



Internet of Things (IoT) Soil Moisture Monitoring System for Automated Precision Irrigation

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Abstract—Water availability is one of the important factors affecting the growth of oil palm seedlings, especially during the pre-nursery phase, where the root system is still shallow and sensitive to changes in soil moisture. Manual irrigation practices often result in inaccurate water distribution, which may cause either water deficiency or excess in the growing media. This study aims to design and implement an Internet of Things (IoT)-based soil moisture monitoring and automatic precision irrigation system for oil palm seedlings. The developed system utilizes a soil moisture sensor for detecting soil moisture levels, an ESP32 microcontroller as the main controller, a relay module for controlling the water pump, and an LCD display with cloud monitoring for real-time data visualization. The sensor is installed at a depth of 5–10 cm according to the root zone of the seedlings. The system is configured with moisture parameters where the pump is activated when the soil moisture value is below 40% and stops when the moisture reaches 60–70%. The testing results indicate that the system is capable of performing automatic monitoring and irrigation in a responsive manner with good accuracy. This system is expected to improve water use efficiency and support the optimal growth of oil palm seedlings.

Keywords: IoT, ESP32, Sensor, Nursery, Irrigation

1. INTRODUCTION

Oil palm (*Elaeis guineensis*) is a strategic plantation commodity that contributes significantly to Indonesia's agribusiness sector and national economy. As one of the world's largest palm oil producers, Indonesia continuously strives to enhance plantation productivity and produce quality through the application of technology across various cultivation stages [1]. A critical stage determining crop productivity is the nursery phase. During this phase, seedlings undergo early growth—including the development of root systems, stems, and leaves—which dictates the plant's adaptability upon transplantation to the main field [2]. High-quality seedlings lead to optimal plant growth, resilience against environmental stressors, and greater productivity potential during the production stage. Consequently, seedling management during the nursery phase is a crucial factor in ensuring the success of oil palm cultivation [3].

One of the primary factors significantly influencing oil palm seedling growth is water availability in the growing medium. Water plays a crucial role in various plant physiological processes, such as nutrient uptake, photosynthesis, nutrient transport, cell division, and the maintenance of turgor pressure in plant tissues [4]. Water availability that does not meet the plant's requirements can negatively impact seedling growth [5]. Water deficiency can lead to drought stress, a reduction in the photosynthetic rate, and inhibited root and leaf growth. Conversely, excess water can cause the growing medium to become oversaturated, thereby reducing oxygen availability in the soil and hindering root system development [6]. Therefore, irrigation management that is appropriate and tailored to the plant's needs is a vital aspect of the oil palm nursery process [7].

In field nursery operations, the watering of oil palm seedlings is still largely performed manually by workers. Manual watering methods have several limitations, such as inconsistent water application, reliance on human operators, and a lack of information regarding actual soil moisture levels [8]. These conditions can lead to either over-irrigation or under-irrigation, ultimately resulting in water wastage and reduced seedling growth quality [9]. Furthermore, the growing need for efficiency in the modern agricultural sector drives the demand for systems capable of monitoring growing medium conditions and controlling irrigation automatically and accurately [10].

The advancement of Internet of Things (IoT) technology offers significant opportunities for the development of smart agriculture systems [11]. IoT technology enables various electronic devices to interconnect





via the internet, allowing for real-time data acquisition, monitoring, information processing, and device control. In the agricultural sector, IoT technology is widely used to monitor various environmental parameters, such as temperature, air humidity, light intensity, water quality, and soil moisture. Implementing IoT technology in irrigation systems allows watering to be performed based on the actual conditions of the growing medium, thereby enhancing water use efficiency and more optimally meeting the plants' needs [12].

Soil moisture is a key parameter in precision irrigation systems. Soil moisture levels can be measured using sensors capable of directly detecting the water content within the growing medium. Data from the sensor readings is transmitted to a microcontroller for processing and serves as the basis for decisions regarding the activation or deactivation of the watering system [13]. This study utilizes the ESP32 microcontroller, which offers robust data processing capabilities and relatively low power consumption, while also featuring built-in Wi-Fi connectivity that supports IoT-based system implementation. Furthermore, the ESP32 offers high flexibility for integration with various sensors and actuators, making it well-suited for the development of automated monitoring and irrigation systems [14].

