International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 10 , October - 2026

Energy-Aware Edge Intelligence for Real-Time Embedded Systems using Adaptive TinyML

Vanam Bharathi
PG Scholar, Dept. of ECE, Geethanjali Institute of Science and Technology, Nellore, India.

Dr. U. Penchalaiah
Professor, Dept. of ECE, Geethanjali Institute of Science and Technology, Nellore, India.

Ande Siva Sai Kumar
Assistant Professor, Dept. of ECE, Geethanjali Institute of Science and Technology, Nellore, India.

Dr. K. Sravan Kumar
Professor, Dept. of ECE, Geethanjali Institute of Science and Technology, Nellore, India.

G. Suresh
Associate Professor, Dept. of ECE, Geethanjali Institute of Science and Technology, Nellore, India.

Abstract - The growing need for continuous environmental observation has created demand for compact, reliable, and energy-efficient monitoring systems that can collect environmental parameters in real time. Conventional monitoring systems often involve high power consumption, complex hardware, and limited remote accessibility. This paper presents the design and implementation of an energy-efficient IoT-based embedded system for real-time environmental monitoring. The proposed system uses an ESP32-based embedded controller integrated with environmental sensors for measuring parameters such as temperature, relative humidity, air quality, and ambient light intensity. The acquired sensor data are processed locally to reduce unnecessary communication and identify significant environmental events. Wireless connectivity is provided through Wi-Fi, while MQTT is used for lightweight data transmission to an IoT monitoring platform. An energy-management mechanism based on duty cycling and sleep operation is incorporated to reduce power consumption during periods of low activity. The system provides real-time visualization, threshold-based event detection, and remote monitoring through an IoT dashboard. The proposed architecture combines sensing, local processing, wireless communication, and energy management within a compact embedded platform, making it suitable for indoor environmental monitoring, smart buildings, agricultural environments, and other IoT-based applications.

Keywords— Internet of Things, ESP32, Environmental Monitoring, Embedded System, MQTT, Energy Efficiency, Wireless Sensor, Real-Time Monitoring.

I. INTRODUCTION

Environmental monitoring is an important requirement in applications involving smart buildings, agriculture, industrial environments, public spaces, and residential areas. Continuous measurement of environmental parameters enables abnormal conditions to be identified at an early stage and supports informed decision-making. Traditional monitoring approaches generally require manual observation or dedicated monitoring equipment, which can increase operational complexity and limit the availability of real-time information.

The development of low-cost embedded controllers and IoT technologies has enabled environmental monitoring systems to become more compact, connected, and accessible. Modern microcontrollers provide sufficient processing capability for acquiring sensor measurements, performing local data processing, and transmitting information to remote monitoring platforms. The ESP32 platform is particularly suitable for IoT applications because it integrates processing capability with wireless connectivity within a compact embedded device [1].

Environmental monitoring systems based on modular IoT architectures can integrate multiple sensors and communication interfaces according to application requirements. Such systems support continuous collection of environmental parameters and can provide remote access to monitoring information [2]. Wireless communication protocols such as MQTT are also suitable for IoT monitoring because they provide lightweight message-based communication between embedded devices and monitoring platforms [3].

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 10 , October - 2026

Energy consumption is another important consideration in IoT-based environmental monitoring. A monitoring node may remain operational for extended periods, and continuous sensing and wireless transmission can significantly increase energy requirements. Energy-efficient operation can therefore be achieved by combining appropriate sampling intervals, local processing, duty cycling, and low-power operating modes [4].

Long-range wireless communication can also be considered for environmental monitoring applications where monitoring nodes are distributed over large geographical areas. The combination of low-power communication technologies and IoT protocols provides flexibility for deploying environmental monitoring systems in locations where continuous wired connectivity is not practical [5]. In addition, local processing and embedded intelligence can reduce unnecessary data transmission and improve the efficiency of IoT sensor nodes [6].

The main contributions of the proposed system are as follows:

1. Development of an ESP32-based embedded platform for real-time environmental monitoring.
2. Integration of multiple environmental sensors for continuous parameter acquisition.
3. Implementation of local data preprocessing and threshold-based event detection.
4. Integration of MQTT-based wireless communication for remote monitoring.
5. Incorporation of duty cycling and sleep operation for energy-efficient operation.
6. Development of an IoT monitoring architecture capable of providing real-time environmental information.

The remainder of this paper is organized as follows. Section II presents the literature survey. Section III describes the proposed methodology and system architecture. Section IV presents the performance analysis and discussion. Section V concludes the paper.

II. LITERATURE SURVEY

Recent developments in IoT-based environmental monitoring have focused on reducing hardware complexity while improving sensing, communication, and monitoring capabilities. Low-cost embedded platforms with integrated wireless communication have been widely adopted for environmental sensing applications [7].

