International Journal of Basic and Applied Sciences, 14 (5) (2025) 549-557

International Journal of Basic and Applied Sciences

Website: www.sciencepubco.com/index.php/IJBAS
https://doi.org/10.14419/8q6dkz10
Research paper

Advancing Sustainable Agriculture in Palm Oil Production: The Role of IoT-Based Soil Monitoring

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Received: July 1, 2025, Accepted: August 25, 2025, Published: September 16, 2025

Abstract

Palm oil plantations are a critical component of Malaysia's economy, being the second-largest global producer and a major exporter. The increasing demand for palm oil necessitates sustainable practices to ensure both quality and environmental stewardship. Soil quality is a pivotal factor in producing high-quality palm oil. This paper presents the development of an advanced Internet of Things (IoT)-based soil monitoring system tailored for palm oil plantations. The system leverages IoT technology to monitor and collect soil moisture data remotely, utilizing moisture sensors, LoRa transmitters, and the ESP32 microcontroller to execute commands and decisions. This innovative approach not only enhances production efficiency but also significantly reduces plantation management costs. By providing real-time soil data, this system empowers farmers to make informed decisions, thereby promoting sustainable agricultural practices and optimizing resource use.

Keywords: *Internet of Things (IoT); Responsible Consumption; Palm Oil Plantations; Process Innovation; Soil Moisture Sensors; Sustainable Agriculture.*

1. Introduction

The palm oil industry is a cornerstone of Malaysia's economy, producing high-quality oil valued for its heat resistance, balanced composition, and natural trans-fat- and cholesterol-free properties. Rich in essential fatty acids, carotenoids, and vitamin E, palm oil provides critical fat-soluble micronutrients and significant caloric energy [1]. Beyond cooking uses, palm oil and its derivatives are widely applied in margarine, detergents, cosmetics, and, more recently, as a biofuel feedstock [2] [3]. Extracted from the mesocarp of the oil palm fruit, crude palm oil is distinguished by its bright orange-red colour.

Oil palms, originally from West Africa, were introduced to Malaysia in the 1870s for ornamental purposes. The first commercial planting in 1917 at Tennamaram Estate (now Bestari Jaya, Selangor) marked the start of industrial-scale cultivation [4]. By the late 20th century, oil palm surpassed rubber as Malaysia's main commodity crop. The Tenera variety—an interspecific hybrid—remains the most cultivated due to its high yield of both palm and kernel oil. For optimal growth, oil palms require approximately 2000 mm of evenly distributed annual rainfall. Consequently, effective water management is essential for preventing soil degradation and ensuring long-term productivity [5 - 7].

Recent advances in technology, particularly real-time soil monitoring, have become pivotal in supporting sustainable palm oil cultivation. Internet of Things (IoT)-based systems, such as Arduino-enabled soil moisture sensors, allow continuous monitoring of field conditions and facilitate data-driven decision-making [6] [8] [9]. These tools can improve irrigation efficiency, optimise resource use, and reduce environmental impact. However, current market solutions often face limitations: high costs, complex multi-parameter setups, limited sampling volumes, and reduced sensor accuracy in certain soil textures.

Applied studies in tropical agriculture show growing adoption of low-cost IoT systems, yet most integrate multiple sensors and advanced analytics, which increase financial and technical barriers for small and medium-scale plantations [10], [11]. LoRa (Long Range) technology is frequently used for its low-power, long-distance communication, though performance can be affected by orchard vegetation and terrain, causing signal attenuation and packet loss [12]. Comparisons of low-cost resistive and capacitive soil moisture sensors also highlight the need for calibration to address accuracy variations across soil types [13]. Energy efficiency strategies, including adaptive transmission intervals and latching solenoid valves, are recommended to reduce field maintenance requirements [14]

Despite these developments, there is limited focus on simple, single-parameter monitoring systems that are affordable, easy to deploy, and tailored to the operational realities of resource-limited plantations. Our prototype addresses this gap by using LoRa-enabled ESP32 boards and a soil moisture sensor to provide actionable irrigation data without the added cost, maintenance, and expertise required for multi-sensor or analytics-heavy platforms.

1.1. Problem Statement

Maintaining optimal soil moisture is critical to sustaining oil palm yields and supporting environmentally responsible cultivation. Manual inspection methods are labour-intensive, prone to human error, and lack the consistency required for precise water management. As a result, plantations risk inefficient resource use, reduced crop performance, and long-term soil degradation.

Real-time soil monitoring offers a practical solution by enabling continuous, accurate measurement of moisture levels. This information, transmitted via low-power long-range communication protocols such as LoRa, allows plantation managers to make timely irrigation decisions, optimise water use, and prevent over- or under-watering. Unlike multi-parameter systems that require significant investment and technical expertise, our approach focuses on a cost-effective, single-parameter prototype designed to be accessible, easy to maintain, and adaptable for small- to medium-scale operations.

By targeting only the most critical parameter for oil palm irrigation soil moisture this system demonstrates how affordable IoT technology can bridge the gap between traditional farming practices and precision agriculture, ultimately contributing to sustainable infrastructure and improved resource management in palm oil plantations.

