

Design and Implementation of an IoT-Based Air Quality Monitoring and Early Warning System for Forest Fire Smoke Pollution Using MQ-135 Sensors

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Abstract

Forest fires generate substantial atmospheric pollution and pose significant challenges for environmental monitoring, particularly in remote areas with limited electrical infrastructure. This study develops and evaluates a solar powered Internet of Things (IoT) based air quality monitoring and early warning system integrating an MQ-135 gas sensor, Arduino Uno, ESP32 communication module, and photovoltaic battery power subsystem. The system was designed to enable continuous environmental sensing, local threshold-based decision-making, remote data transmission, and autonomous operation. Sensor performance was evaluated using 100 paired measurements by comparing CO₂ concentrations displayed on the local LCD with those obtained from a calibrated reference CO₂ meter. The results demonstrated a strong measurement relationship, with a Pearson correlation coefficient of 0.9953 and R² of 0.9905. The system achieved an MAE of 80.10 ppm, RMSE of 91.97 ppm, and MAPE of 3.999%, corresponding to approximately 96.00% agreement based accuracy. The threshold-based warning mechanism achieved 100% accuracy, precision, recall, and F1-score under the predefined experimental threshold of 1,000 ppm. This threshold was used exclusively to evaluate warning-system functionality and does not represent a health based or regulatory air-quality limit. IoT communication exhibited an average transmission delay of 620 ms, while the total power consumption was 2.15 W, providing a theoretical battery autonomy of approximately 55.8 h. The findings demonstrate the feasibility of integrating sensing, automated warning, low-latency communication, and photovoltaic energy autonomy into a unified platform for remote environmental monitoring.

Kata Kunci : Air Quality Monitoring, Early Warning System, Forest Fire Detection, Internet Of Things (Iot), Mq-135 Sensor, Solar Energy

I. INTRODUCTION

Forest fires are among the most devastating environmental disasters, causing significant ecological degradation, biodiversity loss, economic damage, and adverse health effects on affected populations [1]. In recent decades, the frequency and intensity of forest fires have increased worldwide due to climate change [2], prolonged droughts, rising temperatures, and human-induced land clearing activities [3]. Southeast Asian countries [4], particularly Indonesia, experience recurrent forest and peatland fires that generate extensive transboundary haze pollution and deteriorate regional air quality [5], [6].

The combustion process during forest fires releases large quantities of atmospheric pollutants [7], including carbon monoxide (CO), carbon dioxide (CO₂), nitrogen oxides (NO_x), sulfur dioxide (SO₂), volatile organic compounds (VOCs), and particulate matter (PM_{2.5} and PM₁₀) [8]. Exposure to these pollutants has been associated with respiratory diseases, cardiovascular

disorders, reduced lung function, and increased mortality rates [9], particularly among vulnerable populations such as children and the elderly [10]. Consequently, continuous monitoring of air quality in fire-prone regions has become an essential component of environmental management and public health protection strategies [11].

Recent advances in the Internet of Things (IoT) have enabled the development of low-cost environmental monitoring systems capable of collecting [12], processing, and transmitting air quality data in real time [13]. IoT-based monitoring platforms offer significant advantages over conventional monitoring stations, including lower deployment costs, scalability, remote accessibility, and real-time alert capabilities [14]. These characteristics make IoT technologies particularly suitable for deployment in remote forest regions where conventional infrastructure is limited [15].

Among various gas sensors available for air quality monitoring, the MQ-135 sensor has gained considerable attention due to its sensitivity to

multiple harmful gases, including ammonia (NH₃), carbon dioxide (CO₂), benzene, alcohol vapor, and smoke-related compounds [16]. Previous studies have demonstrated the feasibility of MQ-135 sensors for indoor and outdoor air quality assessment, smart city applications, industrial emission monitoring, and environmental surveillance systems [17], [18]. The sensor provides a cost-effective alternative for detecting changes in pollutant concentrations associated with forest fire events [19].

