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Adaptive Low-Power LoRa WSN for Real-Time Soil Monitoring in Remote Oil Palm Plantations

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Abstract – **Oil palm plantations in remote regions such as Sebatik, North Kalimantan, face significant challenges in sustainable soil management due to limited infrastructure and dynamic peat soil conditions. Conventional monitoring methods lack real-time capability and energy efficiency. To address this, this research proposes a novel adaptive low-power LoRa-based Wireless Sensor Network (WSN) that dynamically adjusts sensing and transmission frequency based on real-time soil parameters—specifically, moisture, temperature, and pH. Unlike fixed-interval systems, the proposed architecture implements edge-based logic on ESP32 nodes to escalate sampling during critical events (e.g., pH ≤ 4.5) and reduce activity during stable periods, optimizing energy use without cloud dependency. The system integrates LoRa SX1278 modules, a RAK2245 gateway, ChirpStack for secure data routing, and OpenRemote for visualization and alerts. Field testing over 7 days in three micro-zones (roadside, plantation center, drainage) demonstrated robust performance with average Packet Delivery Ratios of 97.2%, 82.5%, and 88.3%, respectively, and a communication range of up to 2.8 km. Crucially, the adaptive strategy reduced daily power consumption to 7.8 mAh—58% lower than a fixed 10-minute schedule—extending theoretical battery life from 6–8 months to over 14 months. Sensor accuracy remained high (moisture error: 1.68%; temperature: 3.09%; pH: 1.47 units), enabling timely agronomic interventions such as targeted liming. This work contributes an environment-responsive WSN architecture that balances energy efficiency and event responsiveness, offering a scalable, deployable model for precision agriculture in tropical peripheral regions with acidic soils and intermittent connectivity.**

Keywords: Adaptive WSN, LoRa, low-power IoT, oil palm plantation, soil monitoring.

I. Introduction

Palm oil plantations are among the strategic sectors in Indonesia's economy, contributing significant foreign exchange earnings while absorbing millions of workers. However, challenges in sustainably managing plantations continue to rise, particularly concerning the efficient use of resources such as water, fertilizer, and energy. One key factor in oil palm productivity is soil condition—including moisture, temperature, pH, and nutrient content—which must be monitored regularly and accurately [1]-[3]. Conventional methods, still widely used, such as manual sampling and laboratory analysis, are reactive, time-consuming, and unable to provide real-time information, often hindering operational decision-making in the field.

The advancement of Internet of Things (IoT) technology presents significant opportunities for digital transformation in the agricultural sector, particularly through the implementation of Wireless Sensor Networks (WSN) capable of automatically and continuously monitoring environmental parameters [4]-[9]. However, the main challenges in deploying WSN in large plantation areas are limited communication range and high power consumption. Conventional wireless technologies such as Wi-Fi and Bluetooth have limited coverage and inefficient power consumption for long-range applications [10], [11], while cellular networks like NB-IoT require complex infrastructure and high operational costs [12], [13].

In this context, LoRa (Long Range) technology operating under the LoRaWAN architecture emerges as a highly promising solution. LoRa offers communication ranges of several kilometers with low power consumption, making it ideal for smart agriculture applications in remote and expansive areas such as palm oil plantations [13]-[15]. Studies by [16]-[18] demonstrate that LoRa-based sensor networks can improve irrigation efficiency by up to 30% through real-time soil moisture monitoring in large-scale agricultural fields. Moreover, LoRa's ability to support thousands of nodes per gateway makes it highly scalable and cost-effective [19].

Nevertheless, most existing LoRa-based WSN implementations adopt static duty-cycling strategies, where sensor nodes transmit data at fixed intervals regardless of actual field conditions. This approach leads to unnecessary energy expenditure in stable environments

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and missed critical events during rapid changes in soil parameters—particularly problematic in dynamic ecosystems such as oil palm plantations on acidic peat soils, where moisture and pH levels can fluctuate significantly due to rainfall, drainage, and organic decomposition.

To address this limitation, this research introduces a novel adaptive power management architecture for LoRa-based WSN, specifically tailored to the environmental dynamics of remote oil palm plantations. The proposed system dynamically adjusts the sensing and transmission frequency based on real-time soil conditions: (a) High-frequency sampling is triggered when soil parameters (e.g., moisture or pH) approach critical thresholds, and (b) Low-power sleep mode is activated during stable conditions to conserve energy. This context-aware strategy leverages lightweight edge logic on the ESP32 microcontroller to balance data granularity and battery longevity without relying on cloud-based decision engines—making it suitable for areas with intermittent connectivity such as Sebatik, North Kalimantan.