1.2. Objectives

a) Design and develop an IoT-based soil monitoring system using Arduino, incorporating appropriate sensors to enhance soil quality management and promote sustainable agricultural practices in palm oil plantations.

b) Implement a remote monitoring system that leverages IoT technology to facilitate real-time soil data collection, enabling improved resource management and sustainability in large-scale agricultural operations.

2. Materials and Methods

2.1. Proposed Method

The proposed system focuses on the development of a cost-effective and sustainable soil moisture monitoring and irrigation control solution tailored for agricultural applications, particularly oil palm plantations. Leveraging Long Range (LoRa) technology, regarded for its long-distance, low-power wireless communication, the system addresses the need for real-time, site-specific soil condition monitoring in resource-constrained environments.

At its core, the transmitter node is built around the ESP32 microcontroller, chosen for its integrated Wi-Fi and Bluetooth functionalities, low-power operating modes, and ease of programming. A resistive soil moisture sensor serves as the primary sensing element for detecting volumetric water content in the soil. Although resistive sensors are susceptible to long-term drift due to corrosion, their affordability and simplicity make them suitable for small-scale and proof-of-concept deployments. The data acquisition process is complemented by a DHT22 sensor, which measures ambient temperature and humidity, providing additional environmental context for interpreting soil moisture data.

The system integrates an actuator mechanism directly linked to the moisture-sensing process. This actuator, in the form of a solenoid valve or small DC pump, can be selectively activated when soil moisture levels fall below a predefined threshold. This enables automated, targeted irrigation for the monitored area, eliminating the need for constant manual intervention. The actuator is controlled by the ESP32's output pins, with logic programmed to ensure minimal water wastage and prevent over-irrigation. In field scenarios, the actuator can also be repositioned alongside the sensor to irrigate different sections of the plantation in a rotational schedule, thus optimising both coverage and energy use.

Data from the transmitter node is communicated via a LoRa SX1278 module to a central receiver station, which can be located several kilometres away without the need for cellular infrastructure. This is particularly advantageous for plantations in remote areas with poor network connectivity. LoRa's spread spectrum modulation ensures high receiver sensitivity and resilience to environmental interference, making it well-suited for agricultural deployments with dense vegetation or uneven terrain.

Energy efficiency is a critical design consideration. The ESP32 operates in deep-sleep mode between measurement intervals, waking only to acquire sensor data, transmit it, and, if required, activate the actuator. This significantly reduces power consumption and extends the operational life of battery-powered nodes. The actuator control sequence is also optimised to minimise energy draw, with irrigation cycles limited to the exact duration needed to restore optimal soil moisture levels.

From an operational perspective, this integrated sensing-actuation approach supports precision irrigation by delivering timely soil data and automating the water delivery process. Farm managers can also override actuator control manually via the receiver interface if required, allowing flexible responses to changing weather conditions or crop stages. While the current prototype is limited to soil moisture-triggered irrigation, its modular architecture allows for future integration of advanced parameters such as soil temperature probes, capacitive moisture sensors for improved durability, or nutrient sensors to expand its functionality.

2.2. Hardware Used

- LoRa SX1278 Module - It is used for long-range communication and operates on frequencies ranging from 433MHz to 525MHz; features low power consumption for extended battery life.
- NodeMCU ESP32 - This microcontroller with integrated Wi-Fi and Bluetooth capabilities; features dual-core processing for high performance; supports a wide range of interfaces including SPI, I2C, and UART.
- Soil moisture sensor - (3.3 -5V) YL-69 Hygrometer w/HC-38 Works for voltages from 3.3 to 5v, has corrosion resistance probe.
- DHT22 temperature and Humidity sensor - Offers high precision with ±0.5°C temperature accuracy and ±2% humidity accuracy; operates at voltages from 3V to 5V; communicates via a single-wire digital interface.

- SSD1306 Oled display Module- 0.96" SPI/I2C- 128X64 - A 0.96-inch OLED display with a resolution of 128x64 pixels; supports both SPI and I2C communication protocols; low power consumption suitable for battery-powered devices.
- Actuator - DC 12V 300mA 5n/10mm, push-pull linear motion solenoid - electromagnet. Operates on a 12V DC power supply; provides a pushing or pulling force of 5N with a stroke length of 10mm; suitable for precise control in various applications.
- 12v battery

2.3. Hardware Design

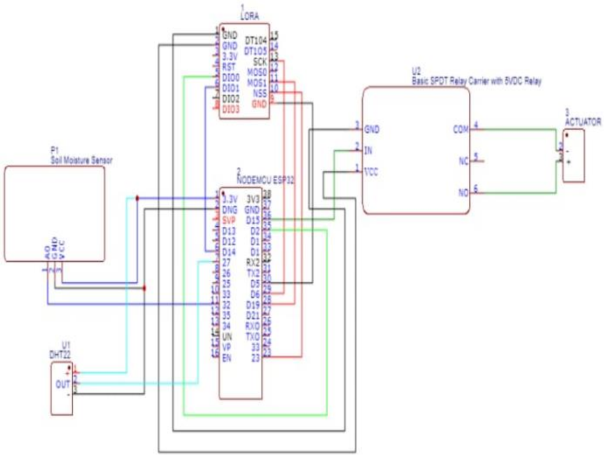

Fig. 1: Schematic Diagram for Transmitter.