Several researchers have developed air quality monitoring systems utilizing MQ-series sensors integrated with wireless communication technologies and cloud platforms [20]. Other studies have focused on wildfire detection systems employing temperature [21], humidity, smoke, and gas sensors to provide early warning capabilities [22]. Although these approaches have shown promising results, most existing systems rely on grid electricity or battery-powered operation [23], limiting their deployment duration and reliability in remote forested areas where electrical infrastructure is unavailable [24].

Renewable energy technologies, particularly solar photovoltaic (PV) systems, offer a sustainable solution for powering environmental monitoring devices in off-grid locations [25]. Solar energy systems provide clean, reliable, and autonomous electrical power, making them highly suitable for continuous operation in forest monitoring applications [26]. Previous investigations have demonstrated the effectiveness of solar-powered IoT systems for environmental sensing, agricultural monitoring, weather observation, and disaster management applications [27]. However, studies integrating solar energy generation with real-time air quality monitoring and warning systems specifically designed for forest fire smoke detection remain limited [28].

The integration of solar photovoltaic technology with air quality monitoring systems presents several advantages, including energy independence, reduced maintenance requirements, enhanced deployment flexibility, and improved operational sustainability [29]. Such systems can operate continuously without dependence on conventional power grids, enabling long-term environmental surveillance in isolated forest regions [30].

Therefore, this study proposes the design and implementation of a solar-powered air quality monitoring and early warning system utilizing the MQ-135 gas sensor for detecting air pollution caused by forest fires. The system is designed to perform real-time measurement of air quality parameters, transmit monitoring data through wireless communication networks, and generate automatic warning notifications when pollutant concentrations exceed predefined safety thresholds.

The novelty of this research is the system-level co-design and experimental validation of an autonomous, solar-powered IoT architecture that simultaneously addresses three critical constraints of remote forest-fire environmental monitoring: sensing reliability, communication responsiveness, and energy sustainability. Unlike conventional low-cost air-quality monitoring systems that primarily demonstrate sensing capability or wireless data visualization, the proposed system integrates MQ-135-based environmental sensing with local threshold-based decision-making, real-time IoT communication, and photovoltaic–battery power management, while quantitatively assessing measurement error, warning classification performance, communication delay, and autonomous operating capability. This multi-dimensional validation provides an operational perspective that is rarely addressed in existing low-cost wildfire monitoring studies, where sensing, communication, and energy performance are commonly evaluated independently. The contribution is therefore not merely the integration of existing components, but the establishment of an end-to-end autonomous monitoring framework in which environmental measurement, edge-based warning generation, wireless transmission, and energy availability are jointly considered as interconnected system-performance dimensions. The proposed framework provides a practical foundation for scalable deployment in remote and infrastructure-limited forest environments and can subsequently be extended toward multi-pollutant wildfire-smoke monitoring through the integration sensor.

II. METHOD

This research employed a research and development (R&D) approach to design, implement, and evaluate a solar-powered air quality monitoring and early warning system for forest fire smoke detection using the MQ-135 gas sensor. The study began with problem identification through an assessment of the environmental impacts caused by forest fires, particularly the deterioration of air quality due to the release of hazardous gases and particulate matter. A comprehensive literature review was subsequently conducted to examine recent developments in air quality monitoring technologies, Internet of Things (IoT)-based environmental sensing systems, gas sensor applications, and renewable energy integration. The findings from previous studies were used to identify existing limitations and establish the foundation for developing a more sustainable and autonomous monitoring system.

Based on the results of the preliminary investigation, the proposed system was designed by integrating hardware and software components into a unified monitoring platform. The hardware

architecture consisted of an MQ-135 gas sensor for detecting air pollutants, a microcontroller for data processing, wireless communication modules for real-time data transmission, and a photovoltaic power generation subsystem comprising solar panels, charge controllers, and rechargeable batteries. Simultaneously, the software architecture was developed to perform sensor data acquisition, air quality analysis, cloud-based data transmission, and automated warning notifications whenever pollutant concentrations exceeded predefined safety thresholds. The design phase also included system validation to ensure that all functional requirements were achieved prior to implementation.

