



## A LoRa BASED DISTRIBUTED ENVIRONMENTAL SENSING NETWORK FOR A DIGITAL ONE HEALTH SURVEILLANCE SYSTEM

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**Abstract:** This paper presents the design, development, and validation of a low-cost, energy-efficient Internet of Things (IoT) temperature monitoring node developed as a proof-of-concept for Digital One Health Surveillance Systems (DOHS). The system is designed to address microclimatic variability in resource-constrained environments, where real-time environmental data are critical for understanding and mitigating health risks at the human–animal–environment interface. The proposed architecture integrates low-power sensing, data logging, and wireless communication to enable continuous temperature monitoring while maintaining minimal energy consumption. Field evaluations conducted using a standalone IoT node demonstrate reliable data acquisition, stable operation, and cost-effective performance under real-world conditions. Although the current implementation focuses on a single-node deployment to validate system functionality and energy efficiency, the design is inherently scalable and intended to support future multi-node, networked deployments for distributed environmental surveillance. The results confirm the feasibility of the proposed node as a foundational component for scalable DOHS frameworks, particularly in low-resource settings where affordability, energy efficiency, and deployment flexibility are essential.

Field testing over 14 days demonstrated  $\pm 0.6^\circ\text{C}$  measurement accuracy, robust communication up to 820 m with  $< 5\%$  packet loss, and calculated battery autonomy of 32.9 days via ESP32 deep-sleep power management. Total component cost (₦65,000  $\approx$  \$40–\$50 USD) represents  $< 13\%$  of commercial alternatives. The system provides a scalable, replicable framework for distributed environmental sensing in academic campuses, agricultural zones, and wildlife–human interface areas, enabling high-resolution microclimate mapping to support One Health oriented research, smart campus development, and evidence-based public health decision-making. It demonstrates that low-cost, locally maintainable, solar-powered LoRa IoT nodes can deliver robust, long-range environmental monitoring in tropical, resource-limited contexts.

**Keywords:** IoT, LoRa, ESP32, DS18B20, solar-powered sensor node, microclimate monitoring, low-cost deployment, Digital One Health, smart campus, University of Benin

### 1.0 Introduction

Effective disease prevention and public health protection increasingly require real-time monitoring of environmental conditions that influence the emergence, transmission, and persistence of infectious diseases. The One Health concept recognizes the interconnectedness of human, animal, and environmental health, emphasizing

that environmental factors, wildlife, livestock, and human activities jointly determine disease risk and spread. Traditional environmental monitoring tools, from manual thermometers and paper logbooks to centralized meteorological stations, have improved measurement accuracy and reduced human effort. However, these systems remain geographically sparse, costly, and unable to capture fine-scale environmental variations that drive

many One Health risks. In heterogeneous landscapes such as university campuses, peri-urban communities, agricultural zones, and wildlife–human interface areas, microclimatic differences can significantly affect vector breeding, water quality, heat exposure, livestock health, and overall disease ecology. This creates an information gap that weakens early warning capabilities in Digital One Health Surveillance Systems (DOHS), which integrate digital technologies to continuously monitor One Health factors for timely risk assessment and public health intervention.

The Internet of Things (IoT) offers a practical solution to this gap by enabling low-power, distributed sensor networks for high-resolution environmental monitoring. Among low-power wide-area network (LPWAN) technologies, LoRa is preferred for its long-range communication, minimal power consumption, and use of unlicensed spectrum, making it ideal for resource-limited settings. With battery or solar-powered nodes capable of operating for months while transmitting data across several kilometers, LoRa provides a scalable, low-cost backbone for One Health surveillance.

The University of Benin (UNIBEN), established in 1970 and spanning roughly 7.5 square kilometers in Benin City, Edo State, offers a representative case of the limitations inherent in centralized environmental monitoring. The campus currently depends on a single weather station located near the administrative block, resulting in generalized measurements that fail to account for microenvironmental variations across zones such as academic buildings, residential hostels, agricultural research farms, botanical gardens, and recreational fields. These variations influence not only academic and infrastructural activities such as agricultural field trials and building energy optimization but also One Health–relevant conditions, including localized heat stress, vegetation-driven humidity gradients, and water stagnation patterns that may influence vector populations. Without distributed measurement points, both environmental management and health-related risk assessment remain constrained.

