet of Things (IoT) system to support land rehabilitation through automated monitoring and control of irrigation and fertilization (pH adjustment). The system is built using an ESP32 microcontroller integrated with a capacitive soil moisture sensor, a PH-4502C pH sensor, a TDS sensor, and a DHT11 sensor to monitor critical soil and environmental parameters in real time. Based on the sensor data, the system autonomously activates a water pump and a fertilizer pump according to predefined threshold logic, and all telemetry data and actuator statuses are transmitted to a Firebase-based interactive web dashboard that displays numerical readings, trigger-logic status, and historical trend graphs. Testing was carried out through sensor-accuracy validation, control-logic functionality testing, and interface testing. The results show that the soil-moisture sensor achieved an average relative error below 8% and the pH sensor below 3.2% compared to standard laboratory instruments, while the automatic control logic consistently activated the irrigation and fertilization pumps in accordance with the defined threshold rules. These findings indicate that the developed system can reliably monitor critical soil parameters and perform automated, data-driven interventions, offering a practical solution to improve the efficiency of water and nutrient use and to support the revegetation of post-landfill critical land.

Keywords: Internet of Things; Land Rehabilitation; Post-Landfill Land; pH Monitoring; Soil Moisture

1. Introduction

Infrastructure and construction development in Indonesia continues to increase in line with economic growth. However, large-scale construction activities, such as the development of buildings, roads, or housing, often leave behind an environmental impact in the form of critical land - soil that has lost its fertility such that its function as a life-supporting medium declines. One common form of critical land found in urban or development areas is post-landfill land, formed from soil-dumping or land-leveling activities in which the fill material is often not fertile topsoil, but rather nutrient-poor subsoil, laterite (red soil), or even residual construction waste.

The main problem with post-landfill land is that its physical and chemical conditions are not ideal for vegetation growth. Landfill material from construction residue tends to be highly compacted, has poor porosity, and contains minimal organic matter. In addition, material such as red soil is often infertile, acidic, and prone to hardening when dry, a condition that is worsened by nutrient imbalance that prevents plants from optimally absorbing nutrients. As a result, rehabilitation or greening efforts on post-landfill land are often slow or unsuccessful; conventional handling methods, such as manual, schedule-based watering and fertilizing, have proven inefficient because this approach cannot respond to the soil's specific and dynamic needs, and improper fertilization or irrigation can even worsen land conditions and waste resources.

To address this challenge, a breakthrough is needed that shifts the rehabilitation approach from manual-reactive to precise and data-driven. The development of Internet of Things (IoT) technology offers a potential solution: by integrating environmental sensors, IoT enables continuous and remote monitoring of critical soil conditions. This study therefore proposes the implementation of an IoT system specifically designed for the rehabilitation of post-landfill land. By performing real-time monitoring of two vital parameters - soil acidity (pH) and soil moisture - the system can intelligently and automatically deliver precise watering and pH adjustment (fertilization) treatments, with the aim of improving rehabilitation effectiveness and accelerating the ecological recovery of post-landfill critical land.

Several related studies have explored IoT-based irrigation and fertilization systems. Pratama and Wibowo [1] developed a pH and TDS monitoring system for cocopeat growing media using an ESP32 and a Firebase database, which is relevant because cocopeat is an inert medium comparable in character to landfill soil and the study uses the same pH and TDS sensors adopted in this research. Sihombing et

al. [2] developed an automatic irrigation control and monitoring system for dry land using an ESP32 and a soil-moisture sensor, successfully maintaining soil moisture at a target setpoint through a website-based dashboard. Rhamadhany and Juliasari [3] designed an automatic irrigation and fertilization monitoring prototype based on the Internet of Things to improve the efficiency of previously manual and time-consuming watering and fertilizing practices. Widodo et al. [4] built an IoT-based irrigation and fertilization prototype for maize cultivation in a rural agricultural setting, demonstrating the applicability of IoT for irrigation and fertilization management, although the system was limited to a single soil-moisture parameter.

Building on these works, the present study integrates three soil-related parameters - moisture, pH, and TDS (nutrient concentration) - together with air temperature and humidity monitoring within a single ESP32-based system, and specifically targets post-landfill critical land rather than normal agricultural land, an area that has rarely been addressed in prior IoT-based irrigation research. Based on this background, the research problems addressed in this study are: (1) how to design an IoT system capable of monitoring soil pH and moisture in real time on post-landfill land media; (2) how to implement automatic control logic in the system so that it can perform watering and fertilization (pH adjustment) according to sensor data; and (3) how to test the performance and functionality of the system prototype to ensure sensor-reading accuracy and actuator reliability. Accordingly, this study aims to design and build a functional IoT system prototype capable of monitoring soil pH and moisture on post-landfill land in real time, to implement automatic control logic on the ESP32 microcontroller to activate the water pump and fertilizer pump based on sensor thresholds, and to evaluate the performance and functionality of the prototype through sensor-accuracy and control-system responsiveness testing.

