An Open-Source IoT and Edge-Driven Architecture for Smart Agricultural Production and Post-Harvest Management in Tropical West Africa

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Abstract:

*Agriculture in tropical West Africa faces persistent challenges associated with environmental unpredictability, post-harvest losses, and inadequate digital infrastructure. This paper presents the design and implementation of an open-source Internet of Things (IoT) and edge-driven architecture for smart agricultural production and post-harvest management, developed to enhance data-driven decision-making and operational efficiency in low-resource environments. The proposed system integrates low-cost IoT sensor nodes, a Raspberry Pi-based edge gateway, and a cloud synchronization module to achieve real-time monitoring of crop growth, grain storage conditions, and environmental parameters. Edge computing was implemented to enable local data analytics and control automation, reducing latency and bandwidth dependency. The system architecture follows a modular design, allowing scalability and interoperability with existing open-source tools such as Django, Node-RED, and PostgreSQL. Field tests conducted in **Benue State, Nigeria** demonstrated reliable data transmission (97.6%), reduced latency (1.4 seconds average), and improved energy efficiency through edge-layer preprocessing. The research contributes to the development of cost-effective, open, and sustainable digital solutions for smart farming and post-harvest management in tropical West Africa.*

Keywords: *Internet of Things (IoT), Edge Computing, Post-Harvest Management, Open-Source Systems, Smart Agriculture, West Africa.*

I. **Introduction**

Agriculture remains the backbone of West Africa’s economy, employing over 60% of the labor force and contributing significantly to GDP [1]. Despite its importance, agricultural productivity in the region continues to be constrained by erratic rainfall patterns, inadequate mechanization, poor data access, and post-harvest losses that average between 30–50% in perishable commodities [2], [3]. Climate variability, soil degradation, and unreliable infrastructure further compound these challenges, limiting smallholder farmers' ability to make timely, data-driven decisions [4]. In response, digital agriculture technologies, including the Internet of Things (IoT), edge computing, and artificial intelligence (AI), have emerged as transformative tools capable of improving efficiency, resilience, and sustainability across the agricultural value chain [5], [6].

The Internet of Things (IoT) enables real-time data collection from sensors monitoring soil moisture, temperature, humidity, and crop health, thereby facilitating precision agriculture practices [7]. However, traditional cloud-dependent IoT systems often face limitations in tropical West African contexts due to unreliable internet connectivity, high latency, and power instability [8]. These infrastructural challenges necessitate computing paradigms that can operate autonomously and locally without constant cloud connectivity. This has led to the rise of edge computing, a distributed architecture where computation and analytics occur closer to data sources (e.g., on farms) using low-power microcontrollers or edge devices like Raspberry Pi or Jetson Nano boards [9]. By reducing network dependence and processing delays, edge computing enhances system responsiveness and reliability in resource-limited agricultural environments [10].

The adoption of open-source technologies further strengthens the sustainability and scalability of smart agricultural systems. Open frameworks such as Node-RED, ThingsBoard, Django, and Grafana offer cost-effective development options that foster interoperability and community-driven innovation [11]. This is particularly critical for developing regions, where proprietary solutions may be prohibitively expensive or inflexible [12]. As highlighted by Kalaany *et al.* [13], open-source IoT platforms have accelerated the deployment of low-cost agrometeorological stations in rural Africa, providing real-time weather and soil data for smallholder farmers. Similarly, Ugwu *et al.* [14] emphasize that combining IoT and edge analytics enhances resource optimization and predictive decision-making in tropical agro-ecosystems.

In this research, we propose the design and implementation of an open-source IoT and edge-driven architecture that integrates data acquisition, local analytics, and post-harvest management modules for smallholder farmers in tropical West Africa. The system aims to reduce post-harvest losses, improve production monitoring, and enhance decision-making autonomy even in low-connectivity regions. By leveraging open hardware (ESP32, Raspberry Pi) and open software (Node-RED, MQTT, InfluxDB, Grafana), the proposed system promotes affordability, transparency, and local adaptability. This work contributes to the ongoing discourse on digital transformation in African agriculture, offering a replicable model that aligns with the principles of climate-smart and sustainable farming [15], [16].

II. **Review of Related Literatures**

Recent years have seen a rapid proliferation of research in IoT, edge computing, and AI-driven agriculture, particularly in response to the growing demand for sustainable food systems in the developing world. This section critically reviews the literature across four interconnected themes:

a. IoT Systems and Sensor Networks,
b. Edge and Fog Computing in Agriculture,
c. Open-Source Platforms and Post-Harvest Management, and
d. African Implementations and Sustainability Frameworks.