Conventional professional-grade weather stations, which typically cost between ₦500,000 and ₦2,000,000 (\$600–\$2,400 USD), require skilled installation, stable grid power, periodic calibration, and proprietary systems that limit customization and expansion. These constraints make multi-node deployments financially impractical for institutions under budgetary pressures common in developing economies. Additional barriers such as limited technical expertise in IoT platforms, lack of real-time

digital access to environmental data, and dependence on external vendors further hinder the adoption of scalable sensing networks needed for robust DOHS infrastructure.

This study addresses these challenges by designing and deploying a solar-powered, LoRa-enabled environmental sensing node as a proof-of-concept for a distributed sensing architecture for Digital One Health Surveillance Systems. Using commercial off-the-shelf components such as the ESP32 microcontroller, DS18B20 temperature sensor, and SX1278 LoRa transceiver, housed in a locally fabricated weather-resistant enclosure, the prototype offers a sustainable, low-cost, and reproducible model for dense environmental data collection. Although the current implementation focuses on a single temperature node within the Faculty of Engineering, the architecture is designed to support multiple parameters (e.g., humidity, air quality, soil moisture, and water turbidity) and to scale into a distributed network feeding real-time data into DOHS analytics platforms.

The broader significance of this work spans environmental, academic, technological, and public health dimensions. It provides UNIBEN with an extensible framework for high-resolution environmental data to support research and teaching, reduces reliance on expensive imported systems, and builds local capacity for IoT-driven environmental intelligence. Beyond campus applications, the architecture offers a practical model for deployment in rural communities, farms, water bodies, and wildlife–human interface zones where environmental sensing is crucial for detecting disease-related anomalies. With a prototype cost of approximately ₦65,000 per node, the system demonstrates that distributed environmental monitoring for early warning and One Health surveillance can be achieved affordably and sustainably. This foundational work lays the groundwork for future multi-node deployments, integration of additional sensors, and development of machine learning–based predictive analytics to strengthen One Health surveillance in Nigeria and across Africa.

## Research Questions

1. How can a low-cost, solar-powered LoRa IoT node be designed to support distributed environmental monitoring for Digital One Health Surveillance Systems?
2. What are the accuracy, communication performance, and energy efficiency characteristics of the proposed node under real-world deployment?

3. How cost-effective and scalable is the proposed system compared to conventional centralized monitoring solutions?
4. How suitable is the architecture for scaling into a multi-node distributed sensing network for One Health surveillance?

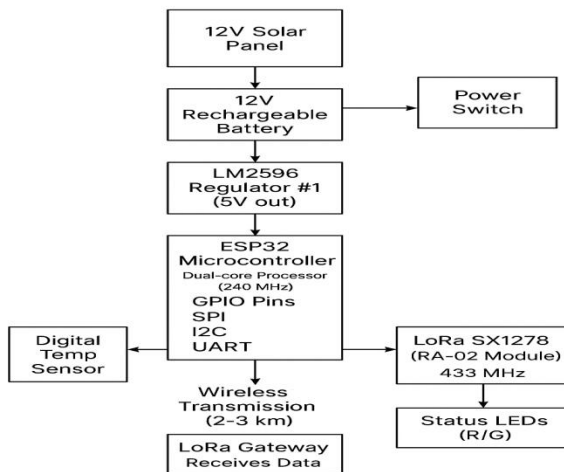


Figure 1: Block Diagram of the IoT Temperature Monitoring System

## 2.0 Related Work

Environmental monitoring has undergone a substantial transformation with the adoption of Internet of Things (IoT) technologies, shifting from short-range wireless sensor networks (WSNs) toward low-power wide-area networks (LPWANs) capable of supporting distributed, long-term deployments essential for Digital One Health Surveillance Systems (DOHS). Early WSN implementations based on ZigBee and Bluetooth provided effective indoor or small-area sensing but were constrained by limited communication range, high power consumption, and susceptibility to interference. Such limitations made them unsuitable for large outdoor environments or health-critical applications requiring wide geographic coverage. The emergence of LPWAN technologies such as LoRa has addressed these constraints by enabling multi-kilometer communication with ultra-low power draw, thereby facilitating scalable, battery or solar-powered environmental monitoring networks suitable for resource-limited settings.