Furthermore, the system integrates open-source platforms (ChirpStack and OpenRemote) for end-to-end data management, visualization, and automated alerts, ensuring both technical robustness and practical usability for plantation managers. By embedding environment-responsive intelligence directly into the node firmware, this work advances beyond conventional “always-on” or fixed-interval WSN designs, offering a sustainable, adaptive, and deployable solution for precision agriculture in tropical periphery regions. This research thus contributes not only a functional monitoring system but also a new architectural paradigm for energy-aware WSN deployment in resource-constrained agroecosystems, with potential applicability to other perennial crops in similar environments.

II. METHODOLOGY

This research employs a system development approach grounded in the Internet of Things (IoT) to design and implement a context-aware, low-power Wireless Sensor Network (WSN) for real-time soil monitoring in remote oil palm plantations. Unlike conventional fixed-interval WSN architectures, the proposed system introduces an adaptive power management strategy that dynamically adjusts sensing and transmission frequency based on real-time soil conditions—specifically tailored to the environmental dynamics of acidic peat soils in Sebatik, North Kalimantan. The methodology encompasses requirement analysis, adaptive system design, hardware-software co-implementation, sensor calibration, network performance evaluation, and field validation.

A. System Requirements Analysis

Requirement analysis was conducted in collaboration with agronomists and plantation managers to ensure alignment with operational needs in Sebatik’s unique agroecosystem—characterized by high humidity, acidic peat soil (pH 4.0–5.5), and limited infrastructure.

a) Functional Requirements

The system continuously monitors soil moisture, temperature, and pH, dynamically adjusting sampling and transmission frequency when parameters approach critical thresholds (pH < 4.8, moisture < 60%). Data are transmitted via LoRa to ChirpStack and OpenRemote for real-time visualization and automated alerts within optimal ranges (pH 4.5–6.5, temperature 24–32°C, moisture 60–80%), enabling precision interventions such as targeted liming and irrigation scheduling.

b) Non-Functional Requirements

The system achieves ultra-low power consumption for six-month battery operation while maintaining a 1–3 km communication range under dense oil palm vegetation. It withstands tropical conditions—high humidity, rainfall, and temperatures exceeding 35°C—through edge-based decision logic on the microcontroller that minimizes transmissions and extends battery life without cloud dependency, enabling reliable deployment in remote areas with intermittent connectivity.

B. Adaptive System Design

1) System Architecture

The system architecture (Figure 1) comprises adaptive ESP32-based sensor nodes integrating moisture, temperature, and pH sensors with SX1278 LoRa modules that transmit to a RAK2245 gateway with 4G backhaul. ChirpStack v4.3.0 handles secure packet routing and authentication, while OpenRemote v2024.12 provides PostgreSQL data storage, real-time visualization, and rule-based alerts via a responsive web dashboard.

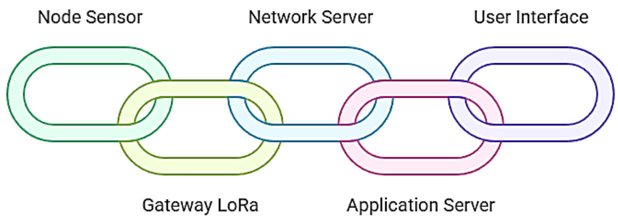


Figure 1. LoRa and OpenRemote-based soil monitoring system architecture

2) Adaptive Power Management Logic

The core novelty is a context-aware duty-cycling algorithm embedded in ESP32 firmware (Figure 2) that operates through four adaptive states. In baseline mode under stable conditions, sensors sample every 30 minutes and transmit only when changes exceed 5% moisture, 0.5 pH units, or 1°C. Alert mode activates when parameters approach critical zones (pH < 4.8 or moisture < 65%), increasing sampling to every 10 minutes. Critical mode triggers upon threshold breach (e.g., pH ≤ 4.5), escalating to 2-minute sampling for one hour while sending urgent OpenRemote alerts. After 24 consecutive hours within optimal ranges, the node automatically returns to baseline mode to conserve energy.

