Faculty of Natural and Applied Sciences Journal of Computing and Applications
Print ISSN: 3026-8133
www.fnasjournals.com
Volume 3; Issue 1; March 2026; Page No. 1-6.
DOI: https://doi.org/10.63561/jca.v3i1.1196

A Secure and Energy-Efficient IoT Architecture for Vegetable Cultivation in Tropical Environment

***[1]Ololo, E.C., & [2]Nwankwo, W.**
[1]Department of Computer Science, Imo State Polytechnic, Omuma, Nigeria
[2]Department of Cyber Security, Southern Delta University, Ozoro, Delta State Nigeria

***Corresponding author email**: meetexcess_386@yahoo.com

Abstract

Vegetable cultivation in tropical environments is affected by inefficient water management, climate variability, and limited real-time farm monitoring. This paper presents a secure and energy-efficient Internet of Things (IoT) architecture for tropical vegetable farming. The system integrates ESP32-based sensor nodes, solar-powered energy management, and cloud-based monitoring to collect and process soil moisture, temperature, and humidity data. Security mechanisms, including device authentication and encrypted communication, are embedded to protect system integrity. The architecture was implemented and evaluated through field deployment, focusing on system reliability, water-use efficiency, and energy performance. Experimental results show improved irrigation control, reduced water usage, and stable system operation under tropical conditions. The proposed architecture demonstrates the feasibility of deploying secure, low-power IoT systems for sustainable vegetable cultivation in resource-constrained tropical environments.

Keywords: IoT Architecture, Smart Agriculture, Energy Efficiency, Tropical Farming, ESP32

Introduction

Vegetable cultivation plays a critical role in food security, nutrition, and income generation in tropical regions (Nwankwo & Ukhurebor, 2021). However, production in these environments is frequently constrained by irregular rainfall, high evapotranspiration rates, soil moisture variability, and inefficient water management practices (FAO, 2021). Small and medium-scale farmers often rely on manual observation and experience-based decision-making, which limits timely intervention and leads to suboptimal resource utilization and reduced yields. The Internet of Things (IoT) has emerged as a promising technology for enabling real-time monitoring and automated control in agriculture through interconnected sensors, data analytics, and remote access (Ayaz et al., 2019; Li et al., 2020; Olayinka et al, 2022). IoT-based smart farming systems have been shown to improve irrigation scheduling, crop monitoring, and resource efficiency by providing continuous environmental data and decision support (Boulos et al., 2021; Onwodi et al, 2024). Despite these advances, many existing agricultural IoT solutions are designed for temperate or controlled environments and are not well-suited to the climatic and infrastructural conditions of tropical regions. One major limitation of current IoT-based agricultural systems is their high energy demand and dependence on grid electricity, which is often unreliable or unavailable in rural tropical areas (Jawad et al., 2017; Mekonnen et al., 2022). Additionally, tropical environments expose IoT devices to high humidity, temperature extremes, and harsh field conditions, affecting system durability and reliability. These challenges necessitate the adoption of energy-efficient designs and renewable energy sources to support sustainable long-term deployment.

Security is another critical concern in agricultural IoT systems. Recent studies have highlighted vulnerabilities related to weak authentication, unsecured communication channels, and lack of access control in IoT deployments, which can result in data manipulation, unauthorized control actions, and system failure (Sicari et al., 2015; Ferrag et al., 2020). In many existing agricultural applications, security mechanisms are either absent or treated as secondary features, increasing the risk of system compromise and limiting trust in IoT-driven decision-making. This paper proposes a secure and energy-efficient IoT architecture tailored for vegetable cultivation in tropical environments. The proposed system integrates low-power sensor nodes, solar-based energy supply, and secure communication mechanisms within

Cite this article as:
Ololo, E. C., & Nwankwo, W. (2026). A secure and energy-efficient IoT architecture for vegetable cultivation in tropical environment. *FNAS Journal of Computing and Applications*, *3*(1), 1-6. https://doi.org/10.63561/jca.v3i1.1196

a layered IoT framework. The architecture is implemented and evaluated through field deployment, with performance assessed in terms of system reliability, water-use efficiency, and operational stability. The results demonstrate that integrating security and energy efficiency as core design principles enhances the practicality and sustainability of IoT-based smart farming systems in tropical regions.