This circuit diagram depicts the transmitter side of the Wireless Soil Moisture Monitor. An actuator is attached to the moisture sensor to selectively place the moisture sensor into the soil only when readings are required. Figure 1 above shows the connection between LoRa, ESP32, relay, actuator, DHT22, and soil moisture sensor. The actuator has a separate power supply, connected with 12V battery.

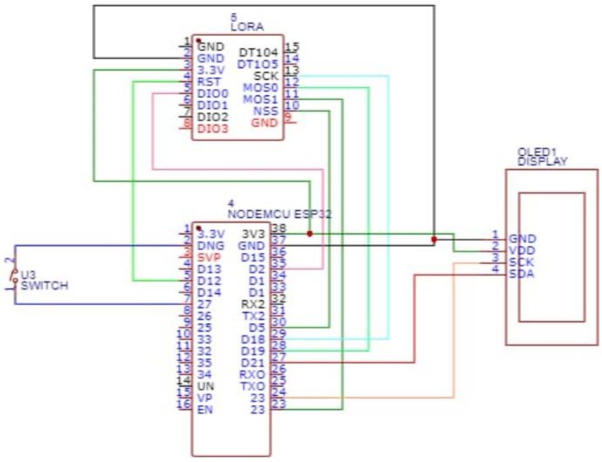

Fig. 2: Schematic Diagram for Transmitter Receiver.

The connections between the LoRa module and ESP32, as well as the wiring for the 5V regulated power supply, remain unchanged. The SSD1306 OLED display module's SDA and SCL (or SCK) pins are connected to the ESP32's D21 and D23 pins, respectively. The VCC and GND pins of the OLED display module are connected to the ESP32's 3.3V and GND pins, respectively. A button is connected to ESP32 digital pin 27 on the transmitter side, which is utilized for controlling the actuator, as in Figure 2.

2.4. Software Design

For this prototype, two different sets of coding were developed for the transmitter and receiver sides. The coding was developed using Arduino IDE. The Arduino IDE is a software platform for writing, compiling, and uploading code to Arduino microcontroller boards, providing a user-friendly interface for electronics projects. It includes features like code editing, library management, and serial communication tools. The flowchart in Figure 3 illustrates the workflow of the entire process.

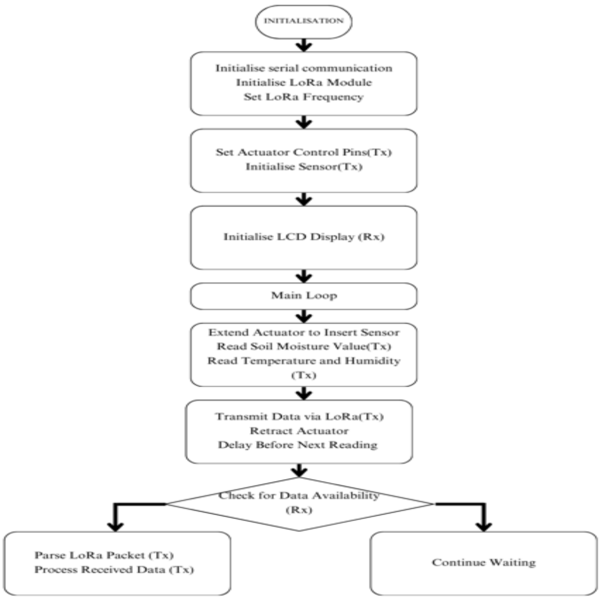

Fig. 3: System Workflow.

3. Results and Discussion

3.1. Testing

Three different types of testing were conducted to understand the working efficiency of the prototype. Figure 4 shows the experiment setup.

3.1.1. Comparison between the gravimetric method (traditional) and a resistive soil moisture sensor (prototype)

Firstly, an efficiency comparison test between the resistive moisture sensor and the traditional gravimetric method was conducted. These experiments represented different moisture conditions: a dry stage with zero water (Table 1), a mid-wet stage with 250ml of water (Table 2), and a fully wet stage with 500ml of water (Table 3).

Fig. 4: Experiment Setup.

Table 1: Comparison Experiment 1(Dry)

No	Experiment	Moisture content	Gravimetric Method(%)	Resistive soil moisture sensor reading(%)	Efficiency (%)
1	Dry	Zero Water	0	36	100
2	Dry	Zero Water	0	35	100
3	Dry	Zero Water	0	35	100

Table 2: Comparison Experiment 1(Mid Wet)

No	Experiment	Moisture content	Gravimetric Method(%)	Resistive soil moisture sensor reading(%)	Efficiency (%)
1	Mid-Wet	250ml	25.6	72	64.6
2	Mid-Wet	250ml	26	70	62.92
3	Mid-Wet	250ml	25.7	73	64.94

Table 3: Comparison Experiment 1(Fully Wet)

No	Experiment	Moisture content	Gravimetric Method(%)	Resistive soil moisture sensor reading(%)	Efficiency (%)
1	Fully Wet	500ml	54.3	100	84.85
2	Fully Wet	500ml	54,3	100	84.85
3	Fully Wet	500ml	54.5	100	83.49