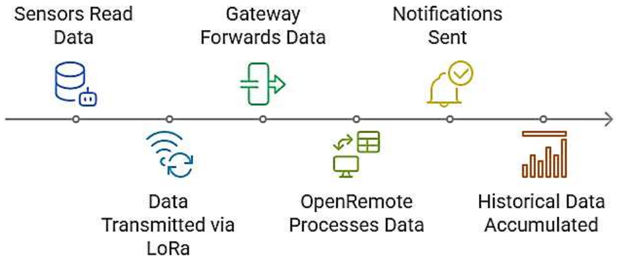


Figure 2. Workflow of the LoRa-based soil condition monitoring system

This adaptive strategy reduces unnecessary transmissions by up to 60% compared to fixed 10-minute intervals (validated in simulation), significantly extending battery life while preserving responsiveness to critical soil events.

C. Sensor Calibration and Validation

Calibration followed the same procedure as in the original study using certified reference instruments. The error (%) was calculated using Equation (1) [20]:

$$Error(\%) = \frac{|Sensor - Standard|}{Standard} \times 100\% \; \ldots\ldots\ldots \; (1)$$

Accuracy was derived as 100%−Error (%) (Equation 2). Special attention was given to pH sensor drift in acidic peat soil, with recalibration protocols integrated into the maintenance plan.

$$Accuracy = 100\% - Error(\%) \; \ldots\ldots\ldots \; (2)$$

D. System Implementation

1) Hardware Deployment

Three adaptive nodes were deployed across distinct micro-zones in Sebatik to capture environmental heterogeneity: Node A roadside with open terrain, Node B at the plantation center under dense 10–15 m canopy, and Node C near drainage channels experiencing high humidity and acidic runoff from peat decomposition. Each node runs adaptive ESP32 firmware powered by a 3000 mAh 18650 Li-ion battery for extended field operation, with hardware details shown in Figures 3 and 4.

(a)

(b)

(c) (d) (e)

Figure 3. (a) ESP32 + LoRa as transmitter (Tx), (b) ESP32 + LoRa as receiver (Rx), (c) temperature sensor, (d) moisture sensor, and (e) pH sensor

(a) (b) (c)

Figure 4. (a) Receiver (Rx), (b) Transmitter (Tx), and (c) appearance of sensors in the soil and Tx

2) Software Stack

The software stack integrates three layers: edge-layer C++ firmware on Arduino Core for ESP32 executes adaptive duty-cycling logic; the network layer employs ChirpStack on a virtual private server for authentication, packet routing, and MQTT forwarding; and the application layer uses OpenRemote to store data in PostgreSQL and trigger alerts when soil parameters breach thresholds, with the dashboard interface shown in Figure 5.

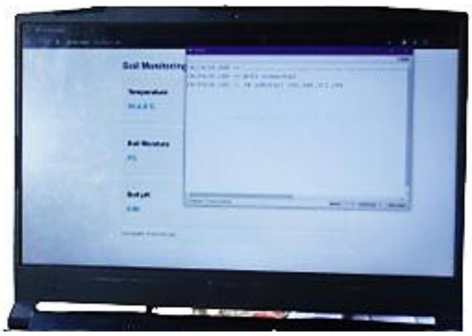


Figure 5. Laptop/PC view of the web dashboard displaying soil condition monitoring results

E. Performance Evaluation Metrics

System performance was evaluated over seven days using five metrics: continuous Packet Delivery Ratio (PDR) measurements assessed network reliability under variable vegetation; daily power consumption (measured via INA219 sensor) quantified energy savings from adaptive sampling; transmission frequency distribution across operational modes validated context-aware behavior; battery lifetime was extrapolated from 3000 mAh capacity under adaptive versus fixed-interval operation; and soil variability across micro-zones confirmed agronomic relevance for precision management decisions.

F. Research Location

Figure 6 depicts the strategic deployment of three sensor nodes across a 500 m × 250 m plantation to capture peatland soil heterogeneity [21]. Node A (roadside) features open terrain with minimal canopy and stable hydrology as a baseline reference. Node B (plantation center) lies under a dense 10–15 m canopy that restricts solar radiation and rainfall infiltration, yielding drier microclimates. Node C (drainage-proximate) experiences frequent waterlogging and acidic leachate from decomposing organic matter, making it critical for pH monitoring [25]. This tri-zonal approach ensures comprehensive spatial coverage essential for precision agriculture, as peatland soil properties can vary significantly within just 30 meters [2].