Methods and Materials

This section describes the design and implementation of the proposed secure and energy-efficient IoT system for vegetable cultivation in tropical environments. It outlines the system architecture, hardware and software components, security mechanisms, and experimental setup used for system evaluation. The methods adopted were selected to ensure reliable data acquisition, efficient energy usage, secure communication, and practical applicability under real farm conditions. The materials and procedures presented provide the basis for reproducibility and performance assessment of the proposed system.

Overall System Architecture

The proposed system adopts a layered IoT architecture designed to support secure and energy-efficient vegetable cultivation in tropical environments. The architecture, as seen in Figure 1, consists of four logical layers: the perception layer, network layer, cloud and processing layer, and application layer. Each layer performs a specific function while interacting seamlessly with the others. Sensor nodes deployed in the farm environment collect real-time environmental data, which is transmitted securely to a cloud platform for processing and storage. Based on predefined decision rules, control actions such as irrigation activation are executed automatically. Security and energy management mechanisms are integrated across all layers to enhance system reliability and sustainability.

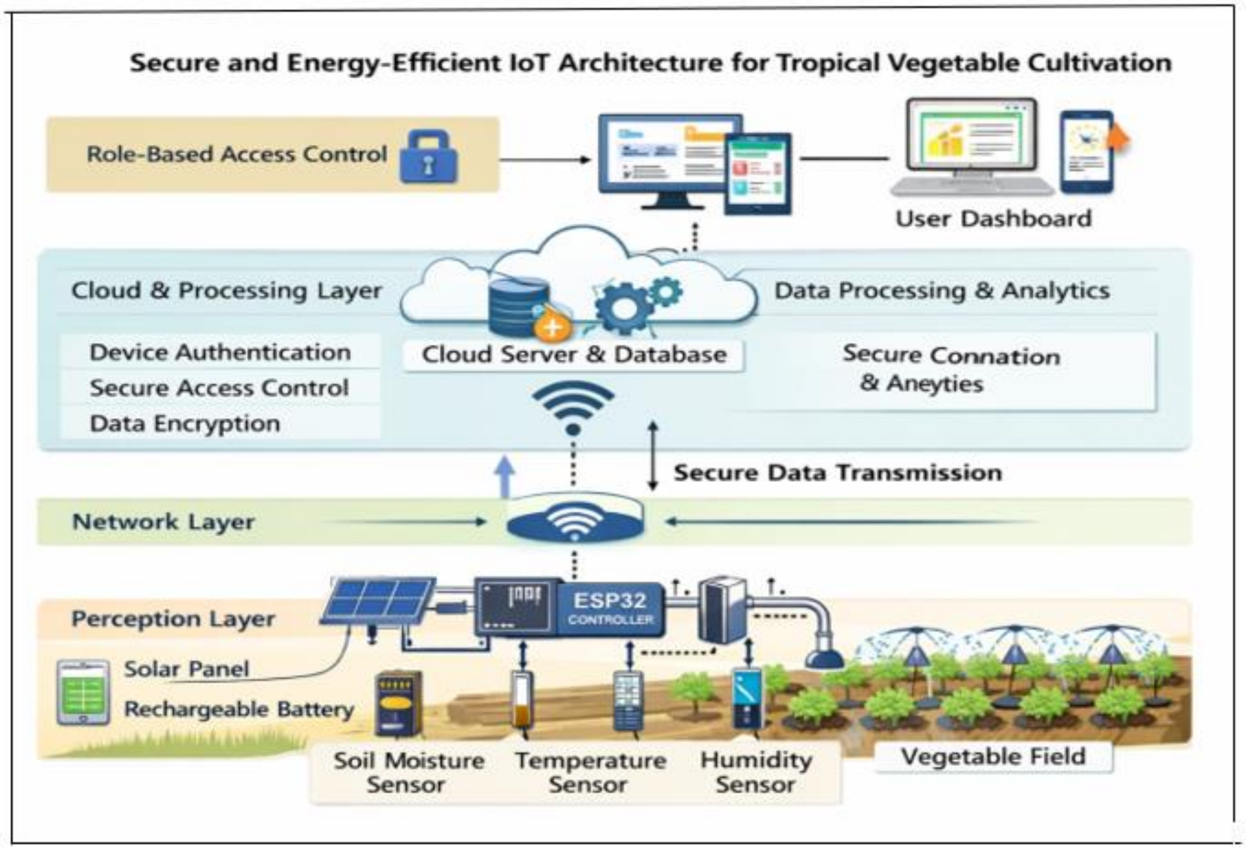

Figure 1. Architecture of the Proposed IoT System

Hardware Components and Design

The hardware subsystem comprises sensing, processing, actuation, and power units. An ESP32 microcontroller serves as the core processing unit due to its low power consumption, integrated Wi-Fi capability, and suitability for outdoor deployments. Soil moisture sensors are used to monitor soil water content, while temperature and humidity sensors measure ambient environmental conditions.

Actuation is achieved through an electromechanical relay module that controls a water pump used for irrigation. An audible alarm module provides local alerts in case of abnormal conditions. For autonomous operation, the system is powered by a solar energy subsystem consisting of a photovoltaic panel, a rechargeable battery, and voltage regulation circuitry. This design (see Figure 2) ensures continuous operation in off-grid and rural farm environments.