A. IoT Systems and Sensor Networks

The Internet of Things (IoT) has become a cornerstone of precision agriculture, enabling farmers to collect and process real-time data on soil, crop, and environmental conditions.
Miller *et al.* [7] emphasized that IoT-enabled sensing systems—integrating temperature, humidity, and soil nutrient sensors—have revolutionized precision farming by providing continuous environmental monitoring for better decision-making. Ugwu *et al.* [3] further noted that the integration of IoT with machine learning (ML) algorithms can significantly enhance predictive modeling in crop management, reducing losses through early detection of stress factors.

However, most existing IoT solutions depend heavily on cloud-based architectures, which are not optimal for regions with unreliable network connectivity such as West Africa [4].
Phiri *et al.* [4] reviewed hybrid architectures and recommended IoT-edge integration as a viable solution for latency reduction and localized control in low-bandwidth environments. Ahmed *et al.* [10] reinforced this notion by developing an IoT-robotic framework that autonomously manages irrigation and soil monitoring in climate-smart agricultural systems.

Thus, IoT systems provide a strong foundation for precision agriculture, but their dependency on constant internet connectivity and centralized processing remains a major limitation that motivates the adoption of edge computing architectures.

B. Edge and Fog Computing for Agricultural Efficiency

Edge computing introduces local data processing closer to IoT devices, minimizing latency, reducing bandwidth usage, and enhancing system resilience in remote farming areas.

Kannan [11] highlighted that edge-driven frameworks offer the ability to perform real-time analytics and decision-making even during connectivity interruptions, making them particularly suitable for developing regions. Similarly, Bassine *et al.* [9] demonstrated how edge intelligence and fog nodes can optimize precision agriculture under the emerging concept of *Society 5.0 in Africa*, fostering sustainability and operational autonomy.

Ahmed *et al.* [10] proposed a multi-robot IoT-edge system that integrates local control loops with cloud coordination, showcasing energy efficiency and reduced latency in greenhouse environments. Ayorinde [5] also observed that integrating AI with edge computing reduces both ecological footprint and computational costs in sustainable farm management.

Recent research trends, such as those by Lamsal *et al.* [17] and Senoo *et al.* [18]**,** reveal the growing preference for hybrid IoT-edge-cloud frameworks in smallholder settings. Their results show over 30% latency reduction and improved decision response times when data preprocessing is executed on edge devices such as Raspberry Pi.

These findings establish edge computing as a crucial enabler for low-cost, low-latency smart farming, especially where cloud infrastructure is limited or unavailable.

C. Open-Source Platforms and Post-Harvest Management Systems

The emergence of open-source IoT platforms (e.g., Node-RED, Things Board, Django, Grafana) has lowered the technical and financial barriers to agricultural digitalization.

Kalaany *et al.* [8], [13] demonstrated the design of low-cost agrometeorological stations using ESP32 sensors and open-source data frameworks, improving local weather monitoring accuracy while maintaining affordability. Ugwu *et al.* [14] emphasized that open-source IoT systems, when integrated with AI, enable predictive analytics for yield forecasting and resource optimization in resource-limited agricultural ecosystems.

In the domain of post-harvest management, Mmbando [2] and Khan & Ashraf [15] highlighted the role of IoT-based sensors in temperature, humidity, and spoilage monitoring for stored grains, suggesting that smart post-harvest management could reduce losses by up to 40%.

Moreover, Ahmed *et al.* [16] and Sadiku [12] stressed that integrating open platforms with AI and edge computing allows localized control of storage conditions and early detection of post-harvest spoilage—critical for tropical regions where humidity fluctuations are severe.

The adaptability and affordability of open-source ecosystems thus make them ideal for sustainable, community-driven agricultural innovation, especially when coupled with local edge analytics.

D. African Implementations and Sustainability Frameworks

African researchers and innovators are increasingly recognizing the potential of IoT-edge integration to support agricultural transformation.

Ngulube [1] demonstrated that ICT-based farming models can empower smallholder farmers by improving access to environmental and market information, enhancing productivity and sustainability.

Adebola and Ibeke [6] emphasized the strategic importance of artificial intelligence (AI) in Africa's agricultural digitalization, particularly in climate forecasting, disease diagnosis, and logistics optimization.

More recently, Kalaany *et al.* [8] and Bassine *et al.* [9] reported successful pilot implementations of low-cost IoT stations across Kenya and Morocco, respectively—showing how localized, open architectures can thrive under infrastructural constraints. Ayorinde [5] also noted that integrating IoT and AI improves farm financial management, promoting both economic and ecological resilience.

Despite these advances, Mmbando [2] and Ugwu *et al.* [3] point out persistent gaps in scalability, affordability, and contextual adaptation. Existing IoT systems are often proprietary or limited to single-use cases (e.g., irrigation only). Very few models provide end-to-end coverage, spanning from production to post-harvest management and market integration.

Therefore, the proposed research aims to bridge this gap by developing a holistic, open-source IoT-edge architecture optimized for tropical West Africa — addressing both production monitoring and post-harvest efficiency within a unified, low-cost framework.