2. Research Methods

This research was conducted at the campus of Politeknik Negeri Samarinda (Polnes), specifically at the Maritime Engineering Department, which provided a suitable experimental plot for testing the IoT system as well as convenient collaboration with lecturers and students who would use and evaluate the prototype directly. The research began in June 2025 with a preparation stage consisting of field observation, requirement identification, and coordination with the research advisors and laboratory staff. Hardware installation and basic sensor function testing were carried out in July 2025, followed by initial field testing for sensor calibration and system-parameter adjustment in August 2025.

The object of this research is a prototype Internet of Things-based irrigation and fertilization system for post-landfill land, designed to monitor soil conditions and control actuators in real time. The system consists of an ESP32-based main control unit, a set of sensors for monitoring soil conditions (moisture, pH, and TDS), and actuator components such as a water pump controlled through a relay module, with all data and control functions accessible remotely through an IoT dashboard.

2.1. Research stages

The system was developed using the waterfall development method, in which each development phase must be fully completed before the next phase begins, thereby minimizing the risk of error and preserving clear documentation at every step. The sequential workflow - from requirement analysis to final evaluation - ensures that both the hardware and software elements of the system are developed systematically and in a controlled manner according to the initial specification, as shown in Fig. 1.

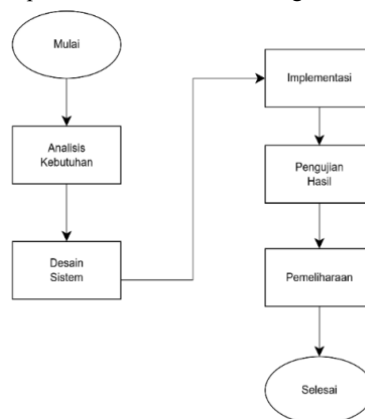


Fig. 1: Research development flow

2.2. Tools and materials

The tools and materials used during the design and testing stages of the system are summarized in Table 1.

Table 1: Tools and materials

No.	Component	Function
1	ESP32 Development Board	Main microcontroller for reading sensor data, executing control logic, and transmitting data via Wi-Fi.
2	Capacitive Soil Moisture Sensor	Measures volumetric soil moisture and signals the ESP32 to trigger irrigation.
3	pH Sensor (PH-4502C)	Measures soil acidity so the system can adjust fertilization dosage.
4	TDS Sensor	Measures nutrient concentration in the fertilizer solution.
5	DHT11 Sensor	Measures air temperature and humidity around the plot.
6	Relay Module (4-Channel)	Switches the water pump and fertilizer pump without overloading the ESP32.

7	Water Pump DC 12V	Pumps water from the tank to the field for automatic irrigation.
8	Power Adapter 12V	Provides stable power to the ESP32, sensors, relay, and pump.
9	Google Firebase Realtime Database	Cloud backend storing telemetry data and powering the web dashboard.

2.3. System architecture

The overall system architecture, illustrating the interaction between the ESP32 microcontroller, the sensor array, the actuators, and the Firebase-based cloud backend, is presented in Fig. 2.

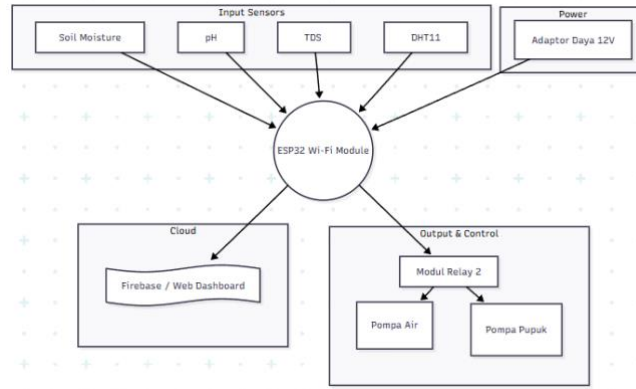


Fig. 2: System block diagram

Based on this architecture, the ESP32 acts as the central processing unit that continuously reads data from the soil-moisture, pH, TDS, and DHT11 sensors, and uses this data to drive the relay module, which switches the water pump and fertilizer pump. The soil-moisture reading, expressed as a 12-bit ADC value (0-4095) that is inversely proportional to water content, is converted into a volumetric moisture percentage through a calibrated normalization formula referencing a dry-air maximum ($ADC_{max} = 4095$) and a fully-saturated minimum ($ADC_{min} = 1800$). Every reading and actuator status is transmitted over Wi-Fi to the Firebase Realtime Database, from which the SmartFarm IoT web dashboard renders numerical values, control-logic status, and historical trend charts for remote monitoring.