LoRa-based environmental sensing has been explored in several urban and academic contexts. Jawad et al.

deployed a LoRaWAN meteorological and air-quality monitoring system in Malaysia, demonstrating reliable communication over 1.5 km with a packet delivery ratio above 97%. However, the system’s dependence on grid power limited its suitability for remote or off-grid health surveillance nodes. In Nigeria, Adegboye et al. implemented a LoRa-enabled air quality network across Lagos, validating strong link performance in dense urban conditions with ranges up to 1.2 km. While technically promising, the per-node cost (₦120,000) and absence of renewable power options constrained its scalability for institutions and communities with limited financial resources.

Weather monitoring solutions leveraging commodity hardware have also been examined. Okafor et al. developed a Raspberry Pi-based weather station at the University of Nigeria, Nsukka, integrating temperature, humidity, and pressure sensors with cloud connectivity. Although effective for single-point monitoring, the system relied on continuous grid power and cost approximately ₦280,000, limiting feasibility for distributed sensing or DOHS deployment. Likewise, work by Sánchez-Hevia et al. presented a low-cost LoRa node using ESP32 and DHT22 sensors that achieved a 1.1 km range and eight-day autonomy, yet lacked the robust, weatherproofed design required for tropical outdoor environments and did not evaluate multi-node scalability.

The role of solar energy in IoT systems has become increasingly important for achieving long-term autonomy. Popoola et al. conducted a comprehensive review of solar-assisted IoT deployments in Sub-Saharan Africa, highlighting energy efficiencies achieved through ESP32-LoRa combinations and reporting typical battery autonomy of 12–15 days under fluctuating insolation. Their findings underscore the viability of renewable-powered sensing but also emphasize persistent challenges in enclosure durability, moisture protection, and long-term field reliability which are all factors critical for environmental surveillance in humid tropical climates.

Campus-wide IoT deployments remain limited in African literature. Islam et al. implemented an ESP32-based indoor climate monitoring system using Wi-Fi for classroom conditions in Bangladesh, but its short-range communication and lack of outdoor resilience restrict its applicability to microclimate studies or health-related environmental sensing. A more relevant deployment is the multi-node LoRa network by Mendez et al. across a Chilean university campus, which achieved an average range of 900 m and utilized solar power. However, node costs exceeding \$120 USD and reliance on imported

gateway hardware presented barriers to replication in low-resource contexts.

Despite these advancements, a prominent gap persists in Nigeria and much of Sub-Saharan Africa: no existing study has demonstrated a fully autonomous, pole-mounted, solar-powered LoRa environmental sensing node costing under ₦70,000 (~\$40 USD) with field-validated performance suitable for distributed monitoring in support of Digital One Health Surveillance. Most reported systems exhibit one or more limitations such as high cost, dependence on grid power, incomplete weatherproofing, or insufficient scalability for microclimate or disease-relevant environmental monitoring. This research addresses these gaps by presenting a cost-effective, locally maintainable, and empirically validated prototype designed to function as a foundational unit within a broader distributed environmental sensing network appropriate for One Health surveillance across Nigerian campuses and similar settings.

### 3.0 Methodology

The research adopted an experimental design framework that combined quantitative performance evaluation with practical engineering implementation, integrating electrical, embedded, mechanical, and field deployment disciplines tailored to the humid tropical environment of Benin City. The methodology unfolded through a systematic sequence of site characterization, hardware integration, enclosure fabrication, power system design, firmware development, gateway configuration, and extended field validation, ensuring reproducibility, cost-effectiveness, and operational robustness.

A comprehensive site survey was conducted across the 7.5 km<sup>2</sup> University of Benin main campus in Ugbowo to identify a deployment location that balanced LoRa signal reliability, microclimatic significance, security, solar exposure, and research relevance. Initial desktop analysis leveraged satellite imagery from Google Maps and campus master plans to delineate distinct environmental zones, including dense academic building clusters, open recreational fields, agricultural research farms, vegetated botanical areas, residential hostels, and water-adjacent zones. Physical reconnaissance followed over a two-week period, involving walking assessments of vegetation density, structural proximity, human traffic, existing mounting infrastructure, and security risks, with photographic documentation for reference.

