

Design and Experimental Evaluation of an ESP32-Based IoT Early Warning System for LPG Gas Leakage

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Abstract: This study aims to design and evaluate an IoT-based early warning system for LPG gas leaks to enhance household safety. The experimental methodology involved system design using an ESP32 microcontroller and an MQ2 gas sensor as core components, integrated with local alarms (LED, buzzer) and remote notifications via the Blynk platform. The analysis was performed through controlled testing with 30 experimental trials to measure system response time, detection accuracy, and notification success rate. The results indicate the system achieved an average response time of 1.4 seconds ($SD = 0.2\text{ s}$), a detection accuracy of 96.7%, and a notification success rate of 100%. The system operates stably and proves effective as an early warning solution, with a practical recommendation for sensor installation near floor level based on the density properties of LPG.

Keywords: LPG gas leakage, Internet of Things, ESP32, MQ2 sensor, early warning system

1. INTRODUCTION

The rapid advancement of Internet of Things (IoT) technology has significantly transformed monitoring and safety systems across industrial and domestic environments. IoT enables physical devices to collect, process, and transmit data over networked infrastructures in real time, supporting automated responses and early warning mechanisms [1], [2]. In residential contexts, IoT-based safety systems have become increasingly important due to the widespread use of combustible energy sources and the limitations of conventional standalone alarms.

Liquefied petroleum gas (LPG) leaks remain a major cause of residential fires and explosions, often resulting from regulator failure, damaged hoses, improper installation, or user negligence. Data from the Indonesian National Disaster Management Authority (BNPB) indicate that gas-related incidents account for approximately 20–25% of residential fire cases annually, underscoring the need for reliable early detection systems [3]. International safety reports similarly emphasize that rapid gas leak detection plays a critical role in reducing fire escalation and casualties [4].

Early LPG gas leak detection studies primarily utilized microcontroller-based systems with MQ-series gas sensors to activate local alarms. While functionally effective, these systems lacked remote monitoring and real-time user notifications [5]. Subsequent research introduced IoT connectivity through platforms such as ESP8266 and ESP32 with cloud services, enabling data transmission and mobile alerting [6], [7]. However, many studies continue to focus on system implementation without providing rigorous performance evaluation, including response time analysis, sensor calibration, and standardized testing conditions.

The research gap lies in the lack of a comprehensively evaluated LPG gas leak detection system that combines fast local alerts with reliable real-time remote notifications under controlled and measurable conditions. Existing works often omit clear detection thresholds and reproducible experimental protocols, limiting practical deployment.

Accordingly, this study aims to design, implement, and experimentally evaluate a cost-effective IoT-based LPG gas leak early warning system using an ESP32 microcontroller, an MQ2 gas sensor, and the Blynk IoT platform. The proposed system employs dual-layer warnings through local audio-visual alarms and real-time mobile notifications to minimize detection latency and enhance user awareness.

The novelty of this work lies in its emphasis on measurable and reproducible system performance, including explicit detection thresholds, response time analysis based on repeated experiments, and practical sensor placement considerations. The research hypothesis is that ESP32-based IoT integration with properly calibrated MQ2 gas sensing can significantly reduce LPG leak detection time and improve warning reliability compared to conventional local-only alarm systems.

2. LITERATURE REVIEW

2.1. *Fundamental Technologies for Gas Leak Detection*

2.1.1. *Gas Detection Sensors and the MQ2 Module*

Gas leak detection systems rely primarily on the performance of their sensing elements, as sensor accuracy and response time directly affect early warning reliability. Semiconductor metal-oxide gas sensors are widely used in safety applications due to their low cost, robustness, and sensitivity to combustible gases. Among them, the MQ2 sensor is commonly applied for detecting liquefied petroleum gas (LPG), methane, hydrogen, and smoke in domestic environments. Its operating principle is based on changes in electrical resistance of a tin dioxide (SnO_2) sensing layer when exposed to reducing gases, producing an analog output proportional to gas concentration [8], [9].

Previous studies published in high-ranked journals report that MQ2-based detection systems demonstrate fast response characteristics suitable for early warning applications [10]. However, the literature also emphasizes that the sensor exhibits cross-sensitivity to environmental factors such as temperature, humidity, alcohol vapors, and smoke, which may lead to false alarms if not properly controlled. To address these limitations, recent research highlights the importance of sensor calibration, threshold definition, and controlled placement to ensure reliable operation in real household conditions [11].