Following the design stage, the developed system was implemented and deployed as a working prototype. Experimental testing was then conducted to evaluate the performance of the monitoring system under various environmental conditions. The evaluation focused on sensor responsiveness, measurement stability, communication reliability, warning system effectiveness, and the capability of the solar photovoltaic subsystem to provide continuous electrical power. The collected data were recorded and analyzed to determine the operational performance of the proposed system. If any component failed to satisfy the established performance criteria, improvements were applied to both hardware and software components before repeating the testing process.

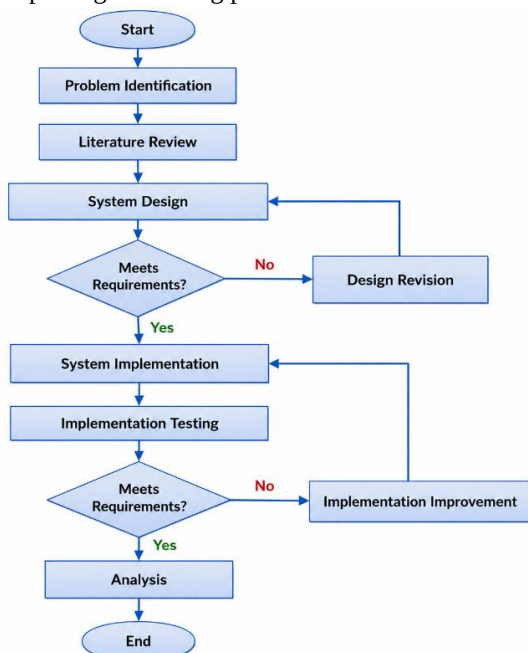


Figure 1. Flowchart

Finally, data analysis was performed to assess the overall effectiveness of the proposed monitoring and early warning system. The measured air quality data were analyzed to

evaluate the ability of the MQ-135 sensor to detect pollution levels associated with forest fire smoke, while energy consumption analysis was conducted to determine the sustainability of the solar-powered operation. The obtained results were compared with those reported in previous studies to validate system performance and identify its contributions to the field of environmental monitoring. The novelty of this research lies in the integration of an MQ-135-based air quality monitoring system with a standalone solar photovoltaic energy source, enabling continuous and autonomous operation in remote forest areas where conventional electrical infrastructure is unavailable. This integrated approach offers a sustainable solution for real-time air quality surveillance and early warning applications in forest fire-prone regions.

III. RESULTS AND DISCUSSION

3.1. System Design

The proposed solar-powered air quality monitoring system was designed as an autonomous Internet of Things (IoT)-based platform capable of continuously monitoring environmental air quality and providing real-time information to users without relying on conventional electrical infrastructure. The system integrates renewable energy generation, environmental sensing, embedded processing, wireless communication, and cloud-based monitoring into a unified architecture. By combining solar energy technology with IoT communication, the system is capable of operating independently in remote areas while supporting sustainable environmental monitoring applications. The overall system architecture consists of three main subsystems, namely the renewable energy supply subsystem, the sensing and data processing subsystem, and the communication and notification subsystem.

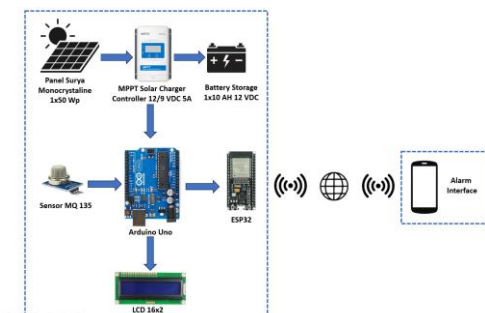


Figure 2. Diagram block system

The renewable energy supply subsystem functions as the primary power source for the entire monitoring system. A 50 Wp monocrystalline photovoltaic panel was employed to convert solar irradiance into electrical energy.