2.4. Control logic and testing method

The complete decision logic of the automatic control system is presented as a flowchart in Fig. 3.

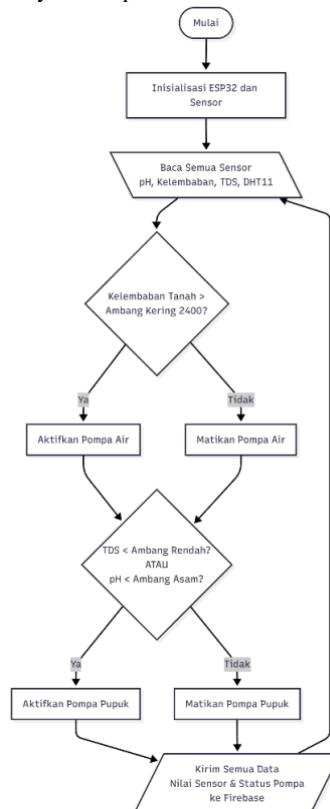


Fig. 3: System control flowchart

Two threshold-based control rules govern the actuators: the water pump is activated when the soil-moisture reading exceeds an ADC value of 2400 (indicating dry soil), while the fertilizer pump is activated when the TDS reading is below 650 ppm or the pH reading is below

1.0. This rule-based approach was intentionally selected over a machine-learning-based approach to keep the control logic transparent, predictable, and easy to validate for a first-generation prototype.

System evaluation was conducted through three main testing scenarios: (1) sensor-accuracy testing, comparing the soil-moisture and pH readings produced by the IoT system against standard laboratory measuring instruments; (2) automatic control-logic functionality testing, verifying whether the actuator-triggering logic operated correctly according to the defined threshold rules; and (3) interface and data-visualization testing, ensuring that all sensor data, logic status, actuator status, and trend charts were displayed correctly on the monitoring dashboard.

3. Result and discussion

3.1. System implementation

The hardware components were assembled into an integrated field-ready unit, consisting of the ESP32 control box, the soil-moisture, pH, TDS, and DHT11 sensors, and the relay-driven water-pump mechanism, installed directly at the test plot as shown in Fig. 4.



Fig. 4: Field documentation of the installed prototype system

The web dashboard provides a live monitoring view displaying air temperature, air humidity, soil moisture, and soil pH in real time together with a "System Online" status indicator, as well as a dedicated panel presenting the evaluation of each control-logic rule and the resulting actuator status, as shown in Fig. 5 and Fig. 6



Fig. 5: Live monitoring dashboard

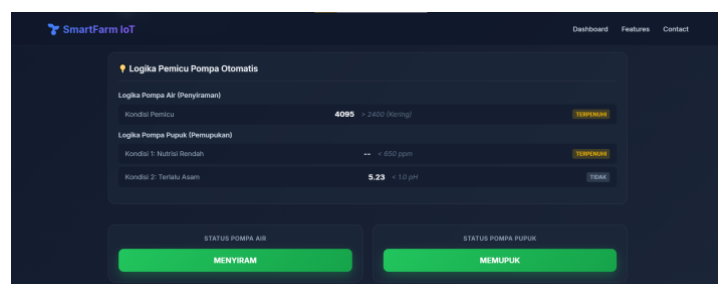


Fig. 6: Automatic control logic and actuator status panel

3.2. Sensor accuracy testing results

Validating sensor accuracy is a fundamental step to ensure the reliability of the data underlying the system's decision-making. The soil-moisture sensor validation results are summarized in Table 2.

Table 2: Soil moisture sensor accuracy validation results

Soil Condition	ADC Reading	Calculated Moisture (%)	Standard Instrument (%)	Deviation	Relative Error
Very Dry	4095	0%	2.5%	-2.5%	-
Dry	3500	25.9%	28%	-2.1%	7.50%
Moist	2650	62.9%	60%	+2.9%	4.83%
Saturated	1850	97.8%	95%	+2.8%	2.95%

As shown in Table 2, the average relative error of the soil-moisture sensor remained below 8%, indicating an acceptable level of accuracy for irrigation monitoring and control. The pH sensor accuracy testing results are summarized in Table 3.

Table 3: Soil pH sensor accuracy validation results

Test Solution Condition	IoT Sensor Reading (pH)	Standard pH Meter (pH)	Deviation	Relative Error
Acidic Soil (from dashboard)	5.23	5.40	-0.17	3.15%
Neutral Buffer Solution	6.91	7.00	-0.09	1.29%

The pH sensor testing results show a relative error below 3.2%, demonstrating very good accuracy for monitoring soil acidity conditions on the rehabilitation plot.

