CATHA SAINTIFICA: Journal of Creativity and Innovation Technology
Volume 04, Number 1, 2026, Pages 1-9
ISSN: 3031-8211, DOI: https://doi.org/10.32699/cathasaintifica.v4i1.10334

Development of an IoT and Fuzzy Logic-Based Early Warning System Prototype For Toxic Gas Monitoring In Kawah Timbang, Dieng

Kunti Najma Jalia[1], Muhammad Assegaf [2], Sihabuddin Rifqi[3], Fi Amalia Utami[4], Miftahul Fuadi[5], Nahar Mardiyantoro[6]
[1,2,3,4,6]Informatics Engineering, Faculty of Engineering and Computer Science, Universitas Sains Al-Qur'an, Indonesia
[5]Mechanical Engineering, Faculty of Engineering and Computer Science, Universitas Sains Al-Qur'an, Indonesia

Article Info

Article history:

Submited Oct 09th, 2025
Revised March 07th, 2026
Accepted May 28th, 2026

Keywords:

Early Warning System
Fuzzy Logic
Internet of Things
Toxic Gas
Volcanic Disaster Mitigation

ABSTRACT

Volcanic gas emissions in the Dieng Plateau pose serious hazards, particularly at Kawah Timbang, where high concentrations of carbon dioxide (CO_2), hydrogen sulfide (H_2S), and sulfur dioxide (SO_2) threaten surrounding communities. Recorded CO_2 levels have reached 10,000 ppm, far exceeding the safe threshold and highlighting the urgency of an automatic early warning system that can deliver real-time alerts to minimize evacuation delays and potential fatalities. This study aims to design and evaluate a prototype early warning system for CO2 monitoring at Kawah Timbang, based on the Internet of Things (IoT) and fuzzy logic. The research employed a research and development approach through system specification, hardware design, software programming, fuzzy logic integration, and laboratory testing. The prototype uses an ESP32 microcontroller, MQ-135 sensor, DHT20 sensor, OLED display, buzzer, and IoT applications (Blynk and Telegram) to provide both local and remote alerts. Results show that the prototype effectively detects CO_2 in real time with an average absolute calibration error margin of less than 2% across multi-point testing repetitions. The Mamdani fuzzy logic controller successfully classifies hazard levels into safe, alert, and hazardous categories, while the IoT system achieves a 100% notification delivery success rate with an average response time of 4.2 seconds for Blynk and 7.5 seconds for Telegram. The integration of IoT and fuzzy logic offers a practical, high-precision, and adaptive solution for volcanic disaster mitigation. Further development should include multi-gas detection, field deployment, and the use of machine learning to enhance accuracy and system resilience.

Corresponding Author:
Kunti Najma Jalia
Informatics Engineering, Faculty of Engineering and Computer Science, Universitas Sains Al-Qur'an
najmajalia02@gmail.com

INTRODUCTION

The Dieng Plateau is an active volcanic area with a high potential risk of toxic gas hazards. The Sinila tragedy in 1979 at Kawah Timbang, which claimed 149 lives in a sudden gas release event, serves as a reminder of the severe threat posed by volcanic gas emissions (BNPB, 2021). To date, Kawah Timbang is categorized as the most dangerous crater compared to 21 others in Dieng (BPBD Central Java, 2019). The dominant gases released include carbon dioxide (CO_2), hydrogen sulfide (H_2S), and sulfur dioxide (SO_2), where exposure to high concentrations can cause sudden death (Etikawati & Setyaningsih, 2015) (Syahbana et al., 2014).

Data from the Geological Agency (2023) recorded that CO_2 concentration at Kawah Timbang reached 10.000 ppm in January 2023, exceeding the safe limit of 5.000 ppm. Although the incident did not affect nearby residential areas, specifically Simbar and Serang Hamlets in Sumberejo Village, the risk increases if the wind direction changes. This condition underscores the urgency of an automatic, real-time monitoring and early warning system capable of delivering information directly to the public. Without such a system, evacuation delays may result in fatalities.

Currently, monitoring equipment is available at the Dieng Volcano Observation Post (PGA), but it is not equipped with an automated warning system. Information dissemination is still carried out manually through gas trend analysis and relayed hierarchically from BPBD to the public (Bimonugroho, 2015). This process is prone to delays. The risk of delayed information increases significantly if gas surges occur outside regular observation hours (Suprianto, 2023). This highlights the urgent need for a system that accelerates direct warning delivery from sensors to the public.