Several previous studies have developed IoT-based soil moisture monitoring and automatic irrigation systems for various types of plants. Research findings indicate that the use of soil moisture sensors combined with automatic control systems can improve water use efficiency, reduce reliance on manual labor, and enhance irrigation accuracy [15]. However, most prior research has focused on horticultural crops, food crops, or ornamental plants, whereas the application of similar systems in oil palm nurseries remains relatively limited [16]. Furthermore, few studies have specifically considered parameters such as sensor placement depth, irrigation water volume, and the specific moisture requirements of oil palm seedlings during the pre-nursery phase. These conditions present an opportunity to develop a system tailored to the specific growth characteristics of oil palm seedlings [17].

To address these issues, this study proposes a solution involving the development of an Internet of Things (IoT)-based system for soil moisture monitoring and automated precision irrigation for oil palm seedlings in the pre-nursery phase [18]. The developed system utilizes a soil moisture sensor to detect moisture levels, an ESP32 microcontroller for data processing, a relay to control the actuator, and a water pump for automated irrigation [19]. Sensor readings are displayed in real-time via an LCD screen and a cloud-based monitoring system, enabling users to monitor soil moisture conditions at any time. The sensor is positioned at a depth of 5–10 cm—aligning with the seedling's root zone—to ensure the data accurately reflects the actual condition of the growing medium. The novelty of this research lies in the integration of real-time monitoring, the establishment of specific moisture thresholds for oil palm seedlings, and the optimization of sensor placement within the root zone to enhance the accuracy of irrigation decision-making [20].

This study aims to develop an IoT-based soil moisture monitoring and automatic irrigation system for oil palm seedlings in the pre-nursery phase to enhance watering efficiency, monitor soil conditions in real-time, and support optimal seedling growth. The system is designed to irrigate based on the plants' water requirements—utilizing precise sensor placement and moisture thresholds—thereby reducing reliance on manual labor and improving irrigation control accuracy. Implementation of this system is expected to ensure more accurate and efficient watering tailored to the plants' needs, ultimately fostering optimal oil palm seedling growth.

2. RESEARCH METHODOLOGY

2.1 Research Stages

This study employs a prototyping method with an experimental approach to design and implement an Internet of Things (IoT)-based soil moisture monitoring and automated precision irrigation system for oil palm (*Elaeis guineensis*) seedlings in the pre-nursery phase. The prototyping method was selected because it enables a systematic, phased development process—encompassing requirements identification, design, implementation, testing, and evaluation—thereby ensuring the system aligns with user needs and actual environmental conditions.

The research began with problem identification through direct observation at an oil palm nursery. These observations aimed to gather data on growing media conditions, existing watering practices, and soil moisture levels during the seedlings' early growth stage. The findings revealed that watering was performed manually, leading to potential inconsistencies in water application, labor inefficiency, and an inability to maintain optimal soil moisture levels. Based on these findings, a literature review was conducted—drawing on scientific journals published over the last five years regarding soil moisture monitoring systems, soil moisture sensors, IoT-based data communication, and automated irrigation control systems—to serve as the foundation for the system design [21].



The next stage is system design, encompassing both hardware and software components. This phase involves creating the system block diagram, designing the electronic circuitry, and developing the automatic watering control algorithm. The system utilizes a soil moisture sensor as the input device to detect moisture levels, an ESP32 for data processing and network communication, a relay module to control the actuator, and a DC water pump for automatic watering. All components are designed to operate in an integrated manner, supporting real-time monitoring and watering control processes.

Following the design phase, the prototype implementation stage is carried out by assembling all components according to the established design. Subsequently, programming is performed using the Arduino IDE to enable the system to read sensor data, process soil moisture readings, transmit data to the cloud, and automatically activate or deactivate the water pump based on predefined threshold values. The final stage of the research involves system testing, covering sensor accuracy, water volume measurement, time delay analysis, and data communication stability. Tests are conducted repeatedly to obtain consistent and valid data, allowing for a comprehensive evaluation of system performance [22]. The sequence of research stages is illustrated in Figure 1.