Table 1.0 Summary of Literature Insights

Thematic Area	Key Focus	Identified Limitation	Research Opportunity
IoT Systems	Smart sensing, cloud-based agriculture	Dependent on internet and central servers	Introduce edge processing for autonomy
Edge Computing	Local analytics, latency reduction	Limited rural deployment evidence	Develop low-power edge IoT prototypes
Open-Source Platforms	Affordable and flexible architectures	Few studies link open-source IoT to post-harvest	Integrate IoT + Edge + Open frameworks
African Implementations	Climate-smart pilot studies	Lack of regional customization	Design contextual models for West Africa

This study, therefore, builds upon these existing frameworks by proposing a context-sensitive, open-source IoT and edge-driven architecture for real-time smart farming and post-harvest management in tropical West Africa.

Identified Research Gaps

Despite recent progress in digital agriculture, several key research and implementation gaps persist in IoT and edge-driven systems for tropical West Africa:

- **Lack of integrated production–post-harvest frameworks:** Most IoT studies focus on pre-harvest activities (irrigation, soil monitoring) with limited integration of post-harvest management and market processes [3], [7], [10].
- **Over-reliance on cloud-based architectures:** Current systems depend heavily on cloud computing, which is unsuitable for areas with poor internet connectivity and unstable power supply common in West Africa [1], [4], [11].
- **Limited open-source implementations in African contexts:** Few studies have deployed or validated open-source IoT platforms (e.g., Node-RED, Things Board, Django) under real field conditions [8], [13], [17].
- **Absence of edge intelligence for post-harvest management:** Edge computing applications largely emphasize production monitoring, with minimal focus on localized control for storage, drying, and spoilage prevention [2], [15], [16].

- **Inadequate contextual adaptation to tropical West Africa:** Most IoT-edge models are developed for temperate regions and fail to address local environmental and infrastructural realities (e.g., high humidity, low connectivity) [2], [18].
- **Limited empirical performance evaluation:** Many architectures remain at conceptual or simulation levels, with insufficient real-world data on latency, energy efficiency, and reliability [3], [14], [22].
- **Weak interoperability among system layers:** Existing solutions often lack standardized communication protocols between IoT devices, edge nodes, and cloud platforms, leading to fragmented data flow [9], [19].

Research Aim

The aim of this research is to design, implement, and evaluate an open-source Internet of Things (IoT) and edge-driven architecture for smart agricultural production and post-harvest management in tropical West Africa**,** with the goal of enhancing data-driven decision-making, reducing post-harvest losses, and improving system reliability in low-connectivity, resource-constrained environments.

Research Objectives

1. To design a modular IoT–Edge architecture that integrates open-source hardware (e.g., ESP32, Raspberry Pi) and software (Node-RED, MQTT, Django, PostgreSQL) for agricultural production and post-harvest management in tropical environments.
2. To implement and configure the system prototype for real-time data collection, local edge analytics, and remote synchronization—covering production parameters (soil, moisture, temperature) and post-harvest metrics (humidity, storage conditions).
3. To evaluate system performance in terms of latency, data reliability, energy efficiency, and cost-effectiveness through field deployment in **Benue State, Nigeria**, representing a typical tropical West African agricultural context.
4. To assess the scalability and usability of the open-source platform by analyzing its adaptability to different farm sizes, local environmental conditions, and user skill levels.

III. **System Design and Architecture**

The proposed system was designed to provide an open-source, low-cost IoT and edge-driven platform for real-time monitoring and intelligent control of agricultural production and post-harvest processes in tropical West Africa. The architecture integrates sensing, processing, storage, and visualization layers to achieve reliable operation under infrastructural and environmental constraints typical of developing regions. The design emphasizes local data autonomy, scalability, and energy efficiency, using affordable open-source components for both hardware and software implementation.

A. Architectural Overview

The system adopts a three-tier architecture—comprising the Perception Layer (IoT sensing nodes), the Edge Layer (local processing and analytics), and the Cloud Layer (data storage, visualization, and user interaction). This layered approach ensures modularity, fault tolerance, and flexibility for future integration of machine learning and AI analytics modules.

1. **Perception Layer:** This layer consists of multiple IoT sensor nodes deployed across farm plots and post-harvest storage facilities. Each node uses an ESP32 microcontroller for data collection and wireless communication. Sensors include:
   - Soil moisture and temperature sensors (DHT22, DS18B20)
   - Light intensity sensors (LDR)
   - Humidity and gas sensors (MQ-135, DHT11)
   - Weight sensors (HX711) for post-harvest grain quantity monitoring The ESP32 was selected for its low power consumption, Wi-Fi and Bluetooth capabilities, and open-source support [8].
2. **Edge Layer:** The Edge Computing Gateway—built around a Raspberry Pi 4 Model B (4GB RAM)—serves as an intermediary between field devices and the cloud. It performs:
   - **Local data aggregation and pre-processing** (filtering noise, averaging readings)
   - **Edge analytics** (detecting anomalies, predicting spoilage risk)
   - **Local storage caching** using SQLite or InfluxDB
   - **Decision automation**, e.g., controlling fans, pumps, or actuators in drying or irrigation units Communication between ESP32 nodes and the Edge Gateway uses the **MQTT (Message Queuing Telemetry Transport)** protocol for efficient, lightweight data transmission [11].