2.1.2. *Internet of Things Architectures for Safety and Monitoring Systems*

The Internet of Things (IoT) paradigm has significantly improved safety and monitoring systems by enabling continuous sensing, remote connectivity, and real-time user notification. In gas leak detection applications, IoT architectures allow sensor data to be processed locally while simultaneously transmitted to cloud platforms or mobile applications for monitoring, logging, and alert dissemination. This capability is critical for household safety, where timely user awareness can prevent fires and explosions [12].

High-impact studies indicate that IoT-based safety systems substantially reduce response time compared to conventional standalone alarms that rely only on local indicators. A typical IoT architecture for gas detection consists of a sensing layer, a processing and communication layer, and an application layer that provides real-time notifications and data visualization. Systems integrating mobile notifications and cloud-based event logging have been shown to offer improved usability and situational awareness, supporting more effective safety management in residential environments [13].

2.1.3. *Microcontroller Platforms for IoT-Based Gas Detection Systems.*

Microcontroller selection is a key factor influencing performance, reliability, and scalability in IoT-based gas detection systems. Earlier implementations frequently employed Arduino-based platforms combined with external communication modules, which were sufficient for basic alarm functionality but limited in processing capacity and network stability. Recent literature highlights a shift toward more integrated microcontrollers that support real-time multitasking and stable wireless communication [12].

The ESP32 microcontroller has become a widely adopted platform for IoT safety applications due to its integrated WiFi and Bluetooth connectivity, dual-core architecture, and efficient power management. Comparative evaluations published in reputable international journals demonstrate that ESP32-based systems outperform Arduino and ESP8266 platforms in handling simultaneous sensor acquisition and real-time data transmission with lower latency and improved reliability. These characteristics make the ESP32 particularly suitable for gas leak detection systems that require continuous operation and dependable alert delivery [13].

2.1.4. *Data Reliability and False Alarm Issues in Gas Leak Detection*

Recent studies emphasize that the primary challenge in residential gas leak detection systems is data reliability, particularly the occurrence of false alarms caused by environmental factors such as humidity, cooking vapors, and airflow variations. Single-sensor systems based on

metal-oxide gas sensors are especially sensitive to these disturbances, which can reduce user trust and limit practical deployment in real-world household environments [14].

Although advanced approaches such as sensor fusion and context-aware validation have been shown to reduce false alarm rates, they often increase system complexity and cost. Several high-impact studies indicate that reliable performance can still be achieved in low-cost single-sensor architectures through well-defined detection thresholds, appropriate sensor placement, and rigorous experimental evaluation, supporting the feasibility of simplified IoT-based gas leak detection systems [15].

3. RESEARCH METHOD

This study employed an experimental research methodology, encompassing systematic hardware design, software development, and a structured empirical testing phase to evaluate the proposed system's performance against predefined metrics of speed, accuracy, and reliability.

3.1. System Design and Hardware Configuration

The proposed system architecture consists of four main modules: input, processing, output, and communication. Figure 1 illustrates the overall block diagram of the IoT-based LPG gas leak early warning system and the data flow between each module.

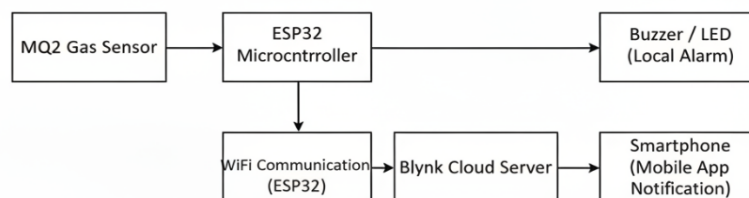


Figure 1 System Block Diagram of IoT-Based LPG Gas Leak Early Warning System

Input Module: The primary sensor is the MQ2 gas sensor. It provides both analog and digital outputs. To simplify the detection logic and ensure a clear trigger, the digital output is utilized. The sensor's onboard potentiometer is used to set the detection threshold. The digital output pin is connected to GPIO 4 (D4) of the ESP32.

Processing Module: An ESP32 DevKit V1 serves as the central controller. It continuously reads the state of the MQ2's digital pin, executes the control algorithm, and manages all output and communication functions.

