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AIoT-Based Soil Moisture Monitoring System for Precision Agriculture and Energy Efficiency in Rural Smart Villages

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ABSTRACT

Alamendah Village is a horticultural area where irrigation and energy use are still managed manually, leading to water inefficiency and unmonitored electricity consumption. This study developed an AIoT-based system using ESP32 microcontrollers and soil moisture sensors to support precision irrigation and energy monitoring. The system design included sensor calibration to convert ADC values into moisture percentages, threshold-based irrigation recommendations, and a placement formula to determine sensor deployment. Field testing in strawberry plots demonstrated that soil moisture often dropped below the 40% threshold, triggering timely irrigation alerts. The dashboard provided real-time data visualization and revealed peak electricity demand in the evening at the village hall. The results indicated that the system enhanced irrigation accuracy, provided a baseline for monitoring energy consumption, and increased community awareness of sustainable resource management. The project offers a replicable model for integrating smart agriculture and energy monitoring in rural areas.

Keywords: *Artificial Intelligence of Things (AIoT), soil moisture monitoring, ESP32, precision irrigation, energy monitoring.*

1. INTRODUCTION

Alamendah Village, located in Rancabali District, Bandung Regency, is a highland horticultural area with major commodities such as strawberries, carrots, and celery. Despite its agricultural potential, local farmers still rely on manual practices, particularly in irrigation management. Watering decisions are often based on intuition and personal experience rather than measurable soil conditions. This frequently results in over-irrigation or delayed watering, leading to water waste and suboptimal crop yields. At the same time, electricity consumption in community facilities such as the village hall and schools is not systematically monitored, making it difficult to identify opportunities for energy savings.

The emergence of Artificial Intelligence of Things (AIoT)—a combination of Internet of Things (IoT) devices and artificial intelligence (AI) analytics—provides a promising pathway to address these challenges. Soil moisture sensors connected to ESP32 microcontrollers can capture real-time data and transmit it to a digital dashboard, where AI models analyze patterns and generate irrigation recommendations. Prior studies have demonstrated that such integration of sensing and predictive analytics improves irrigation scheduling accuracy and enhances precision agriculture outcomes **(Araújo et al., 2024; Kashyap & Kumar, 2021; Sharma et al., 2021).** Similarly, IoT-based energy monitoring systems have been shown to optimize power usage and improve efficiency in both household and microgrid applications **(Hafidz et al., 2023; Tipantuña & Hesselbach, 2021).**

In Indonesia, several community-service initiatives have explored the application of IoT and AI technologies in agriculture and rural settings. Programs have introduced IoT-based systems for monitoring plant growth **(Sulistyo, 2023)**, soil moisture and pH in corn farming **(Multazam, 2025),** and solar-powered smart irrigation that activates only when moisture thresholds are unmet **(Waluyo, 2025).** Other projects have provided training for school communities and farmer groups to design and use IoT-based monitoring systems **(Indrawati, 2024; Nasution, 2024)**, and to detect agricultural pests through simple IoT deterrents (Retno, 2024). Experiments with irrigation controllers built on ESP32 modules **(Putra, 2024),** greenhouse monitoring for melon crops **(Fadlillah & Kamaluddin, 2025)**, and IoT-enabled hydroponic systems **(Hidayat, 2024)** further confirm the adaptability of such solutions to rural contexts. Even low-cost innovations such as 3D-printed irrigation controllers **(Rahman, 2025)** demonstrate that local creativity can support sustainability and replication.

This study builds upon those findings by developing an AIoT-based soil moisture monitoring and energy efficiency system tailored for Alamendah Village. The contributions are threefold: (1) the design of a low-cost sensing and analytics stack using soil moisture sensors and ESP32 microcontrollers to support precise irrigation; (2) integration of energy monitoring in community facilities to promote electricity conservation; and (3) the establishment of a community-driven sustainability model through a local Technology Team to ensure continuity and replication.