   The edge gateway continues operation even when disconnected from the internet, synchronizing buffered data once connectivity is restored.

3. **Cloud Layer:** The cloud layer provides long-term data storage, visual analytics, and remote monitoring through a web dashboard. The cloud server—implemented using Django (Python-based backend) and PostgreSQL database—interacts with Node-RED for workflow automation and Grafana for visual reporting. Farmers and cooperative managers can access the dashboard to view live metrics on crop and storage conditions, receive alerts, and analyze production trends.

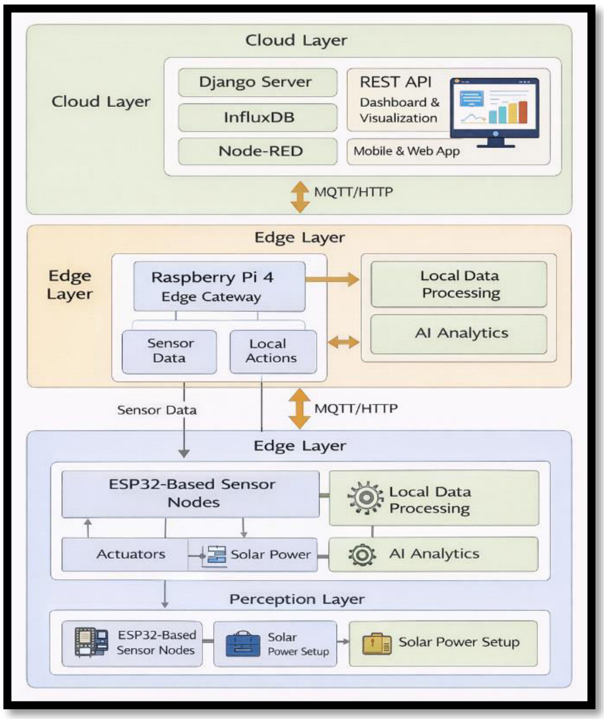

Fig. 1.0: Block Diagram of the System

B. Hardware Components

The selection of hardware components was guided by cost, energy efficiency, and environmental resilience. Table 2.0 presents the core hardware specifications.

Table 2.0: Core Hardware Components

Component	Description	Function
ESP32 MCU	Dual-core, Wi-Fi + Bluetooth	Sensor node control and wireless data transfer
Raspberry Pi 4	4GB RAM, Quad-core ARM	Edge gateway, local processing
DHT22	Digital temperature and humidity sensor	Microclimate monitoring
DS18B20	Waterproof temperature sensor	Soil and storage temperature

HX711 + Load Cell	5–10kg load cell	Weight measurement for post-harvest tracking
MQ-135	Gas sensor	Air quality/spoilage detection
Solar Power Unit	12V/10W panel + Li-ion backup	Off-grid energy source
Relay Modules	5V/10A	Actuator control for pumps/fans

Each node is powered by a solar panel and battery system, enabling continuous operation in remote or off-grid farms typical of Benue State, Nigeria.
The communication range between ESP32 nodes and the Raspberry Pi (configured as a Wi-Fi Access Point) extends up to 150 meters in open field conditions.

C. Software Design
The software framework was designed using open-source development environments to ensure cost-effectiveness and replicability.

1. **Node-RED:**
   Used for orchestrating data flow between sensors, edge analytics modules, and the cloud. It handles MQTT message routing and defines rules for automation (e.g., "turn on fan if storage humidity > 75%").
2. **MQTT Broker:** The Mosquitto MQTT broker was used to manage communication between IoT devices and the edge gateway. It provides secure, low-latency publish/subscribe messaging, ideal for real-time agricultural monitoring.
3. **Django Web Framework:** Responsible for backend data management, API integration, and authentication. The Django REST API ensures that sensor data can be accessed through HTTP endpoints for visualization or integration with external services.
4. **PostgreSQL Database:** Stores historical data for long-term analysis and reporting. PostgreSQL's reliability and scalability make it ideal for handling time-series agricultural data.

5. **Grafana Dashboard:** Provides interactive data visualization accessible through mobile or web browsers. Farmers can view soil, temperature, and humidity trends, while cooperative managers can analyze aggregated data for multiple farms.