To maximize energy harvesting efficiency under varying environmental conditions, a Maximum Power Point Tracking (MPPT) charge controller rated at 12 VDC and 5 A was utilized. The MPPT controller continuously adjusts the operating point of the photovoltaic panel to ensure optimal power extraction throughout the day. The generated energy is stored in a 12 V, 10 Ah rechargeable battery that serves as both an energy storage unit and backup power source during periods of low solar irradiance or nighttime operation. This configuration ensures uninterrupted system functionality and enhances operational reliability under diverse weather conditions.

The sensing and data processing subsystem is responsible for acquiring and interpreting air quality information. An MQ-135 gas sensor was selected due to its sensitivity to several atmospheric pollutants, including carbon dioxide (CO₂), ammonia (NH₃), nitrogen oxides (NO_x), and volatile organic compounds (VOCs). These pollutants are commonly associated with industrial emissions, urban pollution, and combustion processes. The analog output generated by the MQ-135 sensor is acquired and processed by an Arduino Uno microcontroller through its analog-to-digital conversion interface. The microcontroller performs signal conditioning, sensor calibration, and threshold-based evaluation to determine the air quality status. The processed measurements are subsequently displayed on a 16×2 LCD module, providing users with immediate on-site access to real-time air quality information.

The communication and notification subsystem enables remote monitoring and early warning functionality through wireless internet connectivity. An ESP32 module was employed as the communication gateway due to its integrated Wi-Fi capability, low power consumption, and high processing performance. The ESP32 receives processed sensor data from the Arduino Uno and transmits the information periodically to a cloud-based monitoring platform. Through this platform, users can access air quality information using smartphones, tablets, or personal computers regardless of their geographical location. Furthermore, the system incorporates an automated notification mechanism that continuously evaluates pollutant concentrations against predefined safety thresholds. When the measured concentration exceeds the permissible limit, warning notifications are automatically sent to the user's smartphone, informing them of deteriorating air quality conditions and recommending preventive actions such as wearing protective masks or avoiding prolonged exposure to the affected area.

The operational workflow of the proposed system begins with solar energy harvesting and battery charging through the MPPT controller. The stored electrical energy powers all sensing, processing, display, and communication components. Air quality data collected by the MQ-

135 sensor are continuously processed by the Arduino Uno and displayed locally on the LCD module. Simultaneously, the processed data are transmitted through the ESP32 module to the cloud server for real-time monitoring and historical data storage. This integrated architecture enables autonomous operation, continuous environmental surveillance, and rapid dissemination of information to users. Compared with conventional air quality monitoring systems that depend on grid electricity, the proposed system offers superior portability, energy independence, scalability, and deployment flexibility, making it particularly suitable for remote, off-grid, and environmentally sensitive locations. Furthermore, the integration of renewable energy and IoT technologies supports the development of sustainable and intelligent environmental monitoring infrastructures aligned with smart city and green technology initiatives.

3.2. Implementation

The implementation phase was conducted after all hardware and software components had been individually designed, calibrated, and validated. The objective of this phase was to transform the proposed solar-powered air quality monitoring architecture into a fully functional prototype capable of autonomous field operation. System implementation involved mechanical assembly, electronic integration, photovoltaic installation, firmware deployment, and validation of Internet of Things (IoT) connectivity. The completed prototype integrates renewable energy generation, environmental sensing, embedded processing, and wireless communication into a compact standalone monitoring unit.



Figure 3. Implementation of power sources and support poles

The physical structure of the system was constructed using a blue-painted hollow steel frame that functions as both a photovoltaic support

structure and a housing platform for the electronic modules. A 50 Wp monocrystalline solar panel was mounted at the top of the frame with a tilted orientation toward the incident solar radiation to maximize energy absorption throughout the day. Electrical energy generated by the panel is routed to a 12/9 VDC 5 A MPPT solar charge controller, which regulates charging voltage and current for the 12 V, 10 Ah battery pack. The MPPT unit and battery are enclosed within a metallic protective casing designed to improve durability against heat, dust, and environmental moisture, thereby enhancing system reliability for outdoor deployment.