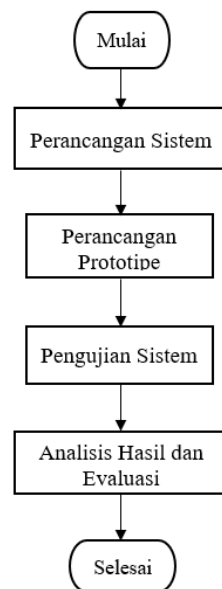


Figure 1. Research Stages

Figure 1 illustrates that this research was conducted in six stages: the initial stage, system design, prototype construction, system testing, analysis and evaluation, and the final stage. The initial stage involved defining the research objectives and scope, focusing on IoT-based soil moisture monitoring and automatic watering. Subsequently, the system was designed by determining the components, workflow, and data processing methods to be employed. A prototype was then constructed through hardware assembly, ESP32 programming, and the integration of sensors, relays, and a pump. The completed system underwent testing to evaluate its soil moisture reading capabilities and automatic watering response. The test results were then analyzed and evaluated to assess the system's performance and identify any shortcomings. Upon completion of all stages, the system was deemed ready for use and suitable for further development.

2.2 Tools and Materials

The equipment used in this study comprises both hardware and software components. The hardware includes an ESP32 as the central data processor, a soil moisture sensor for detecting soil moisture levels, a relay as an actuator control module, a DC water pump for automatic watering, a 16×2 LCD for local display, an 18.650 lithium battery as the power source, and an external charger for power replenishment. The software utilized includes the Arduino IDE for microcontroller programming and a cloud platform for real-time data monitoring [23].

Table 1. System Component Specifications

No	Komponen	Spesifikasi	Fungsi
1	ESP32	Wi-Fi, 240 MHz	Pengolah Data
2	Soil Moisture Sensor	Analog	Sensor Kelembaban

3	Relay	5V	Pengendali Pompa
4	Pompa Air DC	5V	Penyiraman Otomatis
5	LCD	16×2	Tampilan Lokal
6	Baterai 18650	3.7V	Sumber Daya
7	Charger External	USB	Pengisian Daya

Based on Table 1, the developed system utilizes several key components: an ESP32 for data processing, a soil moisture sensor to monitor soil conditions, a relay to control the pump, and a DC pump for automatic watering. A 16×2 LCD serves as the local display, while an 18650 battery acts as the power source, and an external USB charger is used to charge the battery.

2.3 System Design

The system design outlines the relationships between the hardware and software components used in the research. The system incorporates a soil moisture sensor as the input device to detect soil moisture levels, an ESP32 as the data processing unit, a relay as the actuator control module, a DC water pump for automated watering, and an LCD for local display. Additionally, sensor readings are transmitted to a cloud system via Wi-Fi, enabling real-time monitoring. The system circuit schematic is shown in Figure 2.

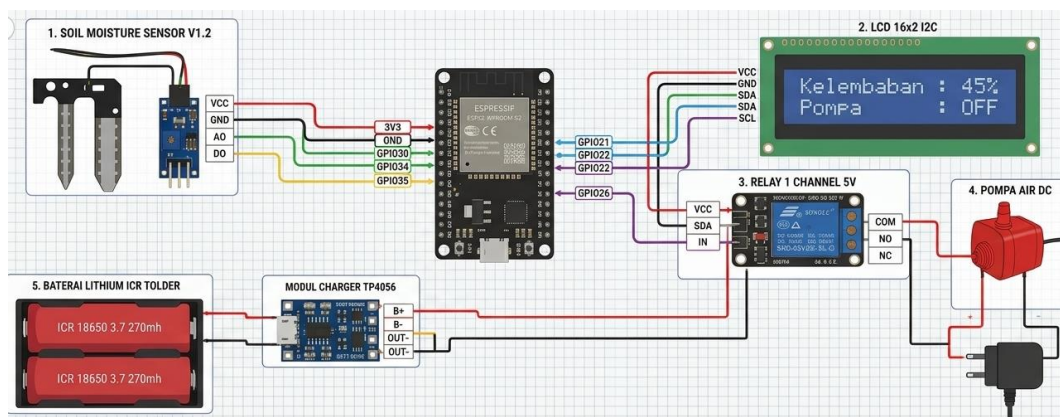


Figure 2. Device Circuit Diagram

Figure 2 illustrates the relationships between the system components, where the soil moisture sensor reads the soil moisture level and transmits the data to the ESP32 for processing. The ESP32 then compares the moisture value against a predefined threshold [24]. If the moisture level falls below the minimum limit, the ESP32 activates the relay to turn on the water pump. Conversely, once the moisture level reaches the optimum condition, the pump stops automatically. The system's logical workflow is depicted in the flowchart shown in Figure 3.