3.3. Automatic control logic functionality results

The functionality of the automatic control logic was validated against real-time sensor data displayed on the dashboard, with the evaluation summarized in Table 4.

Table 4: Automatic control logic evaluation

Control Logic	Trigger Condition	Real-Time Data	Evaluation	Status	Actual Result
Water Pump	Moisture > 2400 (ADC)	4095 ADC	4095 > 2400 (True)	MET	IRRIGATING
Fertilizer Pump	TDS < 650 ppm	-- (inactive)	-- < 650 (True)	MET	FERTILIZING
Fertilizer Pump	pH < 1.0	5.23	5.23 < 1.0 (False)	NOT MET	-

As shown in Table 4, the system correctly detected a soil-moisture value of 4095 ADC exceeding the 2400 threshold, activating the water pump with an "IRRIGATING" status. For the fertilizer pump, the pH condition ($5.23 < 1.0$) was correctly evaluated as not met; however, the TDS condition ($-- < 650$ ppm) was flagged as "MET" because the system interpreted the null reading from the inactive TDS sensor as a value of '0'. While this behavior is functionally consistent with the programmed OR-based logic rule, it reveals a data-handling edge case that warrants explicit null-value handling in future firmware revisions.

3.4. Interface and data visualization testing results

Testing of the dashboard user interface showed that the live monitoring view successfully displayed all sensor data in real time and accurately, with the "System Online" indicator providing visual confirmation that the system was connected and operating. The automatic pump-logic panel dynamically and correctly displayed the evaluation of each logic rule along with the final actuator status, which proved effective for debugging and monitoring. The soil-moisture and pH/TDS trend charts also successfully plotted data consistent with the dashboard readings, confirming that the historical-trend feature is functional for long-term monitoring. Overall, the user interface proved functional, informative, and responsive.

3.5. Discussion

Taken together, the testing results confirm that the SmartFarm IoT prototype operates according to its original design. The system is able to read soil conditions through three main parameters and make automated decisions based on that data without manual intervention, while all readings are rendered on the dashboard in real time. With respect to the research problems defined in Section 1: (1) an IoT system capable of monitoring soil pH and moisture in real time was successfully designed and implemented, achieving a relative error below 8% for moisture and below 3.2% for pH; (2) automatic control logic on the ESP32 was successfully implemented for both pumps, with the water-pump logic operating fully as intended and the fertilizer-pump logic operating according to its programmed rule while revealing a data-handling nuance for inactive-sensor conditions; and (3) the performance and functionality of the prototype were evaluated through sensor-accuracy and control-logic testing, both demonstrating accurate and responsive operation.

Compared with the related studies in Section 1, most prior systems focus on a single parameter and target normal agricultural land. The system developed in this study differs by integrating three parameters (moisture, pH, and TDS) simultaneously and by specifically targeting post-landfill land, which presents more extreme conditions than ordinary farmland due to simultaneous dryness and chemical degradation. This combination addresses a research gap that has received limited attention in prior IoT-based irrigation literature, namely automated monitoring and control systems designed specifically for non-mining critical-land rehabilitation.

From a practical standpoint, the tested prototype shows potential to support area managers in accelerating greening or revegetation efforts on post-landfill land while improving water and fertilizer efficiency through precision-based irrigation. Academically, this research

contributes an additional reference on the application of IoT for non-mining critical-land rehabilitation, and the identified null-value handling issue for the TDS sensor provides a useful technical note for future researchers. Limitations of the current system include its reactive (rather than predictive) threshold-based logic, the need for explicit handling of inactive sensor states, and its reliance on Wi-Fi connectivity, which may limit scalability to larger or more remote rehabilitation sites. Future development could incorporate an industrial-grade NPK nutrient sensor, machine-learning-based predictive control, a long-range low-power communication protocol such as LoRaWAN with solar-battery autonomy, and long-term field validation using a Before-After-Control-Impact (BACI) experimental design.

4. Conclusion

Based on the design, implementation, and testing process described in this study, an IoT-based irrigation and fertilization system prototype for post-landfill land rehabilitation was successfully developed by integrating an ESP32 microcontroller, environmental sensors, and pump actuators controlled through a relay module. The system is able to monitor soil parameters in real time and transmit the data to a Firebase-based dashboard for remote visualization and control. Compared with conventional manual methods, the automated system proved more effective in supporting land rehabilitation, since watering and fertilization are performed based on actual sensor data. The prototype demonstrated reasonably reliable performance, with a maximum relative error of 3.15% for the pH sensor and 7.50% for the moisture sensor under dry conditions, while the automatic control logic consistently activated the actuators whenever soil conditions crossed the defined thresholds. Future development is recommended to focus on higher-grade nutrient sensing, machine-learning-based predictive control, a more scalable and energy-autonomous communication architecture, and long-term field validation.

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