2. METHOD

2.1 System Design

The system consists of soil moisture sensors connected to an ESP32 microcontroller, powered by a battery pack. Each sensor measures the electrical resistance of the soil, which decreases as the water content increases. The ESP32 converts this signal into a digital value and transmits the data to a web-based dashboard via Wi-Fi. Farmers can then view real-time soil moisture conditions and receive irrigation recommendations.

Figure 1 shows the prototype wiring of the system. The AA battery pack supplies power to the ESP32 through the VIN pin, while the ground is connected to GND. The soil moisture sensor is connected to the ESP32 using three lines: VCC, GND, and the signal pin. This prototype demonstrates a simple and portable configuration that can be easily installed in the field.

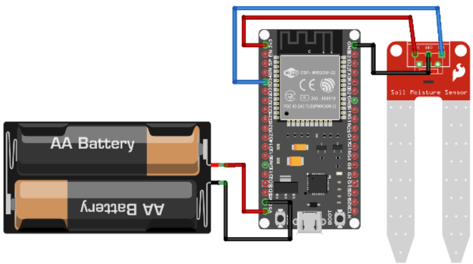

Figure 1. Prototype Wiring of ESP32 with Soil Sensor

Figure 2 presents the schematic diagram of the circuit. The soil moisture sensor's signal (SIG) pin is connected to one of the analog input pins of the ESP32 (e.g., GPIO34). The VCC pin of the sensor is powered by the ESP32's 3.3 V or 5 V output, while the GND is shared. The schematic emphasizes the proper mapping of each pin to ensure reliable operation and provides a clear guide for replication by local communities.

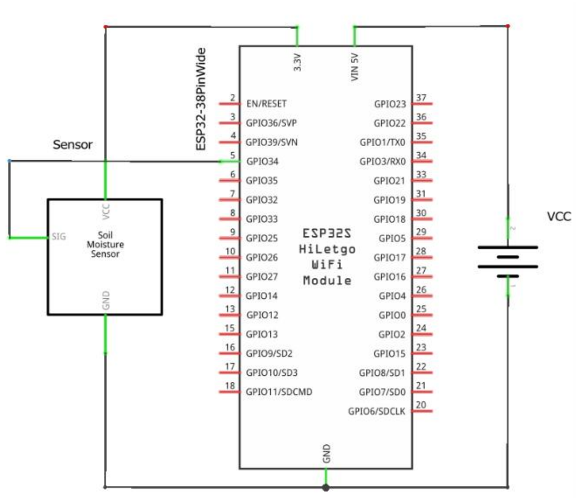

Figure 2. ESP32 Schematic Connection Diagram

2.2 Sensor Calibration Formula

Calibration is performed by recording the sensor readings in two reference conditions: dry soil (ADC_{dry}) and saturated soil (ADC_{wet}). The soil moisture percentage is then calculated using the *sensor calibration formula* as indicated in (1).

$$M = \frac{ADC_{dry} - ADC_{Current}}{ADC_{dry} - ADC_{wet}} x100\% \tag{1}$$

Where $ADC_{current}$ is the ADC value measured in the field, ADC_{dry} is ADC reading in dry soil condition, and ADC_{wet} is ADC reading in saturated soil condition. This formula produces a soil moisture percentage (MMM) ranging from 0% (very dry) to 100% (fully saturated).

2.3 Irrigation Threshold

For practical use, the system determines an irrigation threshold value (M_{thr}) according to the crop type. When the measured soil moisture (M) falls below this threshold, the system will recommend or trigger irrigation automatically. The relationship between measured soil moisture and the irrigation decision is represented in (2).

$$If\ M < M_{thr} => Irrigate \tag{2}$$

This threshold-based approach ensures that irrigation is only conducted when soil moisture reaches critical levels, improving water use efficiency.

2.4 Sensor Placement Formula

To estimate the number of sensors required for a given agricultural plot, the relationship between total land area and coverage per sensor is expressed by the sensor placement formula as indicated in (3).

$$N_s = \frac{A}{A_C} \tag{3}$$

Where N_s is number of sensors, A is total land area (m²), and A_c is coverage area per sensor (m²), typically 100–150 m² depending on soil uniformity. This ensures that soil moisture conditions are represented adequately across the entire plot.