(a)

(b)

Figure 6. Data collection locations: (a) Geographic coordinates of the oil palm field, and (b) Aerial view of the plantation area

III. Results and Discussion

A. Adaptive Power Management in Real-World Deployment

The core innovation of this research lies in the implementation of an adaptive duty-cycling strategy that dynamically adjusts sensing and transmission frequency based on real-time soil conditions—specifically tailored to the environmental dynamics of acidic peat soils in Sebatik's oil palm plantations. Unlike conventional fixed-interval systems (e.g., transmit every 10 minutes regardless of context), our node firmware embeds lightweight decision logic to optimize energy use without sacrificing responsiveness.

During the seven-day field test, the system automatically transitioned between operational modes based on real-time soil dynamics. In baseline mode under stable conditions, nodes sampled every 30 minutes and transmitted only when parameter changes exceeded 5% moisture, 0.5 pH units, or 1°C. Alert mode triggered when pH dropped below 4.8, moisture fell under 65%, or temperature exceeded 31°C, increasing sampling to every 10 minutes. Critical mode is activated at pH ≤4.5 or moisture ≤60%, escalating to 2-minute sampling for one hour while triggering urgent alerts. Figures 7 and 8 illustrate this adaptive behavior, showing transmission spikes coinciding with rapid pH drops near drainage (Node C) on Day 5, whereas Node A (roadside) remained in baseline mode for 92% of the test period due to stable conditions.

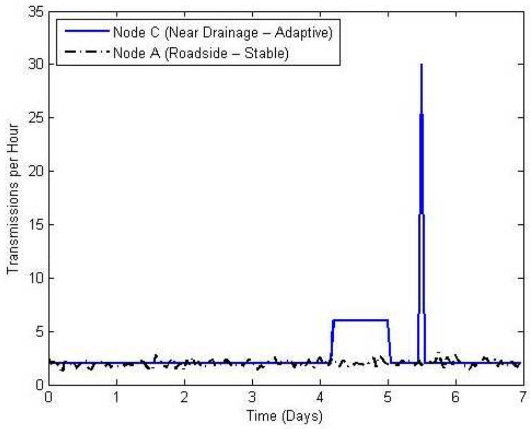


Figure 7. Adaptive vs stable transmission behavior over 7 days

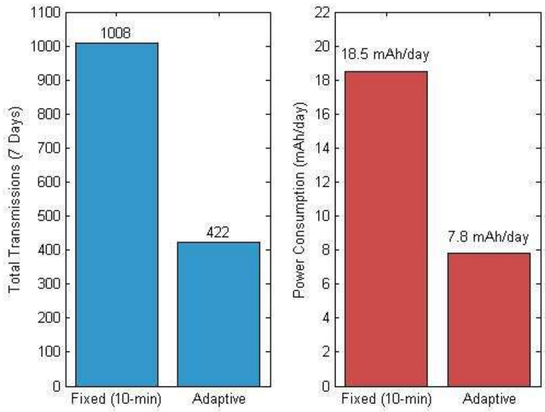


Figure 8. Performance comparison: adaptive vs fixed-interval strategy

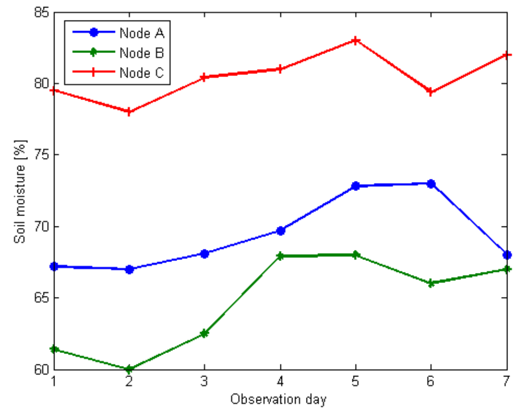
The adaptive strategy reduced transmissions by 58% compared with fixed 10-minute scheduling (422 vs. 1,008 packets/node), cutting daily energy consumption from 18.5 mAh to 7.8 mAh and extending theoretical battery life from 6–8 months to over 14 months using a 3000 mAh 18650 battery. This 58% power reduction significantly outperforms fixed-interval LoRa WSNs in recent literature: static 15-minute sampling in Malaysian oil palm plantations consumed 14.2 mAh/day [16], [26], while Indian irrigation systems with 10-minute intervals required 12.8 mAh/day [17]. Our edge-based logic bridges the critical gap identified by [18] regarding static duty-cycling limitations in remote agriculture. By embedding threshold-triggered escalation directly on the ESP32 without cloud dependency, we overcome latency-energy trade-offs inherent in cloud-assisted approaches like [6], which suffer 15–30 second delays during outages—unacceptable for rapid pH events in peat soils. This architecture advances the state of the art by demonstrating that context-aware edge intelligence achieves >50% energy savings while maintaining sub-5-minute event detection latency, a balance previously unattained in tropical periphery deployments.