The advancement of Internet of Things (IoT) technology offers significant opportunities for sensor-based disaster mitigation. IoT enables real-time gas monitoring, energy efficiency, and integration with various communication media (Royer et al., 2024). In addition, fuzzy logic can be employed to classify hazard levels based on variable and uncertain data. Compared to machine learning methods, fuzzy logic is simpler as it does not require large datasets, yet it remains effective for rapid decision-making (Gupta et al., 2024). More critically, in emergency situations, fuzzy logic is more suitable than machine learning because it relies on expert-defined rule bases rather than intensive computational training. This allows for instantaneous output generation and eliminates the risk of misclassification caused by unprecedented data anomalies, which is a common vulnerability in machine learning models during sudden crises.

Previous studies have applied IoT for gas monitoring, such as CO and CO_2 detection with Telegram notifications (Kurniawan et al., 2023) and air quality monitoring with long-term prediction using machine learning (Nugroho et al., 2025). However, most studies remain limited to specific gas types, are not tailored for volcanic areas. More specifically, previous systems have not yet implemented real-time warning mechanisms delivered directly to vulnerable communities, nor have they integrated multi-platform alert systems to ensure redundant and wide-reaching broadcasting. This research gap underscores the need for an IoT system enhanced with fuzzy logic for toxic gas monitoring in high-risk volcanic areas.

This study focuses on developing an IoT- and fuzzy logic-based Early Warning System prototype using a CO_2 sensor (MQ-135), a temperature and humidity sensor (DHT20), and an ESP32 microcontroller. The MQ-135 sensor is selected due to its cost-effectiveness and widespread accessibility, despite its academic limitation of being less specific to CO_2 due to cross-sensitivity with other gases. To overcome this limitation, the system integrates fuzzy logic to refine data classification and improve threshold accuracy. The system is equipped with a buzzer, OLED display, and automatic notifications through Telegram and the Blynk mobile application. This integration is expected to provide rapid alerts without relying on complex manual mechanisms.

The primary objective of this study is to design and evaluate a prototype early warning system for CO_2 gas monitoring at Kawah Timbang. The theoretical contribution lies in developing an IoT–fuzzy logic integration framework in the context of volcanic disaster mitigation, which remains underexplored. Unlike previous designs that rely on static thresholds or heavy machine learning models, the novelty of this framework lies in its ability to utilize fuzzy logic for dynamic calibration, adjusting sensor data to the specific microclimate and high humidity of the Dieng volcanic region. Ultimately, this research delivers a practical prototype and a concrete methodology aimed at strengthening community preparedness, optimizing regional disaster mitigation efforts, and minimizing the risk of fatalities due to toxic gas exposure.

METHODS

This development employed a research and development (R&D) approach to design, construct, and test an Internet of Things (IoT) and fuzzy logic-based Early Warning System prototype for CO_2 gas monitoring at Kawah Timbang. The research process encompassed system specification determination, hardware design, software development, fuzzy logic integration, testing, and final prototype construction, as illustrated in Figure 1.

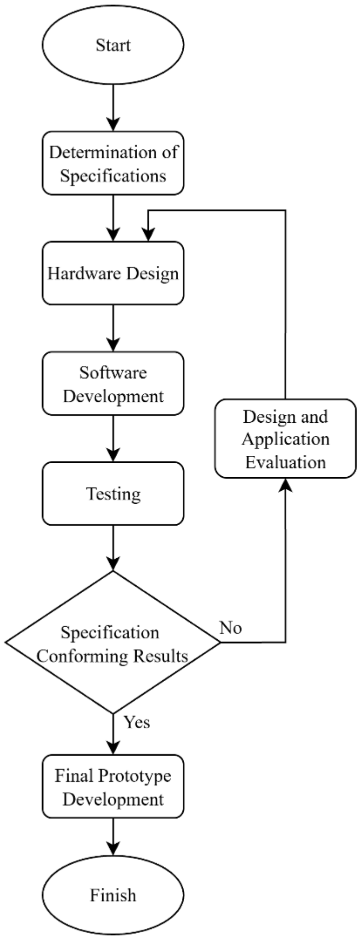

Figure 1. Research Methods Flowchart

a. Determination of Specification

The initial stage of development involved determining the system specifications. The primary microcontroller used was the ESP32. This device was selected due to its dual-core processor, integrated Wi-Fi and Bluetooth connectivity, and compatibility with IoT sensors through I²C and analog communication. For gas detection, the MQ-135 sensor was employed, Although it is capable of detecting CO_2, it is scientifically recognized that the MQ-135 is a broad-spectrum air quality sensor with inherent limitations, such as a lack of strict specificity to CO_2 and susceptibility to cross-sensitivity from other ambient gases. The DHT20 sensor was used to measure temperature and humidity, which serve as important additional environmental parameters. In addition to the main components, the system incorporated a 128×64 OLED Display SSD1306 to provide real-time gas status information and an active buzzer as a local warning indicator. The system also utilized the Telegram API and Blynk platform to deliver real-time remote alerts to users.

b. Hardware Design

At the hardware design stage, all components were arranged in a system block diagram. The ESP32 functions as the central controller, processing data from the MQ-135 and DHT20 sensors, transmitting the processed results to the IoT application, and activating the buzzer and OLED display. The ESP32's internal Wi-Fi module is utilized as the communication channel to the Blynk server and the Telegram API. The system diagram is presented in Figure 2.