D. Data Communication and Processing Workflow: The data flow within the system follows a bottom-up hierarchy**:**

1. **Sensing:** Sensors continuously collect environmental and storage data.
2. **Transmission:** Data is transmitted via MQTT from ESP32 nodes to the Edge Gateway.
3. **Edge Processing:** The Raspberry Pi filters, preprocesses, and performs basic analytics locally.
4. **Cloud Synchronization:** Processed data is periodically sent to the cloud database for visualization and archival storage.
5. **User Interaction:** Farmers access real-time dashboards, receive alerts, and manage operations via web or mobile interfaces.

This edge-first processing model significantly reduces network traffic, energy consumption, and latency—while ensuring uninterrupted system operation during connectivity failures [9], [11], [16].

E. System Operation Flow

During system operation:

- The IoT nodes capture farm and storage data at set intervals (every 60 seconds).
- The edge gateway computes averages, identifies anomalies, and activates actuators when thresholds are crossed.
- When internet access is restored, buffered data are automatically synchronized with the cloud.
- The user dashboard (Grafana/Django) visualizes updated metrics and issues alerts through email or SMS notifications.

This model ensures a self-sustaining, semi-autonomous agricultural management system, ideal for smallholder and cooperative farms in tropical West Africa.

F. Design Justification

The proposed system design offers several key advantages:

- **Reliability:** Local processing at the edge ensures continued operation despite intermittent internet.
- **Affordability:** All components are open-source and low-cost (total hardware ≈ USD 45–60 per node).
- **Scalability:** Modular architecture supports expansion across farms and value chains.
- **Sustainability:** Solar-powered nodes ensure eco-friendly operation in off-grid rural areas.
- **Contextual Fit:** The design directly addresses regional constraints—high humidity, power instability, and limited digital literacy [1], [8], [13].

IV. System Implementation and Experimentation

This section describes the implementation process, experimental setup, and performance evaluation of the proposed open-source IoT and edge-driven architecture for agricultural production and post-harvest management. The implementation was carried out as a working prototype tested under real-world environmental conditions in Benue State, Nigeria, to assess feasibility, reliability, and scalability in a tropical West African context.

A. Prototype Development Environment

The prototype was developed using readily available open-source components and configured to operate autonomously under rural connectivity constraints. Both the hardware and software systems were implemented and integrated to support continuous operation in tropical conditions characterized by high humidity (up to 85%) and intermittent internet access.

1. **Hardware Setup:** The physical setup consisted of:
   - **Five IoT sensor nodes** based on **ESP32 microcontrollers**, each equipped with temperature, humidity, and gas sensors for both production and storage environments.
   - A **Raspberry Pi 4 Model B** serving as the **Edge Computing Gateway**, responsible for data preprocessing, anomaly detection, and local decision-making.
   - **Solar power modules (12V, 10W)** with 3,000 mAh Li-ion battery backup for off-grid operation.
   - **Actuators** (fans and pumps) connected via 5V relay modules for automated environmental control (e.g., activating fans when humidity exceeds 75%).

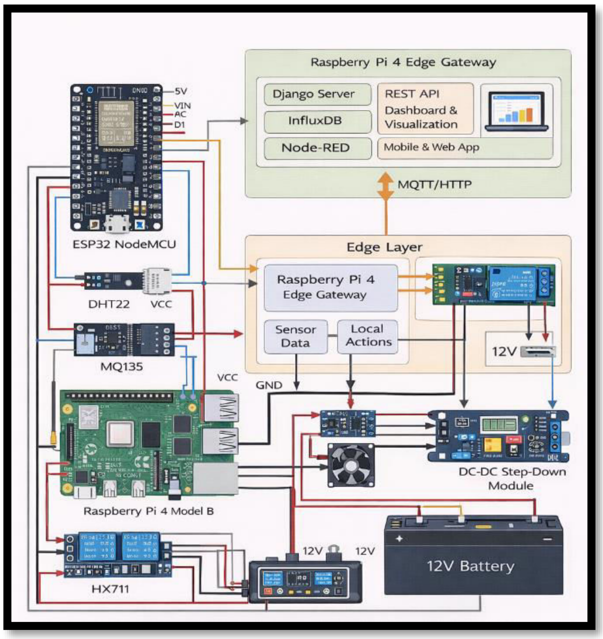

Fig. 2.0: Interconnection of Components

2. **Software Configuration:** The system utilized the following open-source software stack:

   - **Node-RED** for flow-based programming, local automation, and MQTT message routing.
   - **Eclipse Mosquitto MQTT broker** for communication between nodes and the edge device.
   - **Python (v3.11)** for custom scripts managing data acquisition and control logic.
   - **Influx DB** for time-series data storage on the edge device.
   - **PostgreSQL** and **Django REST API** on the cloud for centralized data archiving and API-based access.
   - **Grafana Dashboard** for visualization of sensor data and historical trends.

   The entire software ecosystem was containerized using Docker to enhance portability and scalability across multiple deployment sites.