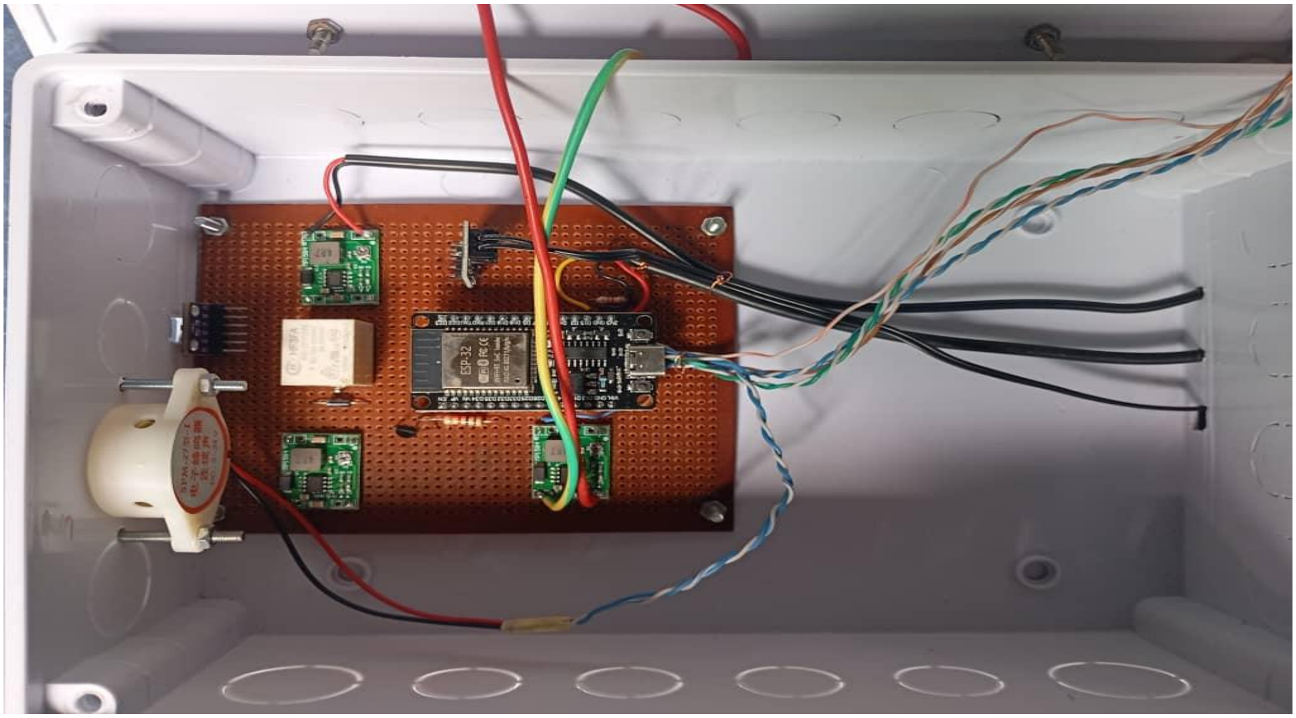

Figure 2. Microcontroller (ESP32) and the Sensors

Software and Communication Framework

The software framework comprises embedded firmware running on the ESP32 and cloud-based services for data management and visualization. The embedded firmware handles sensor data acquisition, local preprocessing, and communication with the cloud server. Data transmission is performed at predefined intervals to minimize energy consumption while maintaining adequate monitoring resolution.

A lightweight communication protocol is employed to reduce network overhead and latency. On the cloud side, received data are stored in a database and processed using rule-based logic to determine appropriate control actions. A web-based dashboard provides real-time visualization of sensor readings, historical trends, and system status, enabling remote monitoring and supervision by authorized users.

Security Mechanisms

Security is incorporated as a core design consideration in the proposed system. Device authentication mechanisms ensure that only authorized sensor nodes can transmit data to the cloud platform. Data communication between the field devices and the cloud server is protected using encryption to prevent eavesdropping and data tampering. At the application layer, role-based access control is implemented to restrict system access based on user privileges. System activities, including data access and control commands, are logged for auditing and monitoring purposes. These security measures enhance data integrity, confidentiality, and trustworthiness of the system.

Experimental Setup and Deployment

The system was deployed on a vegetable farm located in a tropical environment to evaluate its performance under real-world conditions. Test plots were established for commonly cultivated vegetables, including fluted pumpkin (Ugu in Igbo language) and Okra. Sensor nodes were installed at representative locations within the farm to capture accurate environmental data.