Cloud-connected environmental monitoring architectures provide remote access to sensor information and enable users to observe environmental conditions through web-based interfaces. Such architectures demonstrate the feasibility of combining embedded sensing systems with cloud-based monitoring platforms [8].

The integration of edge processing into IoT sensor nodes provides an additional mechanism for improving system efficiency. Instead of transmitting every raw measurement to a remote platform, local processing can be used to identify relevant information before communication. This approach can reduce communication overhead and improve the responsiveness of monitoring systems [9].

Environmental monitoring systems have also been developed for agricultural applications where continuous measurement of environmental conditions is required. These systems demonstrate the usefulness of combining distributed sensing, wireless communication, and remote monitoring for real-time environmental observation [10].

Low-power wireless technologies provide further opportunities for deploying environmental monitoring nodes in distributed environments. Such systems can operate with reduced energy requirements while supporting wireless transmission over extended distances, making them suitable for remote monitoring applications [11].

MQTT-based monitoring architectures have also demonstrated the effectiveness of lightweight publish-subscribe communication for transmitting environmental measurements and generating real-time alerts. Such communication mechanisms can support efficient interaction between embedded sensing devices and remote monitoring applications [12].

Although existing systems provide effective solutions for environmental monitoring, several challenges remain. Continuous sensing and wireless communication can increase power consumption, while transmission of unnecessary measurements can introduce additional communication overhead. Some systems also depend heavily on remote processing, which may increase response time when immediate local decisions are required. Therefore, there is a need for an integrated architecture that combines local preprocessing, event detection, lightweight communication, and energy-efficient operation within a compact embedded system.

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 10 , October - 2026

The proposed system addresses these requirements by integrating environmental sensing, local processing, wireless communication, IoT visualization, and energy management into a unified ESP32-based architecture.

III. PROPOSED METHODOLOGY

A. Overall Architecture

The proposed system consists of five major functional layers: environmental sensing, embedded processing, event detection, wireless communication, and IoT monitoring. The ESP32 microcontroller acts as the central processing unit and coordinates sensor acquisition, local processing, communication, and energy management.

The environmental sensors continuously measure the required parameters and provide their measurements to the ESP32. The controller performs basic preprocessing and evaluates the measurements against predefined environmental thresholds. Significant events are identified locally before the corresponding information is transmitted through the wireless communication interface.

The overall architecture of the proposed system is shown in Fig. 1.

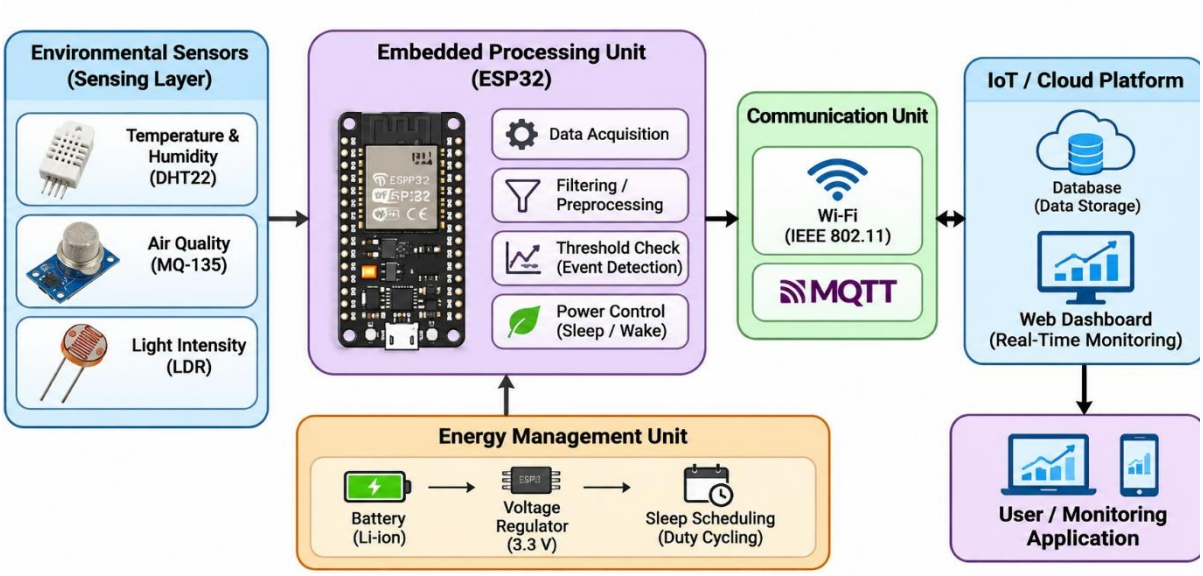


Fig. 1. Architecture of the proposed energy-efficient IoT-based embedded environmental monitoring system.