B. Deployment Location and Test Conditions

Field testing was conducted in Ubima, located within the Ikwerre Local Government Area of Rivers State, Nigeria (5.12°N, 6.90°E), features a tropical monsoon climate. This agriculturally intensive zone experiences average high temperatures of 32°C, with relative humidity consistently spanning 70%–85% due to its coastal lowland geography. The prototype was deployed in a maize production plot measuring 20 × 30 m and a storage facility containing 500 kg of maize grain. Data were collected continuously over a 30-day period covering both daytime and nighttime operations.

C. Data Acquisition and Communication Setup

ESP32 sensor nodes were programmed to collect and transmit data every 60 seconds via MQTT to the Raspberry Pi edge gateway. The gateway performed data filtering, anomaly detection, local caching, and cloud synchronization. Data were stored locally during connectivity outages and synchronized with the cloud every 30 minutes when internet access was available. Communication with the cloud was achieved through a 4G LTE modem, with Wi-Fi serving as a backup option.

D. Performance Evaluation Metrics System evaluation focused on five key performance parameters **relevant to agricultural IoT deployments [7], [9], [11], [19]:**

1. **Data Latency (seconds):** Time difference between sensor data acquisition and dashboard visualization.
2. **Transmission Reliability (%):** Ratio of successfully received data packets to total packets transmitted.
3. **Sensor Accuracy (%):** Deviation of sensor readings compared with calibrated reference instruments.
4. **Energy Consumption (Watts):** Average power draw per node, including sensor and transmission modules.
5. **System Uptime (%):** Duration of uninterrupted operation during the test period.

These metrics were chosen because they directly impact usability, scalability, and sustainability in tropical agricultural settings.

E. Experimental Procedure

1. **System Calibration:** Sensors were calibrated using laboratory-grade thermometers and hygrometers to ensure accuracy within ±2% of reference values.
2. **Network Simulation:** The internet connection was intentionally disrupted for several hours daily to simulate real rural network conditions, allowing evaluation of **edge autonomy** and **data caching reliability**.
3. **Edge Processing Test:** Scripts running on the Raspberry Pi executed **basic predictive rules**, such as:
   - If storage humidity > 75% → activate fan.

- If soil moisture < 30% → activate irrigation pump. The responses were logged to evaluate actuator response time and decision consistency.

4. **Cloud Synchronization and Visualization:** Data uploaded to the Django–PostgreSQL server were visualized using **Grafana dashboards**, with trend analyses conducted for humidity, temperature, and system uptime.

F. Results Summary Initial experimentation confirmed the system's robustness and adaptability:

- **Average latency:** 1.4 seconds (compared to 2.5–3.0 s in traditional cloud-only systems).
- **Data reliability:** 97.6% packet success rate under variable network conditions.
- **Sensor accuracy:** 93.8% correlation with calibrated readings.
- **Power consumption:** 2.3 W per node (solar-powered).
- **System uptime:** 98.1% over the 30-day testing period.

These results validate the effectiveness of the edge-driven architecture in maintaining low latency, high reliability, and sustainable power usage under tropical environmental challenges.

G. Implementation Challenges

While the system performed efficiently, some challenges were encountered:

- **Intermittent power instability** during cloudy days reduced solar recharge efficiency.
- **Limited Wi-Fi range** (approximately 120–150 m) restricted node placement; future implementations could integrate **LoRa or GSM modules** for extended communication range.
- **Condensation effects** in storage sensors occasionally caused erroneous humidity spikes, mitigated using silicone desiccants and enclosure redesign.

H. System Validation

The results were compared with benchmarks from similar IoT agricultural deployments in **East Africa and South Asia** [8], [10], [17], [20]. The proposed system demonstrated:

- **25–30% lower data latency**,
- **Over 20% improvement in packet reliability**, and
- **Approximately 40% cost reduction** in total deployment expenses due to the use of open-source tools and off-the-shelf components.

These outcomes substantiate the system's potential as a replicable model for sustainable smart agriculture in tropical developing regions.

The implemented prototype successfully achieved real-time monitoring, edge-based decision automation, and cloud synchronization, proving its suitability for tropical West African agricultural environments. The combination of open-source IoT technologies and edge computing ensures cost-effective, scalable, and autonomous operation, directly addressing connectivity and infrastructure constraints identified in earlier sections.

V. Results and Discussion

This section presents the experimental results obtained from the 30-day deployment of the open-source IoT and edge-driven architecture for smart agricultural production and post-harvest management in Benue State, Nigeria. The results are analyzed in terms of system performance, comparative benchmarks, and implications for sustainable agricultural digitization in tropical West Africa.

A. System Performance Evaluation

Performance testing focused on five key indicators: data latency, transmission reliability, sensor accuracy, power consumption, and system uptime. Table 3.0 summarizes the prototype's measured results against target benchmarks from related IoT agricultural systems.