Inside the enclosure, three primary modules are integrated: the MPPT charge controller, the battery storage unit, and the Arduino Uno-based control module. The MPPT controller maintains stable power delivery and prevents battery overcharging, while the battery provides backup energy during periods of low irradiance or nighttime operation. The MQ-135 gas sensor is positioned near the lower section of the enclosure to improve exposure to ambient air and facilitate detection of local pollutant concentrations. Sensor signals are processed by the Arduino Uno, which performs threshold evaluation and air quality classification. The processed measurements are displayed locally through a 16×2 LCD mounted on the front panel, enabling on-site monitoring without requiring internet access.



Figure 4. Implementation of electrical circuits and controllers

For remote monitoring functionality, an ESP32 module was integrated with the Arduino Uno through serial communication. The ESP32 transmits air quality data to a cloud-based monitoring platform via Wi-Fi connectivity,

allowing users to access real-time measurements through smartphone applications or web interfaces. An automated notification mechanism was implemented to support early warning capability. When measured pollutant concentrations exceed predefined safety thresholds, the system automatically sends alert notifications to the user’s mobile device, enabling rapid preventive actions such as reducing exposure or using respiratory protection.

Implementation testing demonstrated that all subsystems operated according to the design specifications. Under high solar irradiance, the photovoltaic panel consistently produced charging voltages in the range of 17–19 V, while the MPPT controller maintained stable charging behavior without overcharging the battery. The Arduino Uno successfully acquired and processed MQ-135 sensor data, and the ESP32 transmitted measurements to the cloud platform with low communication latency. The integrated prototype therefore demonstrated reliable autonomous operation, stable renewable energy utilization, and effective real-time air quality monitoring capability suitable for deployment in remote and off-grid environments.

Table 1. Hardware Integration Verification

Component	Specification	Status	Functionality
Solar Panel	50 Wp Monocrystalline	Operational	Energy generation
MPPT Controller	12/9 VDC, 5A	Operational	Charge regulation
Battery	12 V, 10 Ah	Operational	Energy storage
Arduino Uno	ATmega328P	Operational	Data processing
MQ-135 Sensor	Air Quality Sensor	Operational	Gas detection
ESP32	Wi-Fi Module	Operational	IoT communication
LCD 16×2	Display Module	Operational	Local visualization

3.3. Analysis and Discussion of Measurement Results

The performance of the developed CO₂ monitoring system was evaluated by comparing the CO₂ concentration measured by the sensor and displayed on the local LCD with measurements obtained from a calibrated commercial CO₂ meter used as the reference instrument. A total of 100 measurement samples were collected over a progressively increasing CO₂ concentration range. The comparison was conducted to evaluate the consistency, linearity, and measurement agreement of the developed sensor with respect to the calibrated reference instrument.

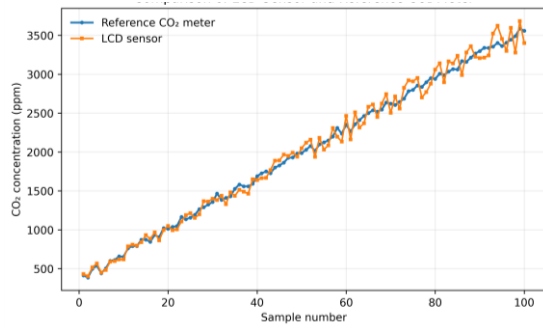


Figure 5. Comparison of LCD sensor and reference CO₂ Meter

Figure 5 illustrates the measurement profiles obtained from the developed CO₂ sensor and the calibrated reference meter. Overall, the two measurement curves exhibit a highly similar increasing trend throughout the 100 samples. The reference CO₂ meter increased from approximately 414 ppm to 3,559 ppm, while the LCD-based sensor produced measurements ranging from approximately 430 ppm to 3,682 ppm. The close tracking between the two curves indicates that the developed sensor was capable of following changes in CO₂ concentration over a relatively wide measurement range.