The results from the laboratory-based testing for dry, mid-wet, and fully wet soil conditions indicate a clear relationship between the moisture content measured using the gravimetric method and the resistive soil moisture sensor readings.
In the dry condition in Table 1, the gravimetric method consistently recorded 0% moisture content, while the resistive soil moisture sensor reported values between 35% and 36%. Despite the absence of actual water content, the efficiency was calculated as 100%, suggesting that the sensor calibration at lower moisture levels led to a high relative efficiency score. This also indicates that the sensor may have a baseline offset due to residual soil conductivity, which should be considered during calibration.
For mid-wet samples in Table 2, the gravimetric moisture content ranged from 25.6% to 26%, while the sensor recorded readings between 70% and 73%. The calculated efficiency ranged from 62.92% to 64.94%, indicating a noticeable reduction compared to the dry condition. This variation suggests that at moderate moisture levels, the resistive sensor tends to overestimate the actual moisture content, likely due to the nonlinear response of resistive sensors when soil conductivity increases with added water.
In fully saturated samples in Table 3, the gravimetric method measured 54.3%–54.5%, with the resistive sensor consistently outputting 100% moisture. The efficiency values ranged from 83.49% to 84.85%, indicating a better alignment between actual and sensor-based readings compared to the mid-wet condition, although the sensor's upper limit reading (100%) prevents it from distinguishing between high-moisture variations.
The data demonstrates that the resistive soil moisture sensor performs with maximum efficiency at very low (dry) and very high (fully wet) moisture extremes, but exhibits reduced efficiency at intermediate moisture levels. This nonlinearity is consistent with the known behaviour of resistive sensors, where soil conductivity changes disproportionately in mid-range moisture conditions.

3.1.2. Field Testing

In the field test, two different types of testing were conducted, where the first test was conducted at the Orchard Plantation, which served as a reference point for validation, where the obtained readings were compared with an industrial soil moisture sensor with a depth of penetration of 3cm. The soil monitoring system shows the soil moisture in terms of percentage(0- dry, 100- fully wet), where the industrial sensor shows the soil moisture (0 -dry, 8- fully wet) as in Figures 5, 6, 7, and 8. The second test was conducted in the oil palm plantation, and readings were collected around the general area to determine the range of the data transmission (Table 4).

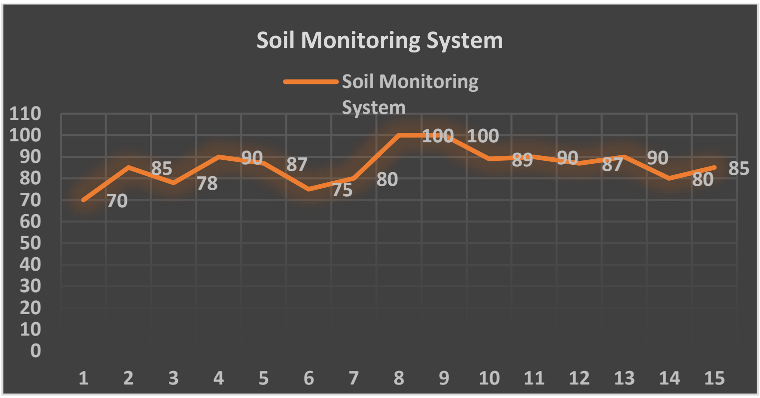

Fig. 5: Graphical Illustration for Soil Monitoring System(Morning).

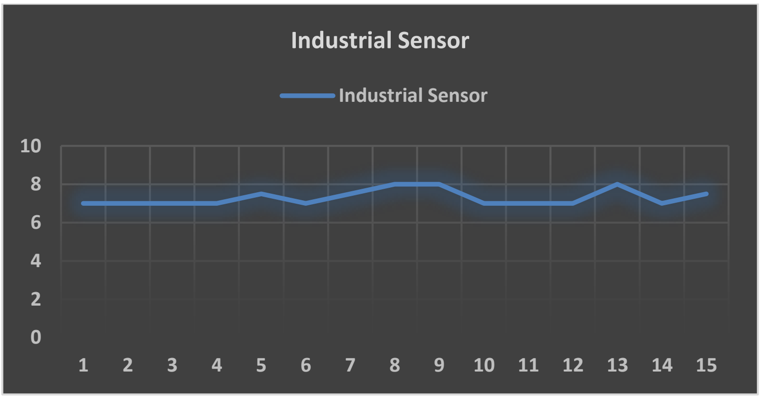

Fig. 6: Graphical Illustration for Industrial Sensor(Morning).

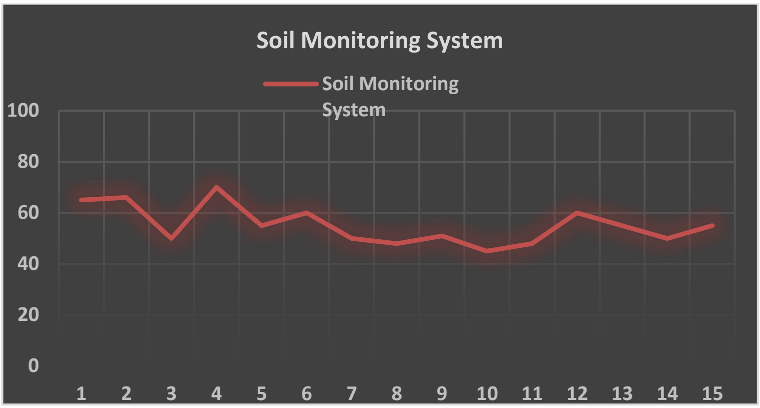

Fig. 7: Graphical Illustration for Soil Monitoring System(Noon).