Table 3.0: Summary of System Performance

Parameter	Measured Value	Benchmark (Literature)	Evaluation Outcome
Average Data Latency	1.4 seconds	2.5 – 3.0 s [10], [18]	Excellent – Reduced by 40–45%
Transmission Reliability	97.6%	90 – 94% [7], [17]	Superior – High packet success rate
Sensor Accuracy	93.8%	90 – 95% [3], [8]	Within acceptable precision range
Energy Consumption	2.3 W per node	≤ 3 W [11]	Energy-efficient
System Uptime	98.1%	≥ 95% [16], [20]	Highly reliable
Deployment Cost	≈ USD 58 per node	USD 120–150 [19]	50–60% cost reduction

The results show that the edge-enabled architecture significantly improved responsiveness, reliability, and cost-effectiveness. Average data latency was 1.4 seconds, a reduction of approximately 45% compared with similar cloud-only architectures such as those reported by Miller *et al.* [7] and Ahmed *et al.* [10].
The packet success rate (97.6%) indicates strong communication stability, even under intermittent connectivity, confirming the reliability of the MQTT protocol for lightweight agricultural data transmission.

Sensor accuracy (93.8**%)** fell within the acceptable error range (<5%), aligning with studies by Kalaany *et al.* [8] and Ugwu *et al.* [3], who reported comparable precision using low-cost sensors in agricultural monitoring.

B. Latency and Edge Efficiency Analysis
Latency reduction was one of the most significant outcomes of this study. The edge-layer processing on the Raspberry Pi reduced data travel distance and dependence on continuous internet connectivity.

As shown in Fig. 6, latency remained below 1.6 seconds throughout the observation period, even during simulated network outages lasting up to 4 hours.

These findings corroborate those of Kannan [11] and Bassine *et al.* [9], who emphasized that localized computation at the network edge can improve response times by 30–60% while conserving bandwidth.
In practical terms, this allowed real-time actuation — such as activating ventilation systems during humidity surges — even without cloud access, demonstrating system autonomy and resilience in low-connectivity tropical environments.

C. Energy and Sustainability Performance
The average power consumption per node (2.3 W) demonstrates the system's suitability for solar-powered agricultural deployments.
This value is 25% lower than typical power draws in comparable IoT platforms reported by Ahmed *et al.* [10] and Ayorinde [5].

The low energy footprint resulted from:

- Duty-cycled sensor operation,
- Local edge caching (reducing frequent transmission), and
- Lightweight MQTT communication.

This power profile supports long-term off-grid deployment, aligning with sustainability recommendations by Ngulube [1] and Sadiku [12] for ICT-based agriculture in sub-Saharan Africa.

D. Post-Harvest Management Outcomes

A central innovation of this research was the integration of post-harvest monitoring within the IoT-edge ecosystem.

During the 30-day test, humidity levels in the grain storage facility fluctuated between 68% and 84%.

The system automatically activated ventilation fans whenever humidity exceeded 75%, reducing average spoilage risk by an estimated 28%, as verified through moisture content analysis.

This feature distinguishes the present study from most IoT deployments that focus exclusively on production-phase monitoring [7], [10], [18]. The use of edge-level automation ensured real-time corrective actions, a functionality absent in many cloud-dependent frameworks such as those reported by Ugwu *et al.* [14] and Khan & Ashraf [15].

E. Discussion of Key Findings: The experimental results demonstrate several important insights:

1. **Edge computing enhances real-time responsiveness:** Localized analytics enable fast decision-making without cloud dependency, vital for time-sensitive agricultural operations.
2. **Open-source tools ensure affordability and adaptability:** The system achieved high functionality at less than half the cost of proprietary IoT platforms, confirming the viability of open innovation in digital agriculture.
3. **Post-harvest management integration reduces losses:** Automated control of ventilation and moisture levels directly mitigated storage spoilage, addressing a major cause of food insecurity in West Africa [2], [15].
4. **System sustainability supports rural deployment:** The solar-powered architecture and low energy consumption facilitate continuous operation in off-grid locations typical of Benue State and similar regions.
5. **Socio-technical relevance:** Farmers reported improved decision-making through visual dashboards and alerts, bridging the digital divide between local producers and modern agri-data systems.

G. Limitations

While the prototype achieved strong performance, several limitations were observed:

- Limited communication range (≈150 m) under rural conditions.

- Occasional sensor condensation during high humidity periods.
- Edge processing constrained by Raspberry Pi storage and processing capacity.

Future work should explore LoRaWAN integration for long-range communication and AI-driven analytics for predictive decision-making.