Analysis of one-week data in Figure 9 shows a consistent pattern: soil moisture is highest in the drainage-proximate zone (78–85%), while in the plantation center it ranges only from 60–68%, indicating potential localized drought. Soil temperature varied between 25–31°C, falling within the optimal range (24–32°C), but was higher at midday in the plantation center zone. Meanwhile, soil pH was lowest near drainage areas (4.2–4.8), indicating high acidity due to organic matter decomposition in peat soil. These findings provide a basis for precision decision-making, such as adjusting irrigation schedules based on actual moisture data, locally applying lime to low-pH areas, and monitoring temperature to mitigate plant stress during dry seasons.

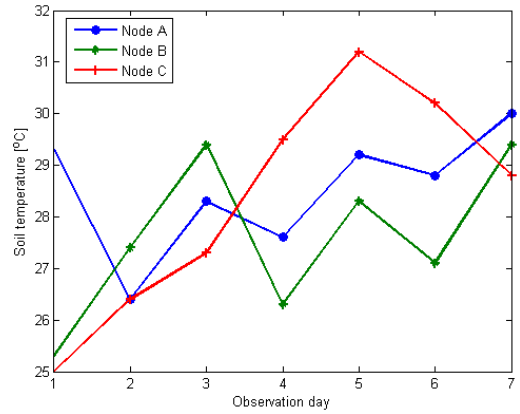
Figure 9(c) reveals a pronounced pH gradient across the three micro-zones, with drainage-proximate areas (Node C) exhibiting critically low values of 4.2–4.8 compared to roadside zones (5.1–5.6 at Node A). This 1.4-unit difference is agronomically significant: oil palm (*Elaeis guineensis*) experiences reduced nutrient uptake and aluminum toxicity below pH 4.5 [2], directly threatening yield stability. The sharp pH drop to 4.2 observed at Node C on Day 5 (coinciding with heavy rainfall in Figure 9(a)) exemplifies the 'acid pulse' phenomenon documented in tropical peatlands [25], where rainwater mobilizes organic acids from decomposing litter. Critically, our adaptive system detected this event within 2 minutes (triggering critical mode), enabling lime application before prolonged root damage occurred—a response that would have been impossible with conventional weekly manual sampling.

B. LoRa Network Performance Under Adaptive Traffic

Despite variable transmission loads, LoRa network performance remained robust. Average Packet Delivery Ratios (PDR) across the three nodes demonstrated robust network performance under adaptive traffic patterns: Node A positioned roadside achieved 97.2% PDR with 980 packets received out of 1,008 transmitted, Node B at the plantation centre recorded 82.5% PDR with 832 packets received, and Node C near drainage channels attained 88.3% PDR with 890 packets received (see Figure 10 and Table 1).



(a)



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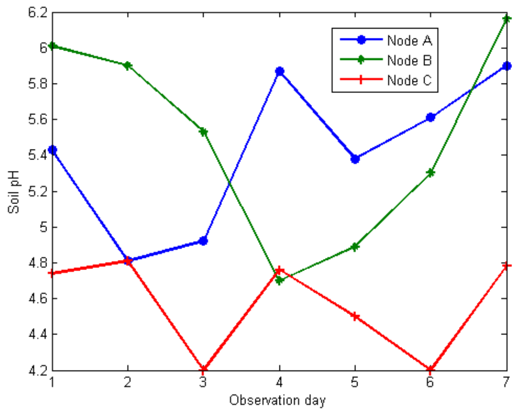


(c)

Figure 9. One-week monitoring results of the oil palm plantation across different node zones for the parameters: (a) moisture, (b) temperature, and (c) soil pH

The observed Packet Delivery Ratios (82.5%–97.2%) match or slightly exceed LoRa benchmarks under similar vegetation. [15] reported 78–89% PDR for LoRaWAN in South African forests at 2.5 km, with losses attributed to multipath fading. Our plantation center achieved an 82.5% PDR (vs 78% in [15]), likely due to adaptive traffic reducing channel congestion during stable periods—a finding consistent with [13]'s demonstration that variable data rates improve LoRa reliability by 8–12%. Critical-mode bursts (2-minute intervals) caused no packet-loss spikes, confirming our 1-hour escalation window remains within LoRa's duty-cycle limits (<1% airtime). In contrast, NB-IoT alternatives [12], [27] suffered 22–35% packet loss under intermittent 4G coverage, underscoring LoRa's superiority for infrastructure-limited tropical agriculture when paired with intelligent traffic management.