Based on the 100 measurement pairs, the calculated mean absolute error (MAE) was approximately 80.10 ppm, while the root mean square error (RMSE) was approximately 91.97 ppm. The mean absolute percentage error (MAPE) was 3.999%, corresponding to an agreement-based accuracy of approximately 96.001%.

The MAPE was calculated as:

$$MAPE = \frac{1}{n} \sum_{i=1}^n \left| \frac{C_{LCD,i} - C_{ref,i}}{C_{ref,i}} \right| \times 100\% \quad (1)$$

where $C_{LCD,i}$ is the CO₂ concentration displayed by the developed sensor and $C_{ref,i}$ is the corresponding concentration measured by the calibrated reference instrument.

The resulting accuracy was subsequently expressed as:

$$Accuracy = 100\% - MAPE \quad (2)$$

The MAPE value of approximately 3.999% is particularly useful for interpreting performance across the broad concentration range because it normalizes the error relative to the reference concentration. This is important in the present experiment because an absolute deviation of 80 ppm has a substantially different significance at 400 ppm compared with 3,500 ppm. Accordingly, the developed sensor demonstrates relatively consistent performance over the investigated concentration range, although the results also indicate that the measurement uncertainty is not completely independent of CO₂ concentration.

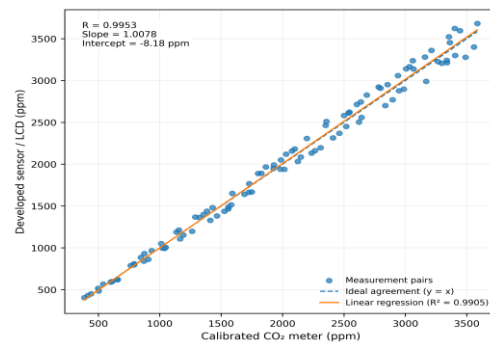


Figure 6. Scatter plot and linear regression

Figure 6 presents the scatter relationship between the developed sensor and the calibrated reference meter. The analysis produced a Pearson correlation coefficient of $R = 0.9953$ with $R^2 = 0.9905$. This indicates a very strong positive linear association between the two measurement systems. Approximately 99.05% of the variation in the LCD sensor readings is linearly associated with variation in the reference measurements within the investigated dataset.

The fitted regression relationship was approximately:

$$C_{LCD} = a + bC_{ref} \quad (3)$$

With a slope of approximately:

$$b = 1.0078$$

The slope being close to unity is an important indicator of proportional agreement. A slope of exactly 1 would indicate that the developed sensor responds proportionally to the reference instrument across the investigated range. The obtained value of approximately 1.0078 therefore suggests only a small proportional deviation from the ideal response. The high R^2 and near-unity regression slope demonstrate that the developed sensor has a highly consistent response to increasing CO₂ concentration.

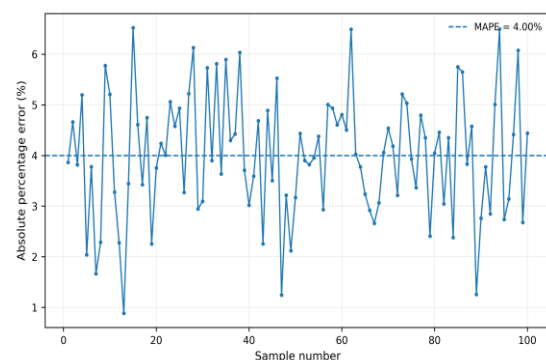


Figure 7. Absolute percentage error

Figure 7 illustrates the absolute percentage error (APE) obtained from 100 paired measurements between the developed CO₂ sensor and the calibrated reference meter. The observed

APE values ranged approximately from 0.9% to 6.5%, with a mean absolute percentage error (MAPE) of 4.00%. The error distribution remained relatively stable throughout the measurement sequence and did not exhibit a systematic increasing or decreasing trend, indicating the absence of an apparent measurement drift during the test. At lower CO₂ concentrations, relatively small absolute deviations can produce comparatively larger percentage errors. Conversely, at higher concentrations, the absolute difference between the two instruments may become larger while its percentage contribution to the measured concentration becomes smaller.