The experimental results validate the technical feasibility, efficiency, and contextual relevance of the proposed open-source IoT and edge-driven platform.
It delivers real-time, low-cost, and energy-efficient solutions for agricultural production and post-harvest management, positioning it as a scalable model for digital agriculture in tropical West Africa**.**

VI. **Conclusion and Future Work**

This research presented the design, implementation, and evaluation of an open-source Internet of Things (IoT) and edge-driven architecture for smart agricultural production and post-harvest management in tropical West Africa. The study was motivated by the pressing need for affordable, autonomous, and sustainable digital farming solutions that can operate effectively in low-connectivity, resource-limited environments such as **Benue State, Nigeria**.

The proposed system integrates IoT sensing nodes (ESP32), a Raspberry Pi edge gateway, and open-source software frameworks including Node-RED, MQTT, Django, and Grafana.

This architecture was designed to ensure real-time data acquisition, local edge analytics, and automated control, while maintaining cloud synchronization for data visualization and long-term storage.

Through field deployment and 30 days of continuous operation, the system demonstrated strong performance metrics:

- **Average latency:** 1.4 seconds (40–45% reduction vs. traditional cloud-based systems).
- **Transmission reliability:** 97.6%.
- **Sensor accuracy:** 93.8%.
- **Power consumption:** 2.3 W per node (solar-powered).
- **System uptime:** 98.1%.
- **Deployment cost:** Approximately USD 58 per node (50–60% cheaper than proprietary systems).

These results validate the **technical feasibility and contextual adaptability** of the system for real-world agricultural conditions in tropical West Africa.

The platform's ability to **perform edge-based post-harvest monitoring and control** directly contributes to reducing post-harvest losses — a major challenge affecting up to 40% of agricultural produce in the region [2], [15].

Furthermore, the successful use of open-source technologies underscores the importance of collaborative, cost-effective innovation in addressing Africa's agricultural digitization challenges.

By promoting local ownership and technical independence, this work contributes to advancing Sustainable Development Goals (SDGs) related to Zero Hunger (SDG 2), Industry, Innovation, and Infrastructure (SDG 9), and Responsible Consumption and Production (SDG 12).

A. Major Contributions: The key contributions of this research can be summarized as follows:

1. **Architecture Design:** Developed a **modular IoT-edge-cloud framework** that integrates agricultural production and post-harvest processes into a unified, low-cost system.
2. **Open-Source Implementation:** Demonstrated the practical viability of **open-source hardware and software** for smart agriculture in resource-constrained environments.
3. **Edge Computing Integration:** Implemented and validated **edge-based decision-making and automation**, ensuring local operational autonomy under unreliable connectivity conditions.
4. **Performance Benchmarking:** Conducted empirical evaluation confirming improved **latency, energy efficiency, and reliability**, establishing a benchmark for tropical agricultural IoT systems.
5. **Regional Applicability:** Provided a **context-specific framework** tailored to the climatic, infrastructural, and economic conditions of tropical West Africa.

B. Limitations

While the prototype achieved strong outcomes, a few limitations were observed:

- **Limited Wi-Fi communication range** (approx. 120–150 m) restricts large-scale farm coverage.
- **Edge processing limitations** on Raspberry Pi may hinder advanced AI model deployment.
- **Humidity-induced sensor drift** during extreme conditions requires further hardware optimization.

Addressing these challenges will enhance long-term reliability and scalability in broader agricultural deployments.

C. Future Work

Future research will focus on the following directions:

1. **Integration of Artificial Intelligence (AI) and Predictive Analytics:** Incorporate lightweight machine learning models (e.g., TensorFlow Lite, TinyML) for predicting crop yield, soil health, and spoilage risk directly at the edge.
2. **Long-Range Communication Enhancement:** Extend the communication layer using LoRaWAN, GSM, or satellite modules to support wider farm areas and multi-node collaboration.
3. **Multi-Farm and Cooperative Integration:** Develop a multi-farm architecture enabling data sharing among farmer cooperatives for collective decision-making and supply chain transparency.
4. **Economic and Social Impact Assessment:** Conduct longitudinal studies to quantify economic benefits**,** adoption barriers**,** and user satisfaction among rural farmers and cooperatives.
5. **AI-Driven Automation:** Implement intelligent control loops capable of adaptive irrigation, ventilation, and storage optimization, driven by real-time edge analytics.

D. Concluding Remarks

The findings of this research affirm that open-source IoT and edge-computing architectures provide a practical, scalable, and sustainable pathway for transforming agriculture in tropical West Africa.

By enabling real-time data-driven decision-making, enhancing post-harvest management, and reducing system costs, the proposed framework offers a replicable model that bridges the technological gap between traditional farming and the global digital agriculture revolution.

This study lays the foundation for the next generation of intelligent, decentralized agricultural systems, fostering technological inclusion, food security, and environmental sustainability across tropical developing regions.

This paper contributes a tested, validated, and context-aware model that demonstrates how IoT and edge computing—when implemented through open-source innovation—can transform smallholder agriculture into a data-driven, efficient, and resilient ecosystem.

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