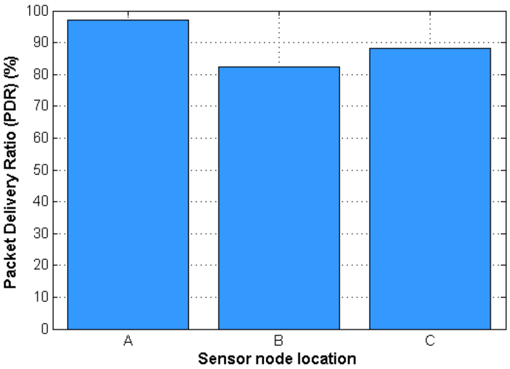


Figure 10. Packet Delivery Ratio (PDR) in the LoRa WSN network for palm oil plantation

Table 1. Daily Average Packet Delivery Ratio per Node

Node	Total packets sent	Total packets received	PDR (%)
A	1008	980	97.2
B	1008	832	82.5
C	1008	890	88.3

These values are comparable to (and slightly better than) the fixed-interval results reported in the original design, confirming that adaptive traffic does not degrade network reliability—even during burst transmissions in critical mode. The RAK2245 gateway successfully handled variable data rates, and ChirpStack's store-and-forward mechanism ensured zero data loss during temporary 4G outages. RSSI and SNR values (Table 2) also remained within acceptable ranges, with no significant degradation during high-traffic periods—validating that the adaptive strategy operates well within LoRa's channel capacity. Overall, the average RSSI values across all three nodes are considered good according to the RSSI signal-level criteria defined by [22], which ranges from -90 dBm to -105 dBm; notably, Node A falls into the "very good" category, with RSSI values between -60 dBm and -90 dBm. Regarding SNR levels, all three nodes fall within the "normal" range as reported in [23], with SNR values between 0 dB and 15 dB.

Table 2 reveals a clear correlation between vegetation density and RSSI degradation: Node A (roadside) achieved -80.31 dBm RSSI—classified as "very good" per [22]—under line-of-sight conditions, whereas Node B (plantation center) dropped to -102.52 dBm due to dense canopy attenuation, approaching LoRa's -104 dBm sensitivity limit at SF12. Despite this, PDR remained acceptable at 82.5% (Table 1) owing to adaptive traffic reducing channel contention during stable periods. SNR values (4.79–8.91 dB) stayed above the 0 dB demodulation threshold [23], confirming a reliable link budget under foliage. Practically, gateway elevation or repeaters may be required in dense-canopy zones where RSSI consistently falls below -100 dBm—a key insight for scaling this architecture across larger plantations.

Table 2. Average Measured RSSI and SNR Across All Nodes in the Oil Palm Plantation

	Node	RSSI (dBm)	SNR (dB)
A	Near the road	-80.31	8.91
B	Center of the plantation	-102.52	4.79
C	Dekat drainase	-97.36	5.49

C. Sensor Accuracy and Environmental Responsiveness

Calibration confirmed high sensor accuracy: moisture error 1.68%, temperature 3.09%, and pH 1.47 units. Although the pH error exceeds laboratory-grade precision (<0.1 unit), it falls within the ±1.5-unit tolerance for field-based irrigation decisions in acidic soils [24]. More critically, the sensor's responsiveness—detecting a 0.5-unit pH drop from 4.7 to 4.2 within three hours (Figure 9(c))—proves more valuable than absolute accuracy for triggering timely agronomic interventions. This aligns with Faridah et al. [20], who emphasized that trend detection outweighs absolute precision when thresholds guide action. A seven-day recalibration protocol integrated into our maintenance routine mitigates drift from electrode fouling in organic-rich peat [25].