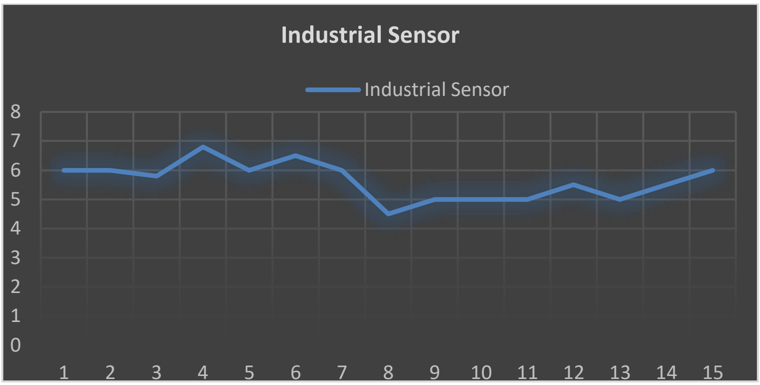

Fig. 8: Graphical Illustration for Industrial Sensor(Noon).

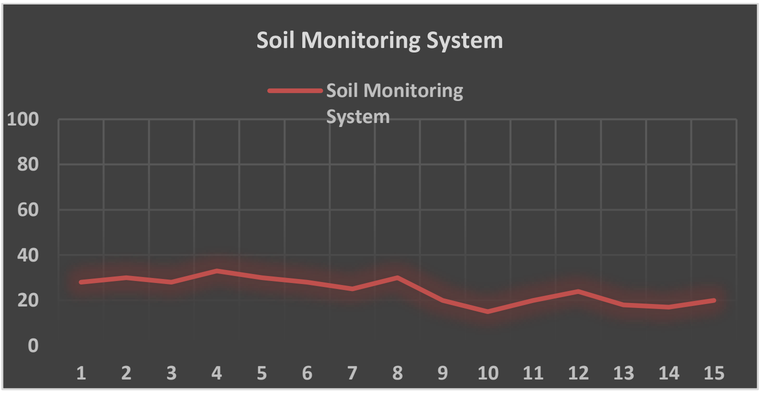

Fig. 9: Graphical Illustration for Soil Monitoring System(Evening).

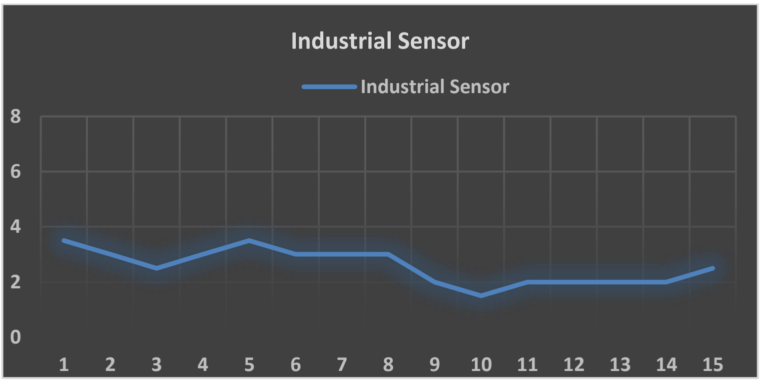

Fig. 10: Graphical Illustration for Industrial Sensor(Evening).

The soil moisture readings obtained from the prototype and the industrial sensor show differences primarily due to the distinct measurement units and sensing principles. The prototype system, using the YL-69 resistive soil moisture sensor, outputs values in parts per million (ppm), while the industrial sensor measures soil moisture in milligrams per liter (mg/L). Despite these differences, when both datasets are normalized to a common percentage scale, their moisture variation trends throughout the day show reasonable agreement. Specifically, the average deviation between the two sensors is highest in the morning, as in Figure 5 and Figure 6 at 57.03%, decreases significantly by noon, as in Figure 7 and Figure 8, to 19.78%, and is lowest in the evening, as in Figure 9 and Figure 10, at 13.70%. This trend suggests that environmental factors such as temperature fluctuations and soil moisture distribution in the morning may affect sensor readings more strongly, particularly impacting the resistive sensor's ppm output. However, the decreasing deviation during later times of the day demonstrates that the prototype sensor is capable of reliably tracking soil moisture changes, making it suitable for practical field monitoring despite the inherent differences in measurement units and sensor characteristics.