Cite this article as:
Ololo, E. C., & Nwankwo, W. (2026). A secure and energy-efficient IoT architecture for vegetable cultivation in tropical environment. *FNAS Journal of Computing and Applications, 3*(1), 1-6. https://doi.org/10.63561/jca.v3i1.1196

The deployment was conducted over a defined cultivation period, during which sensor readings, irrigation events, energy consumption, and system uptime were continuously monitored. For performance comparison, a nearby farm plot using conventional manual irrigation practices was observed concurrently. Data collected from both plots were used to assess the effectiveness of the proposed system in terms of water-use efficiency, crop growth, and system reliability.

Results

This section presents the experimental results obtained from the field deployment of the proposed IoT-based system. The performance of the system was evaluated using sensor data records, irrigation activity logs, energy consumption metrics, and crop growth observations collected during the cultivation period. Results from the IoT-enabled farm plot were compared with those from a conventionally managed farm plot.

Environmental Monitoring Results

The deployed sensor nodes successfully captured continuous soil moisture, temperature, and relative humidity data throughout the cultivation period. Soil moisture readings in the IoT-enabled plot remained within the predefined optimal range for vegetable growth for a greater proportion of time compared to the control plot. Temperature and humidity measurements reflected expected tropical climatic conditions, with daily fluctuations effectively recorded and transmitted to the cloud platform without data loss.