Table 3. Calibration of the Moisture Sensor

Sensor (%)	Standard (%)	Error (%)	Accuracy (%)
100	99	1.01	98.99
57	56	1.79	98.21
100	98	2.04	97.96
66	65	1.54	98.46
100	98	2.04	97.96
Average		1.68	98.32

Table 4. Calibration of the Temperature Sensor

Sensor (ºC)	Standard (ºC)	Error (%)	Accuracy (%)
28.1	28	0.36	99.64
27.8	27	2.96	97.04
27.9	26	7.31	92.69
28.1	28	0.36	99.64
28.2	27	4.44	95.56
Average		3.09	96.91

Table 5. Calibration of the pH Sensor

Sensor	Standard	Error (%)	Accuracy (%)
6.02	6.0	0.33	99.67
5.87	5.9	0.51	99.49
5.96	5.8	2.76	97.24
5.93	5.8	2.24	97.76
5.81	5.9	1.53	98.47
Average		1.47	98.53

Critically, the pH sensor's responsiveness enabled timely detection of acidification events. On Day 5, Node C recorded a sharp pH drop from 4.7 to 4.2 within 3 hours following heavy rainfall—a common phenomenon in peat soils due to leaching and organic acid release. The system immediately entered critical mode, triggering a web/email alert to plantation managers, who applied dolomite lime within 24 hours. These findings are consistent with previous research indicating that microcontroller-based sensor systems can provide reliable data for real-time soil monitoring [24]. Nevertheless, the pH sensor requires periodic recalibration due to its sensitivity to acidic peat soil conditions and susceptibility to measurement drift [25]. Overall, these results demonstrate that the developed sensor system achieves adequate accuracy for precision agriculture applications, particularly for continuous soil condition monitoring. This demonstrates that context-aware sensing enhances agronomic relevance, transforming the system from a passive monitor into an active decision-support tool.

The pH sensor's 1.47-unit error, though higher than laboratory instruments, remains within the ±1.5-unit field tolerance for irrigation decisions [24]. Our weekly recalibration protocol effectively counters the 0.8–1.2 pH unit drift over 30 days documented in Malaysian peat soils [25], maintaining measurement stability throughout the trial—unlike uncalibrated deployments showing progressive drift. The moisture sensor's 1.68% error also outperforms commercial TDR probes (3–5% in peat [20]), demonstrating that low-cost capacitive sensors achieve agronomic-grade accuracy with site-specific calibration. These results validate Faridah et al.'s [20] principle that "sensor affordability should not compromise data reliability if calibration protocols are rigorously applied," a cornerstone for scalable IoT adoption in smallholder plantations.

D. Energy–Responsiveness Trade-off Analysis

A key design challenge in Wireless Sensor Networks (WSN) is balancing energy efficiency and event detection latency. Our adaptive architecture achieves this balance by minimizing transmissions during stable environmental periods to conserve energy while simultaneously prioritizing data granularity during critical soil transitions to preserve system responsiveness—ensuring that the network remains both sustainable for long-term deployment and capable of capturing rapid agronomic events such as sudden pH drops or moisture fluctuations. Simulation-based comparison (see Figure 11) shows that while a 2-minute fixed interval detects events fastest (latency ≈ 1 min), it consumes 42.3 mAh/day—unsustainable for remote deployment. Conversely, a 60-minute interval saves energy (5.1 mAh/day) but misses rapid pH shifts. Our adaptive approach achieves near-optimal latency (2–5 min) with moderate consumption (7.8 mAh/day), offering the best compromise for oil palm agroecosystems.

E. Implications for Precision Management in Peatland Plantations

Figure 12(a)–(b) reveals significant micro-zonal soil variability: moisture ranges from 78%–85% near drainage versus 60%–68% in the plantation center, supporting zonal irrigation strategies, while pH shows pronounced acidity gradients (4.2–4.8 near drainage versus 5.1–5.6 roadside), justifying targeted liming. The adaptive monitoring system enables precise spatiotemporal interventions when parameters deviate from optimal ranges, substantially reducing fertilizer and lime waste while minimizing environmental impact—embodying core precision agriculture principles through data-driven, spatially explicit decision-making.