Table 4: Distance Test

No	Soil Moisture Reading (%)	Data Transmission from point zero (m)	Data Transmission Status
1	100	0	Successful
2	100	10	Successful
3	100	20	Successful
4	100	30	Successful
5	100	40	Successful
6	100	50	Successful
7	100	60	Successful
8	100	70	Successful
9	100	80	Successful
10	100	90	Successful
11	100	100	Successful
12	100	120	Successful
13	100	140	Successful
14	100	160	Successful
15	100	180	Successful
16	100	200	Successful
17	100	220	Successful
18	100	240	Successful
19	100	260	Successful
20	100	280	Successful
21	100	300	Successful
22	100	320	Unsuccessful
23	100	340	Unsuccessful
24	100	360	Unsuccessful
25	100	380	Unsuccessful
26	100	400	Unsuccessful
27	100	420	Unsuccessful
28	100	440	Unsuccessful
29	100	460	Unsuccessful
30	100	480	Unsuccessful
31	100	500	Unsuccessful
32	100	520	Unsuccessful

The prototype soil moisture monitoring system demonstrated reliable wireless data transmission using LoRa technology up to 300 meters from the transmission point, with a 100% success rate in receiving soil moisture readings as tabulated in Table 4. Beyond this range, starting at 320 meters, data transmission became unsuccessful and remained so up to the maximum tested distance of 520 meters. This result indicates that the effective communication range of the system in the tested plantation environment is approximately 300 meters. Factors such as signal attenuation, environmental obstacles (e.g., vegetation density and terrain), and antenna characteristics likely contribute to the drop in transmission reliability beyond this distance. These findings validate the system's suitability for medium-range monitoring in large-scale palm oil plantations, allowing for effective real-time data collection over significant areas without frequent manual intervention.

3.2. Results

The performance of the developed soil moisture monitoring prototype was evaluated through laboratory and field experiments. In laboratory tests comparing resistive soil moisture sensor readings against the gravimetric method, the sensor demonstrated an efficiency of 100% in dry soil conditions despite registering a constant offset reading (~35%). For mid-wet soil samples, the prototype showed moisture readings approximately 2.5 times higher than the gravimetric values, resulting in an efficiency range of 62.9% to 64.9%. Fully wet samples produced sensor readings capped at 100%, corresponding to an efficiency between 83.5% and 84.9%.

Field validation was conducted by comparing prototype readings with an industrial soil moisture sensor at an orchard plantation across morning, noon, and evening intervals. While absolute values differed significantly due primarily to differing sensor technologies and measurement scales, both sensors exhibited consistent temporal patterns. The prototype recorded moisture percentages ranging from 28% to 100%, whereas the industrial sensor's scale ranged approximately from 1.5 to 8 units. Figure 11 shows the normalized average soil moisture for both the prototype and the industrial sensor.

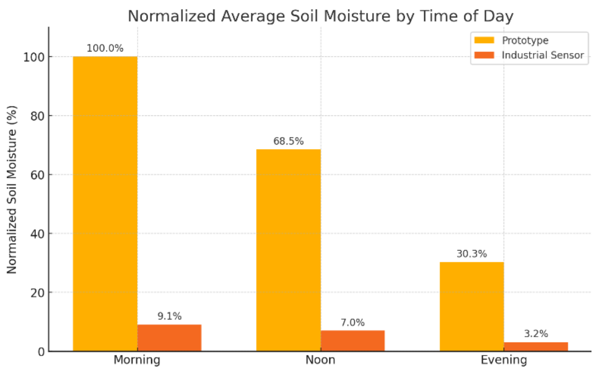

Fig. 11: Normalize Average Soil Moisture for Both Prototype and Industrial Sensor.

The normalized average moisture values for the prototype were approximately 100% in the morning, 68.5% at noon, and 30.3% in the evening. Corresponding normalized values for the industrial sensor were 9.1%, 7.0%, and 3.2%, respectively. While absolute values differ due to distinct sensor calibrations and units, both sensors show consistent daily trends in moisture variation, highest in the morning, decreasing by noon, and further in the evening.

This comparative analysis demonstrates that, although the prototype sensor readings differ in scale, their relative changes throughout the day reasonably correspond with the industrial sensor, validating the prototype's capability to track soil moisture dynamics effectively.

Data transmission tests indicated reliable communication of soil moisture data via the LoRa SX1278 module up to 300 meters. Beyond this range, transmission success declined sharply, with packet loss observed at distances greater than 320 meters.

These results demonstrate the prototype's capability to detect soil moisture trends reliably and maintain long-range wireless data transmission within the operational plantation environment.

4. Discussion

This project successfully demonstrated the development and deployment of an IoT-based soil moisture monitoring system tailored for palm oil plantations, utilizing ESP32 microcontrollers and LoRa wireless communication technology. The system's design prioritizes resource efficiency by selectively deploying the soil moisture sensor using an integrated actuator, minimizing continuous sensor exposure, power consumption, and potential probe degradation.

However, during field testing, the actuator exhibited inefficiencies such as inconsistent operation and heating, likely caused by inadequate power supply management or hardware limitations. These issues highlight the need for improvements in actuator design and power optimization. Future iterations of the system should consider employing lower-power actuators such as servo motors or latching solenoids, which can reduce continuous power draw and heat generation. Additionally, incorporating real-time feedback control for actuator movement and adaptive duty cycling could enhance reliability and further conserve energy, thus extending the operational lifespan of the device in remote agricultural environments.