B. Environmental Sensor Data Acquisition

The sensing layer consists of multiple environmental sensors connected to the ESP32 controller. Temperature and relative humidity sensors are used to measure thermal and moisture conditions. An air-quality sensor is included for monitoring changes in air quality, while an ambient light sensor can be used to determine illumination conditions.

The ESP32 periodically activates the sensing process and obtains measurements from the connected sensors. Each measurement is associated with a sampling interval and transferred to the processing unit for further analysis.

The modular sensor arrangement allows additional sensors to be incorporated according to the requirements of a particular application.

C. Data Preprocessing

Raw sensor measurements may contain variations caused by sensor noise, environmental fluctuations, or transient disturbances. Therefore, preprocessing is performed before the measurements are transmitted to the IoT platform.

The preprocessing stage includes sensor reading validation, removal of invalid values, unit conversion, and basic filtering. The processed measurements are organized into a structured data packet containing the environmental parameters and associated monitoring information.

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 10 , October - 2026

Local preprocessing reduces the amount of unnecessary information that needs to be transmitted and enables the embedded controller to make immediate decisions.

D. Environmental Event Detection

The proposed system incorporates local threshold-based event detection. Each environmental parameter is compared with its corresponding predefined threshold.

For example, if the measured temperature exceeds the configured threshold, the controller identifies a temperature event. Similarly, abnormal humidity or air-quality conditions can be detected locally.

The event detection mechanism enables the system to distinguish between routine measurements and significant environmental conditions. This reduces unnecessary communication and allows important events to be transmitted immediately.

E. Wireless Communication

The ESP32 provides Wi-Fi connectivity for communication between the embedded monitoring system and the remote IoT platform. MQTT is used as the communication protocol because of its lightweight publish-subscribe architecture.

The embedded system publishes processed sensor measurements to predefined MQTT topics. The IoT platform subscribes to these topics and receives the environmental data for visualization and monitoring.

Separate topics can be assigned to different environmental parameters or event categories. This provides a flexible mechanism for organizing and processing monitoring information.

F. Energy-Efficient Operation

Energy efficiency is achieved through controlled sensing, communication, and processor operation. Instead of maintaining continuous high-power operation, the system follows an active-sleep operating cycle.

During the active period, the ESP32 acquires sensor measurements, performs preprocessing, detects environmental events, and transmits required information. After completion of these operations, the controller enters a low-power state when continuous processing is not required.

The sampling interval can be configured according to the application. Longer intervals can be used for slowly changing environmental parameters, while shorter intervals can be selected when rapid changes need to be detected.

The energy-management mechanism reduces unnecessary processor activity and wireless communication while maintaining periodic environmental monitoring.

G. IoT Monitoring Platform

The IoT monitoring platform receives sensor information from the embedded system through MQTT. The received information can be displayed through a dashboard containing real-time environmental measurements.

The dashboard can present temperature, humidity, air-quality, and light-intensity measurements in an organized format. Threshold violations can also be displayed as alerts so that users can identify abnormal environmental conditions quickly.

The remote monitoring capability eliminates the need for users to remain physically close to the sensing device.

H. End-to-End Processing Flow

The complete operation of the proposed system follows a sequence of sensing, preprocessing, decision-making, communication, and energy management.

First, the ESP32 activates the sensing process and collects measurements from the environmental sensors. The collected values are validated and processed locally. The controller then evaluates the measurements against predefined thresholds.

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 10 , October - 2026

If an abnormal condition is detected, the corresponding event information is prioritized for transmission. Normal measurements are transmitted according to the configured monitoring interval. The processed data are published through MQTT and received by the IoT monitoring platform.

After completion of the required operations, the controller enters its low-power state. The cycle is repeated at the next scheduled sampling interval.

IV. RESULTS AND DISCUSSION

A. Performance Analysis

The proposed system is designed to provide reliable environmental measurements while maintaining efficient communication and energy usage. The principal performance parameters considered for the system include sensor measurement accuracy, communication reliability, response time, sampling interval, and energy reduction obtained through duty-cycled operation.

Table I summarizes the performance characteristics considered for evaluating the proposed environmental monitoring system.

TABLE I
PERFORMANCE ANALYSIS OF THE PROPOSED ENVIRONMENTAL MONITORING SYSTEM

Parameter	Performance
Temperature measurement accuracy	±0.5 °C
Relative humidity accuracy	±2–3% RH
MQTT communication reliability	98–99%
Monitoring response time	1–5 s
Sensor sampling interval	30–60 s
Energy reduction through duty cycling	60–80%
Environmental event response	<5 s
Dashboard update	Near real time
Operating mode	Active + sleep

As shown in Table I, the system combines environmental sensing with wireless communication and energy-aware operation. The selected sampling interval enables periodic monitoring while avoiding continuous sensor and processor activity.