Data transmission reliability was high, with over 98% of sensor readings successfully received and logged in the cloud database. No significant communication interruptions were observed during the monitoring period.

Irrigation Control Performance

The automated irrigation system responded dynamically to soil moisture conditions. Irrigation events were triggered only when soil moisture levels fell below the 50% defined threshold, resulting in fewer but more targeted watering cycles.

Compared to the conventional plot, the IoT-enabled plot recorded a reduction in irrigation frequency and total water usage. Cumulative water consumption over the cultivation period was approximately 30–35% lower in the IoT-managed plot, while maintaining adequate soil moisture levels for crop growth.

Energy Consumption and System Stability

The solar-powered energy subsystem provided sufficient power for continuous system operation. Battery voltage levels remained within safe operating limits throughout the deployment period. The system achieved an average operational uptime exceeding 99%, with no extended power-related outages recorded.

Energy consumption analysis showed that the ESP32-based sensor node operated in low-power mode for most of the monitoring cycle, with higher power usage occurring only during data transmission and irrigation control events.

Crop Growth and Yield Outcomes

Crops grown under the IoT-managed plot exhibited more uniform growth patterns compared to those in the conventional plot. Observations indicated improved leaf density and overall plant vigor in the IoT-enabled farm.

At harvest, the IoT-managed plot achieved an average yield increase of approximately 18–22% compared to the control plot. The improvement was consistent across both fluted pumpkin (ugu) and okra crops.

System Reliability and Alert Performance

The alert subsystem functioned as expected, generating notifications when sensor readings exceeded predefined thresholds. All alerts were logged correctly and delivered to the application interface without delay. No false system-triggered irrigation events were recorded during the deployment period.

The system maintained stable operation under varying environmental conditions, demonstrating robustness suitable for tropical agricultural environments. Table 1 summarizes the key performance metrics obtained from both sample farms.

Table 1 :*Summary of Performance Results for IoT-Enabled and the Conventional Farm Plots*

Cite this article as:
Ololo, E. C., & Nwankwo, W. (2026). A secure and energy-efficient IoT architecture for vegetable cultivation in tropical environment**.** *FNAS Journal of Computing and Applications, 3*(1), 1-6. https://doi.org/10.63561/jca.v3i1.1196

Performance Metric	IoT-Enabled Farm Plot	Conventional Farm Plot	Observed Outcome
Environmental monitoring	Continuous, real-time monitoring	Manual, periodic observation	Improved data availability and timeliness
Data transmission reliability	≈ 98–99% successful transmissions	Not applicable	High system reliability
Irrigation control	Automated, threshold-based	Manual scheduling	Targeted and timely irrigation
Total water usage	Reduced by ~30–35%	Higher water consumption	Improved water-use efficiency
Irrigation frequency	Optimized (event-driven)	Fixed or irregular	Reduced unnecessary watering
Power source	Solar-powered with battery backup	Not applicable	Autonomous operation
System uptime	> 99%	Not applicable	Stable continuous operation
Crop growth uniformity	High (consistent plant vigor)	Moderate to low	Improved crop condition
Crop yield	Increased by ~18–22%	Baseline yield	Higher productivity
Alert and fault response	Real-time alerts and logging	Manual detection	Faster response to anomalies

Discussion

The results obtained from the field deployment demonstrate the effectiveness of the proposed secure and energy-efficient IoT architecture for vegetable cultivation in tropical environments. The system achieved its core objectives of improving irrigation efficiency, enhancing crop yield, and maintaining reliable operation under real-world farm conditions. The observed reduction in water usage, estimated at approximately 30–35%, confirms the effectiveness of threshold-based irrigation control driven by real-time soil moisture sensing. Unlike conventional irrigation practices that rely on fixed schedules or farmer intuition, the proposed system ensures that water is applied only when required. This finding aligns with earlier studies that reported improved water-use efficiency through sensor-based irrigation but extends existing work by demonstrating consistent performance in tropical field conditions characterized by high humidity and variable rainfall.