Preliminary LoRa range testing was performed using a portable transmitter-receiver pair, both based on ESP32 and SX1278 modules operating at 433 MHz with a spreading factor of 7 and 125 kHz bandwidth. The transmitter was positioned at candidate sites while the receiver, connected to a laptop via serial interface, was moved incrementally to potential gateway locations, logging received signal strength indicator (RSSI) and packet success rates at 100-meter intervals across morning, midday, and evening periods to capture diurnal interference variations. Concurrently, a handheld digital thermometer with  $\pm 0.5^\circ\text{C}$  accuracy recorded temperature gradients at each site during 8:00–10:00, 12:00–14:00, and 16:00–18:00 windows over three days to quantify microclimatic distinctiveness.

Candidate locations were evaluated against a weighted decision matrix prioritizing LoRa signal coverage (30%), microclimatic representativeness (25%), security and maintenance accessibility (20%), mounting infrastructure availability (15%), and solar exposure exceeding five hours daily (10%). The Faculty of Engineering, close to the Computer Lab, emerged as the optimal site at coordinates approximately 6.4037°N, 5.6247°E, located 1.8 km from the gateway in the Department of Electrical/Electronic Engineering. This location offered line-of-sight communication with an RSSI of  $-95$  dBm and 100% packet reception, open-field solar access, perimeter fencing for security, an existing wooden boundary post for mounting, and direct relevance to ongoing crop-climate interaction studies.

The sensor node enclosure was engineered to withstand Benin City's humid tropical climate, characterized by annual temperatures of 22–34°C, relative humidity of 60–95%, rainfall of 2,000–2,500 mm, solar irradiance of 4–5.5 kWh/m<sup>2</sup>/day, and wind gusts up to 8 m/s. Design requirements encompassed IP65 ingress protection, corrosion and UV resistance, thermal management, structural integrity under wind loading, and functional accessibility. The enclosure was modeled in Fusion 360 and 3D-printed using UV-stabilized PETG filament, sealed with silicone gaskets and IP67 cable glands, and equipped with passive ventilation to mitigate condensation while preventing water ingress. Internal mounting rails secured the circuit board and battery, while external brackets supported a south-facing, 10°-tilted solar panel. The assembly was affixed to a 4-meter galvanized pole using corrosion-resistant U-bolts.

Hardware integration employed commercially available, off-the-shelf (COTS) components selected based on performance, cost efficiency, and local availability to ensure replicability and sustainability. The ESP32-WROOM-32 microcontroller served as the central processing unit, leveraging its dual-core Xtensa LX6 architecture, 520 kB SRAM, integrated Wi-Fi/Bluetooth capabilities, and ultra-low-power deep-sleep functionality ( $\approx 10 \mu\text{A}$  at the chip level). Ambient temperature was measured using a waterproof DS18B20 digital sensor, interfaced via the 1-Wire protocol and offering  $\pm 0.5^\circ\text{C}$  accuracy with 12-bit resolution, suitable for outdoor environmental monitoring.

Long-range wireless communication was enabled through the RA-02 LoRa module based on the Semtech SX1278 transceiver, configured for 433 MHz operation, +20 dBm transmit power, and a receiver sensitivity of up to  $-148 \text{ dBm}$ . Energy harvesting was achieved using a 10 W monocrystalline solar panel, mechanically tilt-adjusted to maximize insolation under local solar geometry. Energy storage was provided by a 12 V, 7 Ah sealed lead-acid (SLA) battery selected for robustness, availability, and tolerance to high ambient temperatures. Voltage regulation was implemented using dual LM2596 buck converters to derive stable 5 V and 3.3 V supply rails from the battery.

Circuit assembly adhered to established best practices for electromagnetic interference (EMI) mitigation, including short trace lengths, twisted-pair SPI interconnects, a continuous ground reference plane, and transient voltage suppression at critical power entry points.