The integration of the soil moisture sensor with the DHT22 temperature and humidity sensor provided reliable environmental data, supporting informed irrigation management decisions. Nonetheless, the absence of a soil pH sensor limits a comprehensive soil health assessment. Including pH monitoring in future developments would enable a more holistic evaluation of soil conditions, thereby improving decision-making related to nutrient management and crop health.

Although this study did not experimentally quantify water savings or cost reductions, existing literature in precision irrigation and soil moisture monitoring supports the potential for significant resource efficiency improvements. Prior research reports indicate that real-time soil moisture monitoring and regulated irrigation practices can reduce water consumption by approximately 20–30% without adversely affecting crop yield [15], [16]. Similarly, sensor-based irrigation management systems have demonstrated notable energy and cost savings through optimized irrigation scheduling. These findings align with assessments by the Food and Agriculture Organization, which emphasize the critical role of smart agriculture technologies in promoting sustainable water use [17]. Therefore, it is reasonable to expect that the developed IoT-based soil moisture monitoring system could contribute to comparable reductions in water consumption and operational costs in palm oil plantations.

Importantly, the system aligns with the sustainability objectives set forth by the Roundtable on Sustainable Palm Oil (RSPO). The RSPO Principles and Criteria emphasize responsible management of natural resources, including water and energy, to minimize environmental impact and ensure sustainable palm oil production [18]. Precision monitoring and targeted irrigation directly support these criteria by enabling efficient resource use and reducing wastage. Deployment of this system within commercial plantations can thus facilitate compliance with RSPO standards, enhance environmental stewardship, and improve market competitiveness.

Future work should focus on extended field trials to accurately quantify water and cost savings, evaluate long-term sensor durability, and incorporate additional soil health parameters such as pH. Such comprehensive evaluations will strengthen the system's practical applicability and adoption potential, providing a valuable tool for sustainable palm oil production and broader agricultural IoT applications.

5. Conclusion

The development and implementation of the advanced soil monitoring system represents a pivotal advancement in sustainable agricultural practices, showcasing a profound commitment to resource efficiency and environmental stewardship. By integrating a strategic actuator that selectively deploys the moisture sensor only when necessary, the system optimizes power consumption and extends sensor longevity, demonstrating a model of efficiency and durability. The application of IoT and LoRa technology not only facilitates real-time, long-range data transmission but also enhances the system's adaptability to diverse and remote environments.

This innovative approach not only streamlines soil management but also significantly reduces the need for manual interventions, aligning with best practices in sustainable agriculture. The system's capacity for precise data collection and its potential for further refinements highlight its role in advancing resource-efficient solutions. Ultimately, this project sets a new standard for sustainable environmental monitoring, offering a robust framework for future advancements and demonstrating a clear path towards more resilient and responsible agricultural practices.

Author Contributions

Conceptualization, SP; methodology, SP; software, KR; validation, KR; formal analysis, SP; investigation, SP, KR; resources, TV; data curation, TV; writing—original draft preparation, TV; writing—review and editing, DD; visualization, DD; supervision, SP; project administration, SP; funding acquisition, DD. All authors have read and agreed to the published version of the

Conflict of Interest

The authors declare no conflict of interest.

References

[1] S. N. Shaharuzzaman, F. H. Hashim, Mohd Shaiful Sajab, and Aqilah Baseri Huddin, "Analysis of Free Fatty Acids (FFA) in Palm Oils Based on the Raman Spectra," pp. 132–137, 2023, https://doi.org/10.1109/I2CACIS57635.2023.10193495.

[2] Soh, A. C., Wong, G., Hor, T. Y., Tan, C. C., & Chew, P. S., "Oil palm generic improvement," *Plant Breeding Reviews*. Wiley, 2003, https://doi.org/10.1002/9780470650202.

[3] V. Lai, N. Yusma, Ali Najah Ahmed, Yuk Feng Huang, K. Beng, and A. El-Shafie, "The benefits and perspectives of the palm oil industry in Malaysia," *Environment, development and sustainability*, 2024, https://doi.org/10.1007/s10668-024-04593-7.

[4] B. NAMBIAPPAN, "MALAYSIA: 100 YEARS OF RESILIENT PALM OIL ECONOMIC PERFORMANCE," *Journal of Oil Palm Research*, vol. 30, no. 1, pp. 13–25, Apr. 2018, https://doi.org/10.21894/jopr.2018.0014.

[5] H. Akram, D. F. Levia, J. E. Herrick, H. Lydiasari, and N. Schütze, "Water requirements for oil palm grown on marginal lands: A simulation approach," *Agricultural Water Management*, vol. 260, p. 107292, 2022, https://doi.org/10.1016/j.agwat.2021.107292.

[6] L. Dutta, Swapna Bharali, P. Barman, and A. Singh, "An IoT-Enabled Smart pH Monitoring and Dispensing System for Precision Agriculture Application," *Agricultural Research*, vol. 13, no. 2, pp. 309–318, 2024, https://doi.org/10.1007/s40003-024-00702-0.

[7] Mohamad *et al.*, "Impact of Industry 4.0 Technologies on the Oil Palm Industry: A Literature Review," *Smart Agricultural Technology*, pp. 100685–100685, 2024, https://doi.org/10.1016/j.atech.2024.100685.