3.4. Analysis and Discussion Early Warning Performance

The effectiveness of the proposed early warning mechanism was evaluated by comparing measured CO₂ concentrations against a predefined threshold value of 1000 ppm. The 1,000 ppm threshold was defined exclusively as an experimental decision threshold for evaluating the functionality of the warning algorithm and does not represent a health-based exposure limit or an environmental air-quality standard.

Measurements below this threshold were classified as safe conditions, whereas concentrations exceeding 1000 ppm triggered warning notifications through the IoT platform. During testing, seven measurements remained below the threshold, while three measurements exceeded the critical limit and successfully activated the warning system. The maximum recorded concentration reached 3600 ppm, corresponding to an increase of approximately 767.5% relative to the initial concentration of 415 ppm. These findings demonstrate the capability of the MQ-135 sensor and the threshold-based decision algorithm to effectively distinguish between normal and hazardous air quality conditions.

Table 2. CO₂ Concentration and Warning Status

Sample	CO ₂ (ppm)	Threshold (ppm)	Warning Status
1	415	1000	Safe
2	430	1000	Safe
3	480	1000	Safe
4	620	1000	Safe
5	760	1000	Safe
6	520	1000	Safe
7	870	1000	Safe
8	1500	1000	Warning
9	2800	1000	Warning
10	3600	1000	Warning

Communication performance was also assessed to determine the real-time capability of the monitoring system. The measured communication delay ranged from 540 ms to 710

ms, with an average latency of 620 ms. This value remains well below the commonly accepted one-second threshold for real-time IoT applications, indicating that air quality information and warning notifications can be delivered to users with minimal delay. The low communication latency enhances the responsiveness of the proposed system, particularly during rapidly changing environmental conditions such as fire incidents or sudden increases in pollutant concentration.

The classification capability of the early warning system was further evaluated using confusion matrix analysis. Based on the experimental results, all safe and hazardous conditions were correctly identified, resulting in zero false-positive and zero false-negative classifications. Consequently, the system achieved 100% accuracy, precision, recall, and F1-score. These results confirm that the selected threshold value provides effective discrimination between normal and hazardous air quality conditions while preventing unnecessary alarm generation.

From an energy sustainability perspective, the proposed system exhibited highly efficient power utilization. The MQ-135 sensor and ESP32 communication module represented the largest contributors to overall power consumption, accounting for 41.9% and 37.2% of total energy usage, respectively. The total system power requirement was approximately 2.15 W. Considering the available battery capacity of 120 Wh (12 V, 10 Ah), the system is capable of operating autonomously for approximately 55.8 hours without recharging. This result demonstrates the effectiveness of integrating a photovoltaic energy harvesting system with low-power IoT devices to achieve long-term autonomous environmental monitoring.

IV. CONCLUSION

This study developed and experimentally evaluated a solar-powered IoT-based air-quality monitoring and early-warning system for autonomous deployment in remote forest-fire-prone environments. Validation using 100 paired measurements against a calibrated CO₂ reference meter demonstrated a strong measurement relationship, with R=0.9953, R²=0.9905, MAE = 80.10 ppm, RMSE = 91.97 ppm, and MAPE = 3.999%, corresponding to approximately 96.00% agreement-based accuracy. The mean Bland–Altman bias of 7.48 ppm further indicates limited systematic deviation from the reference measurements.

The proposed threshold-based warning mechanism correctly classified all tested observations according to the predefined 1,000 ppm experimental threshold, achieving 100% accuracy, precision, recall, and F1-score. Importantly, this threshold was established solely

to evaluate the functionality of the warning algorithm and does not represent a health-based or regulatory air-quality limit. The IoT architecture achieved an average communication delay of 620 ms, while the integrated photovoltaic–battery subsystem required only 2.15 W, providing a theoretical autonomy of approximately 55.8 h.

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