2.5 Energy Monitoring

In addition to soil moisture measurement, the ESP32 module is connected to a simple energy monitoring system for public facilities (e.g., the village hall or school). The total energy consumption is determined by multiplying the measured power by the duration of use, as shown in the *energy monitoring formula* in (4).

$$E = P\ x\ t \tag{4}$$

where $E$is the total energy consumption (kWh), $P$is the measured power (W), and $t$is the usage time (hours). This helps the community identify peak consumption periods and potential energy savings opportunities.

3. RESULTS AND DISCUSSION

The AIoT-based soil moisture monitoring and energy efficiency system was successfully implemented in Alamendah Village, Rancabali District. The deployment began with the official handover of the devices to the Head of Village, which symbolized institutional support and community commitment to digital innovation in agriculture. This moment was important in ensuring that the system would not only be tested technically but also embedded within local governance and community practice.

Figure 3 shows the handover ceremony, where the research team formally transferred the prototype devices to the village leadership, marking the start of community-based implementation. The prototype hardware was built using an ESP32 microcontroller, a soil moisture sensor, and a battery pack, designed to be portable and low cost. Its simplicity made it suitable for replication by local farmers with minimal training. During testing, the device functioned reliably in outdoor environments, successfully transmitting real-time soil moisture data to the dashboard without interruption. As presented in Figure 4, the hardware unit was compact and neatly assembled, demonstrating how the ESP32 served as the core controller with the sensor module attached for field measurements.

Figure 3. Handover of Device to Head of Village

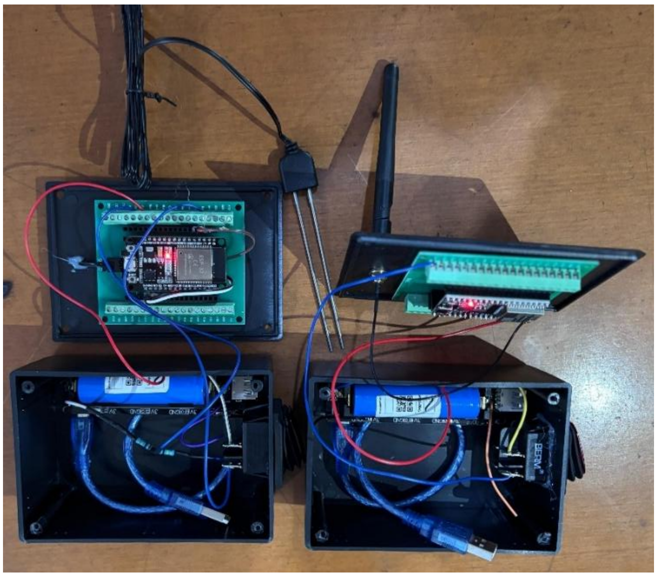

Figure 4. Assembled Hardware Prototype

Field installation was carried out on three horticultural plots planted with strawberries, carrots, and celery. Each plot was equipped with two sensors to capture variations in soil condition, with probes placed at a depth of 10–15 cm in the root zone to ensure accurate representation of plant water availability. Figure 5 illustrates the actual field installation, where the sensors were embedded in the soil while the ESP32 unit was protected within a simple waterproof casing. Continuous monitoring over a period of seven days, with measurements every ten minutes, revealed distinct differences between crops. Moisture levels in strawberry and celery plots often fell below the 40% threshold during midday, prompting irrigation recommendations, while carrot plots maintained relatively higher levels, reducing the need for frequent watering. These findings confirm that threshold-based irrigation strategies tailored to specific crops can effectively optimize water usage.

Figure 5 Field Installation in Strawberry Plot

Beyond technical results, community engagement played a central role in sustaining the system. Local youth were trained as part of a Village Technology Team to calibrate sensors, maintain the devices, and manage dashboard operations. Farmers reported that the system was straightforward to use and immediately beneficial for their cultivation practices. The active involvement of the village government ensured policy-level support and opened opportunities to expand the system to additional plots and public facilities.