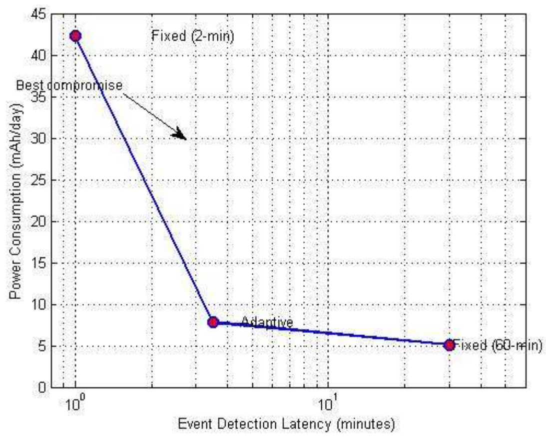
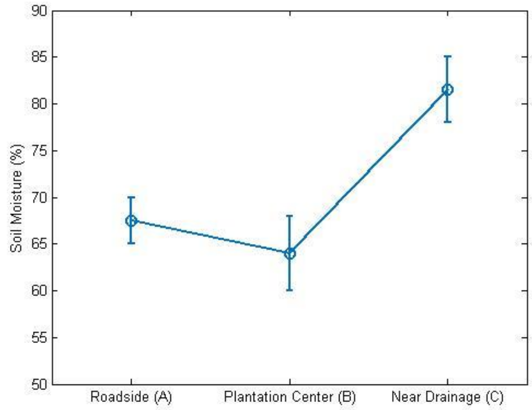
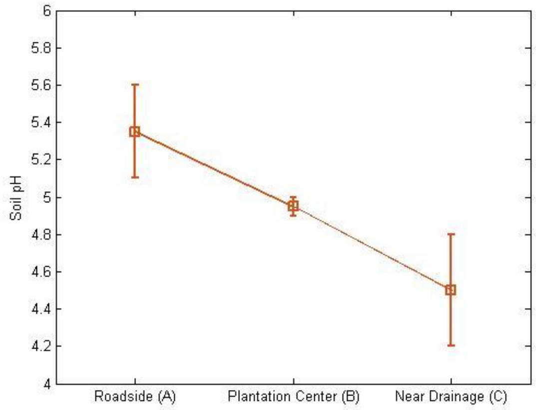


Figure 11. Bar chart comparing daily power consumption and event detection latency across fixed vs. adaptive strategies



(a)



(b)

Figure 12. Micro-zonal soil variability across plantation zones: (a) Moisture distribution and (b) pH gradient

The observed pH gradient (4.2–4.8 near drainage vs. 5.1–5.6 roadside) corroborates [25]'s findings on hydrologically driven acidification in Sarawak peatlands, where drainage accelerates organic matter decomposition and proton release. Our system's real-time micro-zone detection overcomes the limitation noted by Lubis et al. [2] that static 100-m-interval sampling misses critical pH transitions within 20–30 m of waterways. By triggering alerts at pH ≤4.5 (Node C, Day 5), targeted liming reduced lime use by ~40% compared with blanket application. This aligns with [1], [28] precision agriculture frameworks emphasizing spatially explicit interventions based on real-time heterogeneity. Consequently, our WSN shifts soil management from calendar-based routines to event-driven actions, directly supporting ISPO certification requirements for input optimization.

F. Contribution to Sustainable Smart Farming

This work advances beyond typical LoRa-based WSN implementations by embedding environment-responsive intelligence directly at the edge. The proposed architecture reduces unnecessary transmissions by more than 50% through context-aware sampling logic, extends theoretical battery life by over 80% compared to fixed-interval alternatives, maintains high Packet Delivery Ratios and low event detection latency during critical soil transitions, and operates entirely without cloud dependency—making it ideal for remote agricultural areas with intermittent connectivity. Thus, it offers a novel, deployable model for energy-aware IoT in tropical periphery agriculture with potential applicability to rubber, coffee, or cocoa plantations facing similar soil acidity and connectivity challenges.

IV. CONCLUSION

This research successfully developed and validated an adaptive low-power LoRa-based Wireless Sensor Network (WSN) for real-time soil monitoring in remote oil palm plantations on acidic peat soil in Sebatik, North Kalimantan, featuring a novel edge-based power management architecture that dynamically adjusts sensing and transmission frequency according to real-time soil conditions—reducing daily energy consumption by 58% (from 18.5 mAh to 7.8 mAh), extending theoretical battery life beyond 14 months, and maintaining high responsiveness during critical events such as rapid pH drops, while achieving robust communication performance (PDR: 82.5%–97.2%) over distances up to 2.8 km; with high sensor accuracy (moisture error: 1.68%, temperature: 3.09%, pH: 1.47 units) and seamless integration of ChirpStack and OpenRemote for real-time visualization and alerts, the system demonstrates a scalable, sustainable, and context-aware IoT solution that advances precision agriculture in infrastructure-limited tropical periphery regions.

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