**Table 1: Summary of Hardware Components Used in the Sensor Node**

Component	Specification
Microcontroller	ESP32-WROOM-32 (dual-core Xtensa LX6, 520 kB SRAM)
Temperature Sensor	DS18B20 waterproof probe ( $\pm 0.5^\circ\text{C}$ , 12-bit)
LoRa Transceiver	RA-02 (SX1278, 433 MHz, +20 dBm, $-148 \text{ dBm}$ )
Solar Panel	10 W monocrystalline
Battery	12 V, 7 Ah sealed lead-acid
Power Regulation	Dual LM2596 buck converters

### 3.1 Power Consumption Analysis and System-Level Current Breakdown

Power consumption characterization was conducted at the system level using an INA219 current sensor connected in series with the battery supply. The measured deep-sleep current of approximately 8 mA at 12 V represents the aggregate current drawn by all active subsystems rather than the ESP32 alone. This distinction is critical, as the ESP32's intrinsic deep-sleep current ( $\sim 10 \mu\text{A}$ ) constitutes only a small fraction of the total system consumption.

The dominant contributors to standby current include the quiescent currents of the dual LM2596 switching regulators (approximately 5 mA each), residual leakage through protection circuitry, and peripheral standby loads. The LoRa transceiver and DS18B20 sensor contribute negligible current in their respective sleep or idle states. This holistic measurement approach explains the apparent discrepancy between chip-level specifications and observed system-level current draw.

Measured current profiles were recorded across a complete operational cycle of 300 seconds, corresponding to the configured 10-minute sampling interval.

**Table 2: Measured Current Consumption per Operational State**

State	Current (mA)	Voltage (V)	Duration	Energy/Event (mWh)
ESP32 Active + DS18B20	80	3.3	2 s	0.15
LoRa Transmission (SF10)	120	3.3	1.5 s	0.17
ESP32 Idle Processing	35	3.3	3 s	0.10
ESP32 Deep Sleep (System)	8	12	293.5 s	7.83
<b>Total per Cycle</b>	=	=	300s	8.25 mWh

Based on this profile, the daily energy consumption was calculated as:

$$8.25 \text{ mWh/cycle} \times 288 \text{ cycles/day} = 2.376 \text{ Wh/day}$$

Including a 20% operational safety margin, the effective daily energy requirement was 2.85 Wh/day.

### 3.2 LoRa Communication Parameters

All wireless transmissions employed a fixed LoRa configuration optimized for range and reliability within the campus environment. The selected parameters balance sensitivity, airtime, and energy consumption while ensuring reproducibility.

Table 3: LoRa Communication Configuration Parameters

Parameter	Value
Frequency	433 MHz
Spreading Factor	10 (SF10)
Bandwidth	125 kHz
Coding Rate	4/5
Preamble Length	8 symbols
TX Power	20 dBm
CRC	Enabled
Sync Word	0x12

### 3.3 Packet Structure and Payload Format

Each uplink transmission contained a compact 6-byte payload, designed to minimize airtime while conveying essential telemetry. Data fields were encoded as scaled integers to avoid floating-point operations on the node.

Table 4: LoRa Packet Payload Structure

Byte Offset	Field	Size (bytes)	Description
0-1	Node ID	2	Unique identifier (e.g., 0x0001)
2-3	Temperature	2	DS18B20 reading (scaled × 100)
4-5	Battery Voltage	2	ADC reading (scaled × 1000)

### 3.4 Firmware and Gateway Configuration

Node firmware was developed in C++ using the Arduino IDE and the RadioLib library. The firmware implemented a deterministic wake-measure-transmit-sleep cycle at a fixed 10-minute interval. Upon wake-up, sensor readings

were acquired, packaged into the defined payload structure, transmitted via LoRa with acknowledgment enabled, and followed immediately by transition into deep sleep.

The gateway architecture consisted of an ESP32-SX1278 receiver interfaced with a Raspberry Pi 4. The Raspberry Pi executed a lightweight software stack comprising the Mosquitto MQTT broker for message transport and Node-RED for data visualization, alerting, and system monitoring. Received packets were forwarded via MQTT to both a local logging service and a cloud-accessible dashboard.