Figure 3 illustrates the system's operational process, beginning with device initialization, the reading of soil moisture sensor data, and data transmission to the cloud system. Subsequently, the ESP32 makes a decision based on a pre-determined moisture threshold. If the moisture level falls below the minimum limit, the relay activates, automatically turning on the pump. Conversely, if the soil moisture is at an optimal level, the pump remains inactive. This process repeats continuously, enabling real-time, ongoing monitoring and watering [25].

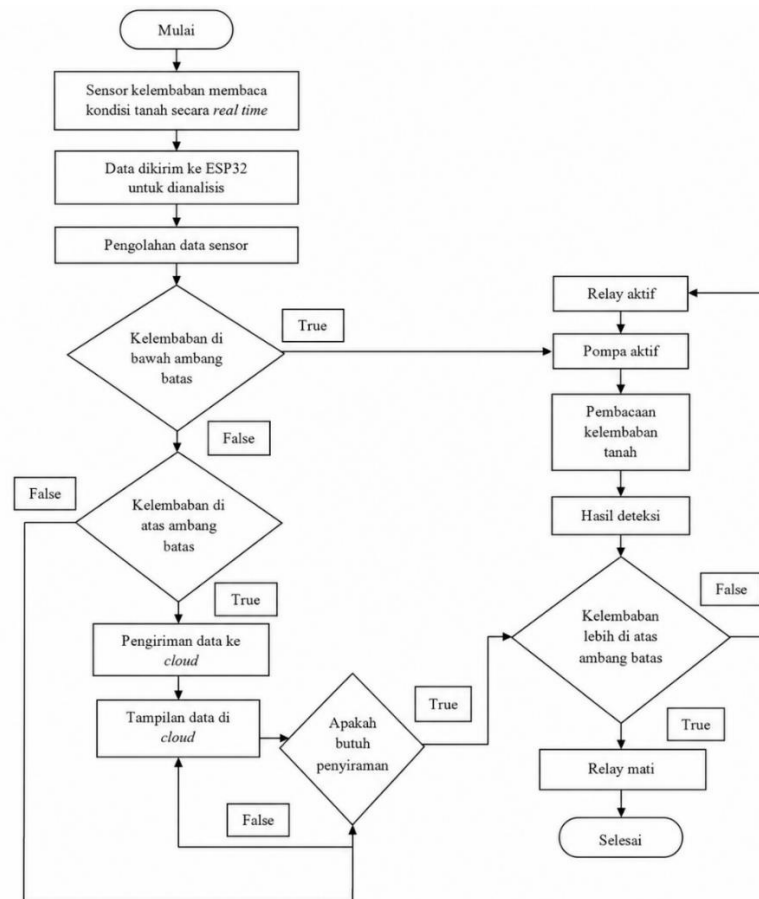


Figure 3. Flowchart of the Automatic Monitoring and Watering System

2.4 System Implementation and Testing

The implementation phase involves assembling all components based on the established system design. Once assembly is complete, the hardware and software are integrated through programming using the Arduino IDE. The system is then connected to a Wi-Fi network to enable real-time monitoring of soil moisture data via a cloud platform.

System testing is conducted based on several parameters, namely:

1. Sensor accuracy testing
Conducted by comparing sensor readings under dry, moist, and wet soil conditions.
2. Water volume testing
Conducted by measuring the amount of water discharged by the pump using a graduated cylinder in milliliters (mL).
3. Delay testing
Conducted by measuring the time interval between the sensor detecting a change in moisture and the pump activating [2].
4. Data communication testing
Conducted to assess the stability of real-time data transmission from the ESP32 to the cloud system.