Crop yield improvements of 18–22% in the IoT-managed plot indicate that optimized irrigation and continuous environmental monitoring contribute positively to plant growth and productivity. The improved uniformity and vigor observed in crops such as fluted pumpkin and okra suggest that maintaining optimal soil moisture levels plays a critical role in vegetable development in tropical soils. These results address a key gap in prior research, which often focuses on water savings without quantitatively linking IoT deployment to measurable yield gains in small-scale tropical agriculture. The high system uptime exceeding 99% highlights the reliability of the proposed architecture. The solar-powered energy subsystem proved adequate for sustained operation, confirming the suitability of renewable energy solutions for off-grid agricultural environments. This is particularly important in rural tropical regions where access to stable grid power is limited. The low-power operation of the ESP32-based sensor node further contributed to energy efficiency, supporting long-term autonomous deployment.

From a security perspective, the successful integration of device authentication, encrypted communication, and access control mechanisms ensured secure data handling throughout the deployment period. No unauthorized access or data integrity issues were observed, demonstrating that security can be effectively incorporated into agricultural IoT systems without imposing excessive computational or energy overhead. The findings indicate that the proposed system not only improves resource efficiency and productivity but also provides a robust and secure platform suitable for real-world agricultural deployment. The results validate the feasibility of deploying secure, energy-efficient IoT solutions in tropical vegetable farming and highlight their potential to support sustainable agricultural practices.

Conclusion

This study presented a secure and energy-efficient Internet of Things (IoT) architecture for vegetable cultivation in tropical environments. The proposed system integrated low-power sensor nodes, automated irrigation control, renewable energy supply, cloud-based data processing, and embedded security mechanisms to address key challenges faced by small- and medium-scale tropical farmers. Field deployment results demonstrated that the system effectively improved water-use efficiency through sensor-driven irrigation scheduling, achieving a substantial reduction in water consumption while maintaining optimal soil moisture conditions. The IoT-enabled farm plot also recorded improved crop growth and higher yields compared to conventional farming practices, confirming the practical benefits of real-time monitoring and automated decision support. The solar-powered design ensured reliable operation with minimal maintenance, while the implemented security mechanisms safeguarded data integrity and system access. The findings validate the feasibility and effectiveness of deploying secure, energy-efficient IoT solutions for sustainable vegetable

Cite this article as:
Ololo, E. C., & Nwankwo, W. (2026). A secure and energy-efficient IoT architecture for vegetable cultivation in tropical environment. *FNAS Journal of Computing and Applications, 3*(1), 1-6. https://doi.org/10.63561/jca.v3i1.1196

production in tropical regions. The proposed architecture offers a scalable and practical framework that can support precision agriculture initiatives aimed at improving productivity, resource efficiency, and resilience in climate-sensitive agricultural systems.

Recommendations

Based on the findings of this study, several recommendations are proposed to enhance the effectiveness, scalability, and adoption of secure IoT-based agricultural systems in tropical environments.

1. Future implementations should incorporate advanced data analytics and machine learning techniques to further improve decision-making accuracy. Predictive models based on historical sensor data and weather forecasts could enable proactive irrigation and fertilizer scheduling, leading to additional gains in water-use efficiency and crop yield.
2. Large-scale field trials across different crop types, soil conditions, and climatic zones within the tropics are recommended to validate the generalizability of the proposed architecture. Such studies would provide deeper insights into system adaptability and long-term performance under varying agricultural conditions.
3. Integration with additional sensors, such as soil nutrient, pH, and pest detection sensors, is recommended to support more comprehensive farm management. This would allow the system to evolve from irrigation-focused automation to a holistic precision agriculture platform.
4. Efforts should be made to optimize system cost and usability to encourage adoption by smallholder farmers. Simplified user interfaces, mobile-based dashboards, and local language support can significantly improve system accessibility and user engagement.
5. Policy makers and agricultural extension services are encouraged to support the deployment of secure IoT solutions through training programs, subsidies, and infrastructure development. Such initiatives would accelerate the adoption of smart farming technologies and contribute to sustainable agricultural development in tropical regions.