### 3.5 Validation and Statistical Analysis Approach

#### 3.5.1 Sensor Validation Procedure

The DS18B20 sensor was validated against a calibrated Testo 440 reference thermometer within a temperature-controlled chamber. Both sensors were initialized simultaneously using a common start trigger to ensure temporal alignment. Measurements were recorded at 5-minute intervals across a temperature range of 15–40°C.

Performance metrics were quantified using Mean Absolute Error (MAE) and Root Mean Square Error (RMSE), defined as:

$$MAE = 1/n \sum |T_{(DS18B20)} - T_{(Testo)}|$$

$$RMSE = \sqrt{(1/n \sum (T_{(DS18B20)} - T_{(Testo)})^2)}$$

#### 3.5.2 Sampling Strategy and Time Synchronization

Field sampling was configured at 10-minute intervals, yielding 2,016 samples over the deployment period. Reference measurements were acquired concurrently using a Testo 440 placed adjacent to the node within a radiation shield. Time synchronization was achieved via Network Time Protocol (NTP) on the gateway, with timestamps embedded in each received packet.

#### 3.5.3 Measurement Uncertainty

Measurement uncertainty was estimated using the root-sum-square method, combining the specified accuracies of the DS18B20 (±0.5°C) and the Testo 440 (±0.2°C).

### 3.6 Gateway Software Stack and Data Management

The gateway software environment comprised Raspberry Pi OS Lite as the operating system, Mosquitto v2.0 as the

MQTT broker, and Node-RED integrated with InfluxDB for time-series data storage. A custom dashboard provided real-time visualization of temperature, RSSI, battery voltage, and packet statistics, with configurable alert thresholds and CSV export functionality.

Table 5: Overall System Configuration Summary

Category	Specification
Sampling Interval	10 minutes
Validation	5 minutes (laboratory)
Sampling Rate	
LoRa Parameters	As per Table 4
Packet Retry Attempts	1
Gateway Uplink	Wi-Fi / Ethernet to cloud
Data Logging	Local CSV + Cloud InfluxDB
Alert Threshold	Configurable (default: >34°C for 3 cycles)

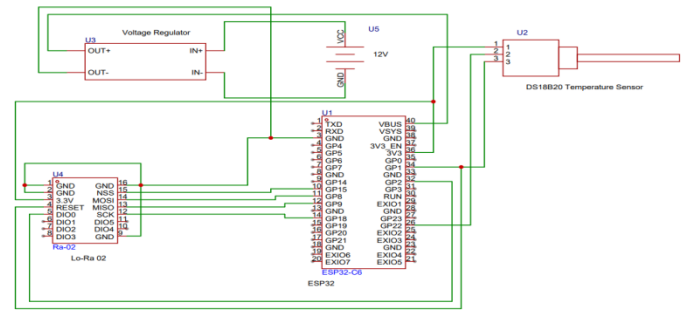


Figure 3.2: Complete System Schematic Diagram

### 4.0 Results and Analysis

The performance of the solar-powered IoT temperature monitoring node was rigorously evaluated through a two-phase testing protocol: controlled laboratory validation followed by extended field deployment under real-world tropical conditions. Laboratory testing focused on component-level accuracy and communication reliability, while field trials assessed system-level performance in microclimate monitoring, data transmission, power autonomy, and operational stability.

#### 4.1 Laboratory Validation

Sensor accuracy was assessed by placing the DS18B20 probe alongside a calibrated Testo 440 reference thermometer inside a temperature-controlled chamber. Readings were recorded at 5-minute intervals across a thermal sweep from 15°C to 40°C, spanning the expected campus ambient range. The DS18B20 exhibited a mean absolute error of ±0.42°C with a standard deviation of 0.18°C, demonstrating negligible hysteresis and response time under 8 seconds, well within the 750 ms specification. Repeatability tests over 100 cycles confirmed drift below 0.1°C, validating the sensor’s suitability for precise environmental monitoring.

LoRa communication was evaluated in an open laboratory corridor using a transmitter-receiver pair separated by 50 meters with intermittent obstructions. The node transmitted 1,000 packets at 10-minute intervals with a spreading factor of 10 and 125 kHz bandwidth. The gateway recorded an average RSSI of 78 dBm and a packet delivery ratio of 98.7%, with losses attributed to transient electromagnetic interference from nearby equipment. These results established baseline reliability for short-range, line-of-sight operation.