[8] M. S. Kumar, T. R. Chandra, D. P. Kumar, and M. S. Manikandan, "Monitoring moisture of soil using low cost homemade Soil moisture sensor and Arduino UNO," *IEEE Xplore*, Jan. 01, 2016. https://ieeexplore.ieee.org/document/7586312?denied=.https://doi.org/10.1109/ICACCS.2016.7586312.

[9] A. Tyagi, A. Apoorv Reddy, J. Singh, And S. Roy Chowdhury, "A Low Cost Portable Temperature-Moisture Sensing Unit With Artificial Neural Network Based Signal Conditioning For Smart Irrigation Applications," *International Journal on Smart Sensing and Intelligent Systems*, Vol. 4, No. 1, pp. 94–111, 2011, https://doi.org/10.21307/ijssis-2017-428.

[10] A. A. Ruslan, S. M. Salleh, S. F. W. M. Hatta, and A. A. B. Sajak, "IoT Soil Monitoring based on LoRa Module for Oil Palm Plantation," *International Journal of Advanced Computer Science and Applications*, vol. 12, no. 5, 2021, https://doi.org/10.14569/IJACSA.2021.0120527.

[11] A. A. B. Sajak, N. F. Mohd Shukor, M. S. Kassim, and S. R. Rahman, "Comprehensive LoRa-based IoT real-time soil monitoring for oil palm plantation," *International Journal of Technology*, vol. 16, no. 5, pp. 65–75, 2022.

[12] MDPI Staff, "Vegetation effects on LoRa-based wireless sensor communication for remote monitoring of automatic orchard irrigation status," *Electronics*, 2025, https://doi.org/10.3390/electronics14030497.

[13] S. Chowdhury, S. Sen, and S. Janardhanan, "Comparative analysis and calibration of low-cost resistive and capacitive soil moisture sensors," *arXiv preprint*, arXiv:2210.03019, 2022. [Online]. Available: https://arxiv.org/abs/2210.03019.

[14] L. Aldhaheri, N. Alshehhi, I. I. J. Manzil, R. A. Khalil, S. Javaid, N. Saeed, and M.-S. Alouini, "LoRa communication for Agriculture 4.0: Opportunities, challenges, and future directions," *arXiv preprint*, arXiv:2409.11200, 2024. [Online]. Available: https://arxiv.org/abs/2409.11200. https://doi.org/10.1109/JIOT.2024.3486369.

[15] E. Fereres and M. A. Soriano, "Deficit irrigation for reducing agricultural water use," *Journal of Experimental Botany*, vol. 58, no. 2, pp. 147–159, 2007, https://doi.org/10.1093/jxb/erl165.

[16] H. G. Jones, "Irrigation scheduling: advantages and pitfalls of plant-based methods," *Journal of Experimental Botany*, vol. 55, no. 407, pp. 2427–2436, 2004, https://doi.org/10.1093/jxb/erh213.

[17] Food and Agriculture Organization (FAO), "The future of food and agriculture – Trends and challenges," FAO, Rome, 2017. [Online]. Available: http://www.fao.org/3/i6583e/i6583e.pdf.

[18] Roundtable on Sustainable Palm Oil, "RSPO Principles and Criteria for the Production of Sustainable Palm Oil," 2018. [Online]. Available: https://rspo.org/resources/rspo-principles-and-criteria.

[19] M. Batumalay, "IoT based Intrusion Detection for Edge Devices using Augmented System," *Journal of Applied Data Sciences*, vol. 5, no. 3, pp. 1412–1423, Sep. 2024, https://doi.org/10.47738/jads.v5i3.358.

[20] H. Purnomo *et al.*, "Reconciling oil palm economic development and environmental conservation in Indonesia: A value chain dynamic approach," *Forest Policy and Economics*, vol. 111, p. 102089, Feb. 2020, https://doi.org/10.1016/j.forpol.2020.102089.

[21] E. N. Setiawan, A. Maryudi, R. H. Purwanto, and G. Lele, "Opposing interests in the legalization of non-procedural forest conversion to oil palm in Central Kalimantan, Indonesia," *Land Use Policy*, vol. 58, pp. 472–481, Dec. 2016, https://doi.org/10.1016/j.landusepol.2016.08.003.

[22] Malaysian Palm Oil Council, "About Palm Oil – MPOC," *Mpoc.org.my*, 2025. Available online: https://mpoc.org.my/about-palm-oil.

[23] P. Tullis, "How the World Got Hooked on Palm Oil," *The Guardian*, Feb. 19, 2019. Available online: https://www.theguardian.com/news/2019/feb/19/palm-oil-ingredient-biscuits-shampoo-environmental.

[24] Rivulis, "Oil Palm." Available online: https://naandanjain.com/wp-content/uploads/2018/10/NDJ_OilPlam_booklet_eng_240314F_72.pdf.

[25] WWF, "Palm Oil | Industries | WWF," *World Wildlife Fund*, 2019. Available online: https://www.worldwildlife.org/industries/palm-oil.

[26] V. Sharma, "Soil moisture sensors for irrigation scheduling," *extension.umn.edu*, 2019. Available online: https://extension.umn.edu/irrigation/soil-moisture-sensors-irrigation-scheduling.