Taken together, these results demonstrate that a low-cost AIoT system combining soil moisture monitoring with energy usage tracking can provide tangible benefits for rural communities. Water was applied more efficiently, electricity consumption patterns became visible for the first time, and local capacity for digital technology was strengthened. Unlike implementations confined to laboratory settings, this project showed how sensor-based agriculture and energy monitoring can be successfully introduced in a real village context, supported by strong community ownership.

The system was deployed in strawberry plots at Alamendah Village. Calibration was carried out using dry soil and saturated soil as reference points, following the formula described in the Methods. The calibration results, including the average ADC readings, calculated moisture percentage, and irrigation threshold, are summarized in Table 1. The data show that during peak daytime hours, average soil moisture values dropped below the 40% threshold, indicating the need for irrigation.

Table 1. Calibration Results and Irrigation Threshold for Strawberry Plot

Crop	ADC_{dry}	ADC_{wet}	Average Field ADC	Moisture (%)	Threshold (M_{thr})	Irrigation Triggered
Strawberry	3850	1400	3100	37%	40%	Yes

Calibration was conducted before field deployment to ensure accurate sensor readings. The process took place in a 200 m² strawberry plot consisting of three planting beds at Alamendah Village. Two sensors were positioned 10–15 cm deep to represent the plant root zone. The ADC_{dry}value (3850) was obtained after air-drying soil samples for 48 hours, while the ADC_{wet}value (1400) was recorded after saturating the same soil until field capacity. Field data were collected continuously for seven days with readings taken every ten minutes. During peak daytime hours, the average field ADC was 3100, corresponding to 37% soil moisture below the 40% threshold—thus triggering an irrigation recommendation as shown in Table 1.

The distribution and number of sensors used in the strawberry plot were determined using the placement formula (3). The deployment details, including total area, sensor coverage, and number of sensors installed, are presented in Table 2.

Table 2. Sensor Deployment for Strawberry Plot

Crop	**Area (m²)**	**Coverage per Sensor (m²)**	**Number of Sensors (N_s)**
Strawberry	200	100	2

As shown in Table 2, with a plot size of 200 m² and an effective coverage of 100 m² per sensor, two sensors were installed to adequately represent the soil condition across the strawberry field.

In addition to irrigation monitoring, the system also recorded daily energy usage in the village hall as a baseline for future energy efficiency analysis. The energy monitoring results are summarized in Table 3, showing the average power, duration, and calculated energy consumption across different times of day.

Table 3. Daily Energy Consumption at Village Hall

Time of Day	**Average Power (W)**	**Duration (h)**	**Energy Consumption (kWh)**
Morning	120	4	0.48
Afternoon	150	5	0.75
Evening	300	6	1.80
Total	–	–	**3.03**

As indicated in Table 3, the highest electricity usage occurred during the evening period, primarily due to lighting and electronic device operation. While direct efficiency improvements were not yet measured, this monitoring activity provided valuable insights for the community regarding energy consumption behavior and potential savings opportunities. The recorded data established an initial benchmark that can later be used for comparative analysis once energy-saving measures are implemented.

4. CONCLUSIONS

This study demonstrated the successful development and deployment of an AIoT-based soil moisture monitoring and energy monitoring system in Alamendah Village, where ESP32 microcontrollers and soil sensors provided real-time irrigation recommendations while power measurement modules recorded electricity usage patterns in community facilities. The results confirmed that the system improved irrigation accuracy and provided a clear baseline for monitoring daily electricity consumption. Although direct comparison data to quantify energy efficiency improvement were not yet available, the monitoring results offered new awareness and insights into energy-saving opportunities at the village level. The project also empowered local youth through the Village Technology Team and received strong support from the village government, forming a sustainable foundation for future development. Further research will focus on extending sensor integration, comparing pre- and post-deployment energy data, and scaling the system to larger agricultural and community contexts.

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