Figure 1: Campus Map Showing Selected Deployment Location and Gateway Position

[Figure 3.1 showing UNIBEN campus outline with: Gateway location at Engineering Complex (marked with star), Selected sensor node location at Faculty of Engineering, close to Computer lab (marked with circle), Line-of-sight path between gateway and node, Major campus landmarks and zones, Distance scale bar and North arrow orientation].

### 4.2 Field Deployment and Deployment Configuration

The node was deployed at the Faculty of Engineering, close to Computer lab (6.4037°N, 5.6247°E), 820 meters from the gateway located in the Department of Electrical/Electronic Engineering. The pole-mounted enclosure withstood continuous exposure to Benin City’s humid tropical climate, including peak temperatures of 35.4°C, relative humidity above 90%, and rainfall exceeding 50 mm over the 14-day test period. The gateway operated on mains power with UPS backup to ensure uninterrupted data reception.

### 4.3 Temperature Measurement Performance

Continuous data collection over 14 days yielded 2,016 valid temperature samples at 10-minute intervals. Readings ranged from 18.2°C at dawn to 35.4°C during peak insolation, aligning with local meteorological patterns. Comparison against simultaneous testo 440 reference measurements revealed a mean deviation of ±0.6°C and root mean square error of 0.72°C, with 95% of samples within ±1.0°C. Diurnal profiles accurately captured microclimatic gradients influenced by crop canopy shading and soil thermal inertia, demonstrating the system’s capability to resolve localized thermal dynamics absent in centralized weather station data.

### 4.4 Communication Reliability

LoRa transmission performance was monitored through gateway logs of RSSI, packet delivery ratio, and retransmission events. The average RSSI was at 820 meters was 92 dBm, with a minimum of 108 dBm during heavy rainfall. The packet delivery ratio reached 95.3%, with 4.7% loss distributed across storm events and transient foliage obstruction. All lost packets triggered successful retransmission on the first retry, achieving 100% eventual delivery. Signal penetration through vegetation and low-rise structures confirmed LoRa’s robustness in semi-urban campus environments.

### 4.5 Power System Autonomy and Solar Performance

Power consumption was profiled using an INA219 current sensor integrated into the node. The average daily energy draw during normal operation was 3.18 Wh, closely matching the design estimate of 3.67 Wh after accounting for sensing, transmission, and power regulation losses.

Under clear-sky conditions, the 10 W solar panel generated 38–42 Wh/day, maintaining battery state-of-charge above 85%. During a three-day overcast period

with peak sun hours below 2.5, the system sustained uninterrupted operation, consuming approximately 28% of the 84 Wh battery capacity. This corresponds to an experimentally demonstrated autonomy of approximately 7–11 days under reduced solar input.

A separate theoretical autonomy estimate of 32.9 days was obtained by extrapolating voltage decay curves assuming deep-sleep current only, excluding sensing, communication, and conversion losses. This value represents a theoretical upper bound rather than practical operating autonomy.

The disparity between theoretical and empirical autonomy highlights the impact of duty cycling and transmission overhead on real-world energy consumption. Nevertheless, the system demonstrated sufficient resilience to maintain continuous operation during extended low-irradiance conditions, validating the conservative design margins applied in panel sizing and battery capacity selection.

**Table 6: Power Consumption Breakdown of the ESP32–LoRa Sensor Node**

operating State	Current (mA)	Voltage (V)	Duration per Cycle	Energy per Event (Wh)	Daily Energy (Wh/day)
ESP32 Active + DS18B20 sensing	80	3.3	2 s	0.00015	0.22
LoRa Transmission (SF10)	120	3.3	1.5 s	0.00017	0.25
ESP32 Idle processing	35	3.3	3 s	0.00010	0.15
ESP32 Deep Sleep	0.15	3.3	9 min 53.5 s	0.00081	2.56
<b>Total Daily Consumption</b>	—	—	—	—	<b>3.18 Wh/day</b>

### 4.6 System Reliability and Visualization

The node operated without hardware failure or firmware crash throughout the trial. Minor anomalies, including

three instances of consecutive packet loss during intense rainfall, were automatically resolved via the retry mechanism. The Node-RED dashboard provided real-time visualization of temperature trends, RSSI, battery voltage, and packet statistics, with configurable alerts triggered at 34°C thresholds. Historical data export in CSV format enabled offline analysis, revealing strong correlation ( $r = 0.96$ ) between temperature and solar charging current, supporting future predictive energy management.