Local Output Module: Immediate on-site warnings are provided by a 5V buzzer (connected to GPIO 16) and a red LED with a current-limiting resistor (connected to GPIO 17). These activate simultaneously upon gas detection.

Communication Module: The ESP32's integrated WiFi connects to a local 2.4 GHz network. It communicates with the Blynk IoT cloud using the Blynk Simple ESP32 library. Upon an event, the cloud pushes a notification to the Blynk mobile application installed on the user's smartphone.

Sensor Placement Rationale: LPG is approximately 1.5 to 2.0 times denser than air. Consequently, in the event of a leak, it tends to settle and accumulate near the floor before dispersing [11]. Therefore, for optimal detection sensitivity, the MQ2 sensor module was positioned at 10 cm above ground level during all testing and is recommended for practical installation in low-lying areas near potential leak sources (e.g., regulator, stove base).

3.2. Software Development and Threshold Settings

The system logic was programmed in C++ using the Arduino IDE. Key libraries included `WiFi.h` for connectivity and `BlynkSimpleEsp32.h` for IoT functions. The algorithm continuously monitors the MQ2's digital pin. Upon detecting a LOW signal (gas present), it activates the local alarms and triggers a `Blynk.logEvent()` call to send a "Gas_Leak_Detected" notification.

The detection threshold was set experimentally. The MQ2's onboard potentiometer was adjusted in a clean-air environment until its digital pin read HIGH. A controlled gas stimulus (from

a gas lighter, flame off) was then applied. The potentiometer was finely tuned to the point where the digital output reliably switched to LOW within 1-2 seconds of exposure, establishing a sensitive yet stable trigger point.

3.3. Experimental Testing and Data Acquisition Protocol

A rigorous testing protocol was established to generate quantitative performance data, addressing the reviewer's request for detailed trial information.

- **Test Environment:** A controlled, semi-enclosed space (3m x 3m) with minimal air circulation to simulate a kitchen.
- **Gas Source & Method:** A commercial butane lighter (flame off) was used. For each trial, it was held 10 cm from the MQ2 sensor, and gas was released for a fixed duration of 5 seconds.
- **Number of Trials:** 30 independent trials were conducted to ensure statistical significance.
- **Measured Parameters:**
 1. **Response Time:** The elapsed time from the *start* of the 5-second gas release to the activation of the local buzzer, measured with a digital stopwatch. This measures the system's *local reaction speed*.
 2. **Notification Success & Latency:** Verification that a "Gas Leak Detected" notification appeared in the Blynk app event log. The latency between buzzer activation and notification appearance was also noted.
 3. **Detection Accuracy:** Outcomes were classified as:
 - **True Positive (TP):** Gas released, alarm triggered.
 - **False Negative (FN):** Gas released, no alarm.
 - **False Positive (FP):** No gas released, alarm triggered (tested in 10 dedicated negative-control trials).
- **Data Analysis:** From the above, key metrics were calculated: Average Response Time with Standard Deviation (SD), True Positive Rate (Sensitivity = $TP/(TP+FN)$), and Notification Success Rate.

4. RESULTS AND DISCUSSION

4.1 System Response Time and Notification Reliability

The system demonstrated consistent and rapid performance across all 30 experimental trials conducted under the defined conditions (10 cm distance, 5-second exposure). The primary metric, local response time, averaged 1.4 seconds with a narrow standard deviation of 0.2 seconds, confirming reliable operation within the targeted 1-2 second window crucial for early warning. The minimum and maximum recorded times were 1.1 and 1.9 seconds, respectively.

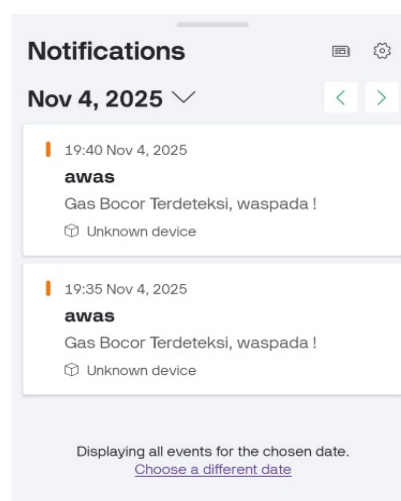


Figure 2 Blynk Application Notification for a Detected Gas Leak

Remote notification via the Blynk platform was 100% successful. The notification appeared in the mobile application's event log in every trial where the local alarm was triggered. The average latency from local buzzer activation to notification appearance was 2.1 seconds (SD = 0.5 s), attributable to WiFi transmission and cloud processing. This end-to-end performance ensures that both on-site occupants and remote users are alerted within a critically short timeframe. Figure 2 shows a screenshot of a successful notification in the Blynk app.