2.5 Data Analysis

The test data were analyzed using a quantitative descriptive approach to evaluate the system's overall performance. The parameters analyzed included sensor accuracy, water volume stability, time delay, and data transmission consistency. The system was deemed successful if it could monitor soil moisture in real-time, automatically activate the pump based on predefined parameters, and maintain the growing medium's moisture at optimal levels for oil palm seedling growth [26].

3. RESULT AND DISCUSSION

3.1 System Implementation

The implementation phase involved assembling all hardware components according to the system design—comprising an ESP32, soil moisture sensor, relay, DC water pump, 16×2 LCD, 18650 lithium battery, and external charger. These components were integrated via programming in the Arduino IDE, enabling the system to read soil moisture levels, display data locally on the LCD, and transmit data to Blynk in real-time.

Implementation results demonstrate that the system operates as designed. The soil moisture sensor continuously monitors moisture levels, and the data is processed by the ESP32 to automatically determine watering status based on a predefined threshold. In this study, the sensor was positioned at a depth of 5–10 cm—corresponding to the root zone of pre-nursery oil palm seedlings—thereby ensuring the data obtained was more representative of the actual conditions of the growing medium [27]. The component assembly is illustrated in Figure 4.



Figure 4. Apparatus Setup

Figure 4 shows the developed circuit assembly, comprising an ESP32, a soil moisture sensor, a relay, a DC water pump, and a 16×2 LCD connected within a single system. The sensor measures the soil moisture level and transmits the data to the ESP32 for processing. Based on the obtained moisture value, the ESP32 controls the relay to automatically activate or deactivate the pump. The moisture value and system status are displayed on the LCD, while an 18650 battery serves as the power source for the circuit.



Figure 5. System Implementation

Figure 5 illustrates the system implementation, which integrates an ESP32, a soil moisture sensor, a relay, a DC water pump, and a 16×2 LCD. The sensor measures soil moisture levels and transmits the data to the ESP32 for processing against a predefined threshold. If the soil moisture falls below the set limit, the ESP32 activates the

relay, turning on the pump to perform automatic watering. Reading results and system status are displayed on the LCD, allowing for real-time monitoring of the watering process.

3.2 Soil Moisture Sensor Testing

Soil moisture sensor testing was conducted to evaluate the sensor's ability to measure soil moisture levels under dry, moist, and wet conditions. Five test repetitions were performed for each condition to ensure stable and consistent data. The test results are presented in Table 2.

Table 2. Soil Moisture Sensor Testing

No	Kondisi Tanah	Nilai Sensor (%)	Status
1	Kering	28	Pompa ON
2	Kering	30	Pompa ON
3	Lembap	58	Standby
4	Basah	78	Pompa OFF
5	Basah	80	Pompa OFF

Based on Table 2, the soil moisture sensor effectively detects changes in soil moisture. Under dry soil conditions with moisture levels below 40%, the system automatically activates the water pump. At moisture levels between 40% and 70%, the system remains in standby mode, whereas at levels above 70%, the pump is inactive. These results demonstrate that the sensor is capable of providing an appropriate response to changes in the moisture content of the growing medium [28].

3.3 Water Volume Testing

Water volume testing was conducted to determine the pump's consistency in distributing water during the automatic watering process. Measurements were taken using a graduated cylinder in milliliters (mL), with five repetitions performed. The results of the water volume test are presented in Table 3.

Table 3. Water Volume Testing

No	Pengujian	Target (mL)	Hasil (mL)
1	Uji 1	250	248
2	Uji 2	250	252
3	Uji 3	250	249
4	Uji 4	250	251
5	Uji 5	250	250

Based on Table 3, the volume of water discharged by the system shows relatively stable results, with only minor deviations from the target. This indicates that the automatic watering system is capable of distributing water consistently and in accordance with the needs of the oil palm seedlings [29].

3.4 System Delay Testing

Delay testing was conducted to determine the system's response time from the moment the sensor detected a change in soil moisture until the water pump activated. The test was repeated five times. The results of the delay test are presented in Table 4.

Table 4. System Delay Testing

No	Pengujian	Delay (ms)
1	Uji 1	925
2	Uji 2	948
3	Uji 3	932
4	Uji 4	955
5	Uji 5	940

Based on Table 4, the system exhibits a sufficiently fast response in making decisions and automatically activating the pump.