References

Ayaz, M., Ammad-Uddin, M., Sharif, Z., Mansour, A., & Aggoune, E. H. M. (2019). Internet-of-Things (IoT)-based smart agriculture: Toward making the fields talk. *IEEE Access, 7*, 129551–129583. https://doi.org/10.1109/ACCESS.2019.2932609

FAO. (2021). *The state of food and agriculture 2021: Making agrifood systems more resilient to shocks and stresses*. Food and Agriculture Organization of the United Nations. https://www.fao.org

Ferrag, M. A., Maglaras, L., Moschoyiannis, S., & Janicke, H. (2020). Deep learning for cyber security intrusion detection: Approaches, datasets, and comparative study. *Journal of Information Security and Applications*, *50*, 102419. https://doi.org/10.1016/j.jisa.2019.102419

Jawad, H. M., Nordin, R., Gharghan, S. K., Jawad, A. M., & Ismail, M. (2017). Energy-efficient wireless sensor networks for precision agriculture: *A review. Sensors, 17*(8), 1781. https://doi.org/10.3390/s17081781

Kamel Boulos, M. N., Peng, G., & VoPham, T. (2021). An overview of GeoAI applications in health and healthcare. *International Journal of Health Geographics*, *20*(1), 7. https://doi.org/10.1186/s12942-021-00266-1

Li, L., Zhang, Q., & Huang, D. (2020). A review of imaging techniques for plant phenotyping. *Sensors, 20*(3), 787. https://doi.org/10.3390/s20030787

Mekonnen, Y., Namuduri, S., Burton, L., Sarwat, A., & Bhansali, S. (2022). Review Machine learning techniques in wireless sensor network based precision agriculture. *Journal of the Electrochemical Society, 167*(3), 037522. https://doi.org/10.1149/2.0222003JES

Nwankwo,W. and Ukhurebor, K.E.(2021). Big Data Analytics: A Single Window IoT-enabled Climate Variability System for all-year-round Vegetable Cultivation. In 2021 *IOP Conference Series: Earth and Environmental Science*, 655 012030. doi:10.1088/1755-1315/655/1/012030

Olayinka A.S., Adetunji C.O., Nwankwo W., Olugbemi O.T., Olayinka T.C. (2022) A Study on the Application of Bayesian Learning and Decision Trees IoT-Enabled System in Postharvest Storage. In: Pal S., De D., Buyya R. (eds) Artificial Intelligence-based Internet of Things Systems. Internet of Things (Technology, Communications and Computing). *Springer*, Cham. https://doi.org/10.1007/978-3-030-87059-1_18

Onwodi, G., Nwankwo,W., Ojosu, O.A., Oyenusi,F., Awodele,O.,Ebem, D., Ukaoha, K.C.(2024). Development of Intelligent Anti-Cannibalistic Prototyping for Sustainable Catfish Farming. *2024 IEEE 5th International Conference on Electro-Computing Technologies for Humanity (NIGERCON)*, Ado Ekiti, Nigeria, 2024, pp. 1-5, doi: 10.1109/NIGERCON62786.2024.10927292.

Sicari, S., Rizzardi, A., Grieco, L. A., & Coen-Porisini, A. (2015). Security, privacy and trust in Internet of Things: The road ahead. *Computer Networks, 76*, 146–164. https://doi.org/10.1016/j.comnet.2014.11.008

Cite this article as:
Ololo, E. C., & Nwankwo, W. (2026). A secure and energy-efficient IoT architecture for vegetable cultivation in tropical environment. *FNAS Journal of Computing and Applications, 3*(1), 1-6. https://doi.org/10.63561/jca.v3i1.1196