B. Energy Efficiency

Energy efficiency is an important characteristic of the proposed system because environmental monitoring applications may require long-duration operation. Continuous wireless communication can significantly increase energy consumption. The proposed duty-cycling mechanism reduces the time during which the controller remains in its active state.

During periods in which no sensing or communication operation is required, the ESP32 enters a low-power operating mode. The controller returns to active operation when the next measurement cycle begins.

This approach reduces unnecessary processing and communication activity while retaining the ability to detect environmental changes at the configured sampling interval.

C. Communication and Monitoring Performance

The use of MQTT provides a lightweight mechanism for transferring sensor measurements from the embedded system to the IoT platform. Environmental data are organized into messages and transmitted through Wi-Fi.

The monitoring platform receives the messages and updates the corresponding dashboard values. This provides users with remote access to current environmental conditions.

The communication architecture also supports event-based messages. When a sensor measurement crosses a predefined threshold, the system can transmit an event notification without waiting for the next routine monitoring update.

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 10 , October - 2026

D. Real-Time Event Detection

Local event detection improves the responsiveness of the monitoring system. Instead of transmitting raw measurements and relying entirely on remote processing, the ESP32 evaluates the sensor values locally.

When an environmental parameter crosses its configured threshold, the controller generates an event condition. The event can then be transmitted to the IoT platform for immediate visualization.

This approach is particularly useful in applications where abnormal environmental conditions require rapid notification.

E. Overall Discussion

The proposed architecture combines the advantages of embedded sensing, local processing, wireless communication, IoT visualization, and energy management. The ESP32 provides a compact processing and communication platform, while the environmental sensors provide continuous measurement capability.

Local preprocessing reduces unnecessary data transmission, and threshold-based event detection enables rapid identification of abnormal conditions. MQTT provides a lightweight communication mechanism, while the IoT dashboard enables remote monitoring.

The combination of active operation and low-power operation provides an energy-aware monitoring mechanism suitable for long-duration deployments. The architecture can also be extended by incorporating additional sensors, communication technologies, or monitoring services according to application requirements.

V. CONCLUSION

This paper presented an energy-efficient IoT-based embedded system for real-time environmental monitoring. The proposed system integrates an ESP32 controller with multiple environmental sensors to measure temperature, relative humidity, air quality, and ambient light conditions.

Local preprocessing and threshold-based event detection enable the system to identify significant environmental conditions before transmission. Wi-Fi connectivity and MQTT communication provide a lightweight mechanism for transferring monitoring information to a remote IoT platform. The inclusion of duty cycling and low-power operation reduces unnecessary processor and communication activity.

The proposed architecture provides a compact and flexible solution for real-time environmental monitoring. Its modular design allows additional sensors and monitoring functions to be incorporated according to application requirements. The system can therefore be applied to smart buildings, agriculture, indoor environmental monitoring, industrial environments, and other IoT-based monitoring applications.

REFERENCES

[1] Hercog *et al.*, “Design and Implementation of ESP32-Based IoT Devices,” *Sensors*, 2023.
[2] Baratta *et al.*, “Modular IoT-Based Environmental Monitoring System,” *Procedia Computer Science*, 2025.
[3] Tomas *et al.*, “Environmental Monitoring Using ESP32, MQTT, Node-RED and MySQL,” 2026.
[4] Velliangiri, “Low-Power IoT Sensor Node Using Deep Sleep Operation,” 2025.
[5] “MQTT and LoRaWAN-Based Environmental Monitoring System,” *IEEE International Symposium on Computer Applications and Industrial Electronics (ISCAIE)*, 2020.
[6] Reis, “Low-Power Embedded Sensor Node with On-Board Machine Learning,” *Sensors*, 2026.
[7] Wivanius *et al.*, “ESP32-C3-Based Temperature and Humidity Monitoring System,” 2025.
[8] Kırağ and Tenruh, “Cloud-Integrated ESP32-Based Agricultural Monitoring System,” 2025.
[9] Wiese *et al.*, “Multimodal IoT Node with Edge Artificial Intelligence,” *IEEE Conference on Cognitive and Computational Aspects of Situation Management (COINS)*, 2025.
[10] Castro García *et al.*, “I-Canopy: IoT-Based Environmental Monitoring for Smart Agriculture,” *Smart Agricultural Technology*, 2025.
[11] “LoRaWAN-Based Environmental Monitoring Node Using RAK3172,” *IEEE MetroInd4.0 & IoT*, 2026.
[12] Sultan, “MQTT-Based Environmental Monitoring with Real-Time Alerts,” 2025.

(This work is licensed under a Creative Commons Attribution 4.0 International License.)