3.5 Real-Time Data Monitoring

Monitoring tests were conducted to evaluate the ESP32 microcontroller's ability to read, process, and transmit soil moisture data to a cloud system in real-time. In this study, the monitoring application was developed using Android Studio for the Android operating system, while the Blynk platform served as the cloud service providing authentication tokens, an Application Programming Interface (API), and the data communication medium between the hardware and the application. This integration enabled sensor data to be transmitted, stored, and displayed on the application in real-time.

Test results demonstrated that soil moisture sensor readings could be displayed consistently on both the device's onboard LCD and the developed Android application. Data transmission from the ESP32 to the Blynk server—and subsequently to the Android application via the API—proceeded smoothly without significant communication interruptions, allowing users to monitor soil moisture levels remotely [30].

The developed system is designed to operate in two modes: automatic and manual. In automatic mode, the water pump activates automatically when the soil moisture level drops below 40%, indicating that the growing medium is dry. Conversely, the pump stops automatically when the moisture level reaches 80% or higher, indicating that the growing medium is sufficiently moist and the plant's water requirements have been met.

In manual mode, the watering process can be directly controlled by the user via ON/OFF buttons available in the Android application. This mode offers the flexibility to activate or deactivate the pump as needed—particularly during system testing, calibration, or specific situations requiring direct control.

The Android application interface displays information such as soil moisture levels (in percent), the choice between manual and automatic operating modes, and the watering status indicator (ON or OFF). Test results demonstrate that the monitoring process operates in real-time, responsively, and stably, enabling users to monitor the condition of oil palm seedlings more effectively and flexibly [31]. The system monitoring results are shown in Figure 6.

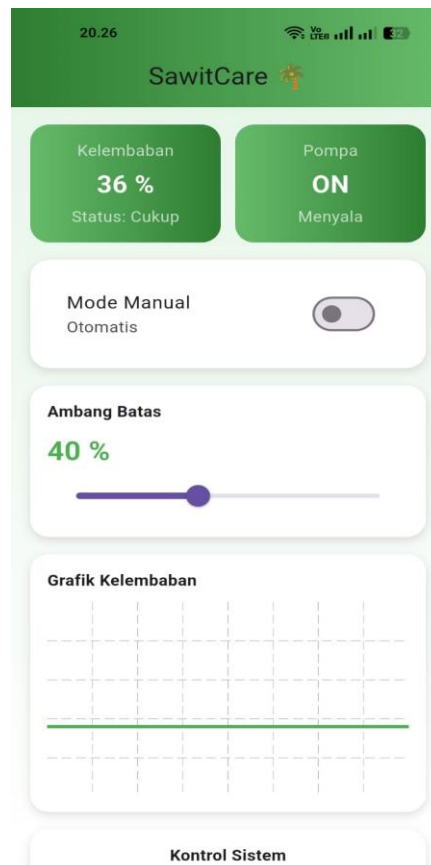


Figure 6. Display on the Blynk App

Figure 6 shows the SawitCare application interface, displaying key information such as soil moisture levels, pump status, operating mode, and moisture thresholds. The application also provides moisture graphs to monitor



changes in soil conditions, as well as system control features to support both automatic and manual irrigation management.

4. CONCLUSION

This study successfully designed and implemented an automated, Internet of Things (IoT)-based precision irrigation system for monitoring soil moisture in oil palm (*Elaeis guineensis*) seedlings during the pre-nursery phase. Developed using soil moisture sensors, an ESP32 microcontroller, relays, and a water pump, the system is capable of real-time soil moisture monitoring and executing automated watering based on pre-set moisture thresholds. Testing results demonstrate that the soil moisture sensor effectively detects changes in soil moisture across various growing media conditions, allowing the system to trigger automatic watering tailored to the seedlings' needs. Furthermore, water volume tests indicate stable and consistent distribution, while response time (latency) tests show the system performs efficiently in decision-making and pump activation. Monitoring data is successfully displayed locally via an LCD and transmitted to the Blynk platform in real-time, enabling more effective and flexible monitoring. Overall, the developed system enhances watering efficiency, maintains stable growing medium moisture, reduces reliance on manual watering, and supports the adoption of precision agriculture technology in oil palm seedling production. Consequently, the system holds significant potential for implementation and further development within the digital-technology-driven plantation sector.

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