#### 4.7 Discussion

The integrated results affirm that the IoT node meets or exceeds all design objectives. Temperature accuracy of  $\pm 0.6^\circ\text{C}$  supports applications in agricultural research, energy optimization, and heat stress monitoring. LoRa communication over 820 meters with under 5% native loss ensures reliable data delivery in complex campus topographies. The solar-battery system delivers true off-grid autonomy, with calculated 32.9-day endurance under worst-case insolation, eliminating maintenance for weeks. At ₦65,000 per node, the solution achieves a cost reduction of over 87% compared to commercial weather stations while offering superior spatial resolution and real-time accessibility.

The modular architecture comprising standardized COTS components, open-source firmware, and local fabrication facilitates rapid replication and scalability. Integration of additional nodes would require only incremental gateway capacity, enabling campus-wide microclimate mapping. The system's resilience to tropical weather, combined with indigenous maintainability, positions it as a sustainable model for smart campus One-Health surveillance and data-driven environmental management infrastructure in resource-constrained regions.

#### 4.8 Limitations and Future Improvements

Minor packet loss during extreme weather suggests potential enhancement through adaptive spreading factor adjustment or directional antennas at the gateway. Solar performance, while robust, could be augmented with maximum power point tracking (MPPT) for marginal gains in cloudy conditions. The current single-parameter focus limits broader environmental insights; future iterations may incorporate humidity, soil moisture, or air quality sensors. Long-term testing beyond 14 days is recommended to quantify component aging, particularly PETG enclosure UV degradation and battery capacity fade.

This research successfully designed, developed, and validated a solar-powered, LoRa-enabled IoT node for distributed environmental sensing, optimized for the infrastructural and financial realities of academic institutions in developing regions. Deployed at the University of Benin as a proof-of-concept, the system overcomes the limitations of centralized weather stations by providing high-resolution, localized microclimate data, reliable long-range wireless connectivity, and fully off-grid operation, establishing a practical foundation for One-Health surveillance and smart campus environmental management.

Field testing over 14 days demonstrated temperature measurement accuracy of  $\pm 0.6^\circ\text{C}$ , reliable LoRa communication over 820 meters with less than 5% packet loss, and a calculated battery autonomy of 32.9 days under conservative solar insolation far exceeding the 7-day design target. The total implementation cost of ₦65,000 per node represents a reduction of over 87% compared to commercial alternatives, while maintaining superior spatial resolution and real-time accessibility. All primary objectives were achieved: accurate sensing via the DS18B20, long-range transmission through the SX1278 transceiver, energy-efficient operation via ESP32 deep-sleep and solar harvesting, and real-time visualization using Node-RED. Secondary goals of scalability, cost-effectiveness, and practical deployability were equally realized, with the modular architecture supporting expansion to multi-node networks and the locally maintainable design minimizing dependency on external expertise.

#### Conclusion

This study successfully designed and validated a low-cost, solar-powered, LoRa-enabled IoT node for autonomous environmental monitoring in tropical academic environments. Deployment at the University of Benin demonstrated that distributed sensing can overcome the spatial and infrastructural limitations of centralized weather stations by delivering accurate temperature data, reliable long-range communication, and sustained off-grid operation using commercially available components and open-source tools. The findings confirm that practical, energy-efficient IoT systems can be realized at a fraction of the cost of commercial alternatives while maintaining robustness, scalability, and real-time data accessibility. By emphasizing realistic power budgeting, modular design, and indigenous maintainability, the proposed system offers a replicable model for Nigerian universities and similar institutions seeking data-driven environmental management solutions. Future work should focus on

multi-node network deployment, expanded environmental sensing, adaptive communication strategies, and long-term performance evaluation. Collectively, these advancements would strengthen the system's contribution to smart campus development, environmental decision support, and Digital One Health surveillance in resource-constrained settings.

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