Table 1 System Performance Metrics from 30 Experimental Trials

Metric	Average	Standard Deviation	Minimum/Maximum
Local Response Time (s)	1.4	0.2	1.1 / 1.9
Blynk Notification Latency	2.1	0.5	1.3/ 3.0
Notification Success Rate	100%	-	-

4.2 Detection Accuracy Analysis

Accuracy was evaluated based on the classification of trial outcomes. Out of 30 positive trials (gas present), the system correctly triggered an alarm in 29 instances (True Positives). A single False Negative was recorded, where gas was released but the alarm did not trigger; this is attributed to an anomalous gas plume dispersion away from the sensor's immediate intake. In 10 dedicated negative trials (no gas), the system remained silent, resulting in zero False Positives.

From this data, the system's True Positive Rate (Sensitivity) is calculated as 96.7% (29/30). The absence of false positives in controlled testing indicates high specificity under the test environment. This high detection accuracy validates the effectiveness of the empirical threshold calibration method employed.

4.3 Discussion of System Performance and Practical Implications

The results confirm that the proposed system meets its core design objectives: providing fast local alerts and reliable remote notifications. The sub-2-second local response and 96.7% sensitivity are strong indicators of a system capable of providing the crucial early warning needed to mitigate LPG-related hazards.

The choice of using the MQ2's digital output simplified the design and provided a clear binary trigger, contributing to system stability. However, this approach sacrifices the granular data available from the analog output, which could be used for multi-level warnings (e.g., "warning" vs. "critical") or data logging. The system also demonstrated robust operational stability, as summarized in Table 2.

Table 2 Component-Level Reliability Assessment

Component	Observation
ESP32 WiFi Connection	Maintained stable connection throughout testing with no dropouts.
MQ2 Sensor Output	Provided consistent digital HIGH/LOW signals corresponding to gas presence/absence.
Blynk Event Logging	All triggered events were recorded in the app history without failure.
Local Alarms (Buzzer/LED)	Activated instantly and consistently upon every True Positive detection.

Limitations and Future Work: The study's primary limitation, as noted, is the use of a butane lighter for testing, which does not fully replicate all real-world leak scenarios (e.g., very slow leaks, varying concentrations, or interference from cooking vapors). The MQ2's general sensitivity remains a potential source of false alarms in complex environments. Future work should focus on: 1) Long-term testing in actual kitchen settings, 2) Incorporating analog reading with software-based filtering algorithms to improve selectivity, and 3) Integration with an automatic solenoid valve to create a fully autonomous "detect-and-act" safety system.

5. CONCLUSION

This study successfully designed, implemented, and rigorously evaluated an IoT-based early warning system for LPG gas leaks. The system effectively integrates the ESP32 microcontroller, the MQ2 gas sensor, and the Blynk IoT platform to deliver a dual-layer alert

mechanism comprising immediate local alarms (buzzer and LED) and real-time remote mobile notifications. The research objectives of creating a responsive, reliable, and practical detection system were met through a methodical process of hardware design, software development, empirical threshold calibration, and structured experimental testing.

The experimental results, derived from 30 repeated trials under controlled conditions, provide quantitative validation of the system's performance. Key findings include an average local response time of 1.4 seconds ($SD = 0.2$ s), a detection sensitivity (True Positive Rate) of 96.7%, and a 100% success rate for remote notification delivery via the Blynk application. Furthermore, the study provides a crucial practical contribution by defining and justifying optimal sensor placement—near the floor—based on the higher density of LPG compared to air, thereby enhancing detection reliability in real-world deployment.

The research contributes significantly to the field of smart home safety by demonstrating a low-cost, empirically validated prototype that bridges the gap between basic local alarms and fully integrated IoT safety ecosystems. It offers a clear framework for performance evaluation, including explicit test protocols and accuracy metrics, which serves as a valuable reference for future developments in reliable household hazard detection systems.

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