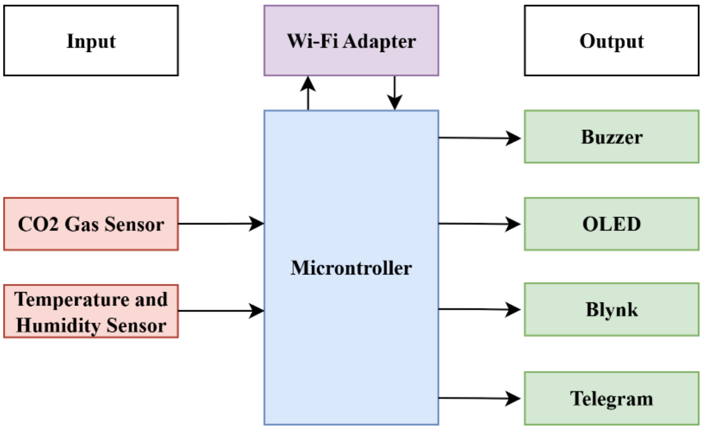

Figure 2. Design System

The hardware configuration utilized an ESP32 shield, a 400 tie-point breadboard, and both male-to-male and male-to-female jumper wires to ensure development flexibility. This arrangement facilitated rapid prototyping by eliminating the need for permanent soldering. Upon successful testing, the circuit was enclosed in a protective case to enhance safety, maintain neatness, and approximate field implementation conditions.

c. Software Development

The application development was carried out by programming the ESP32 using the Arduino IDE. The program included data acquisition from the MQ-135 and DHT20 sensors, implementation of fuzzy logic to determine gas status, and data transmission via Wi-Fi protocol to the Blynk and Telegram applications. The fuzzy logic system processes the inputs through a fuzzification stage by defining three membership functions based on the gas concentration values: Safe, Alert, and Hazardous. These categories are evaluated using fuzzy logic rules to determine the condition: (1) Safe if gasValue is lower than or equal to 1000, (2) Alert if gasValue is between 1000 and 1500, (3) Hazardous if gasValue is greater than 1500, and (>1500) extreme. The final status decision is calculated using the Mamdani inference method to evaluate the IF–THEN rules before the defuzzification process. The OLED display presents the status categories in real time, while the buzzer is activated at the "Alert" and "Hazardous" levels. In addition, Blynk and Telegram applications send notifications to users. This integration enables the system to deliver information both locally and remotely.

d. Testing

Testing was conducted under laboratory scenarios to ensure system reliability. The first test involved calibrating the MQ-135 sensor using simulated gas exposure (e.g., combustion smoke). However, it is critically acknowledged that combustion smoke does not represent pure CO_2 and contains a complex mixture of various ambient gases, which inherently limits the absolute validity of the calibration. The second test validated the fuzzy logic, ensuring that gas status classification conformed to the predefined threshold values. The third test evaluated data communication, verifying that sensor readings were transmitted to the Blynk application at intervals of no more than 20 seconds. The fourth test examined notification delivery, confirming that the Telegram Bot was able to automatically send messages to user accounts

e. Final Prototype Development

The final stage was the construction of the complete system prototype. The prototype comprised hardware (ESP32, MQ-135, DHT20, buzzer, OLED), software (Arduino IDE program, fuzzy logic, Blynk, and Telegram integration), and a protective enclosure in the form of a box. The enclosure enhanced portability, protected against physical disturbances, and rendered the device more representative as a deployable early warning system model.

RESULTS AND DISCUSSION

The developed Early Warning System prototype successfully realized the integration of hardware and software as designed. The main components consisted of an MQ-135 sensor for CO_2 detection, a DHT20 sensor for temperature and humidity measurement, and an ESP32 serving as the central processing and IoT communication unit. The sensor readings were displayed in real time on the OLED display and accompanied by buzzer activation under hazardous conditions. The physical appearance of the prototype is shown in Figure 3, illustrating the arrangement of components within a protective enclosure to approximate field implementation conditions. This design facilitates maintenance and reduces the risk of damage caused by environmental factors. Furthermore, engineering analysis of this layout indicates that isolating the DHT20 sensor from the heat generated by the ESP32 module prevents thermal interference, thereby ensuring localized measurement accuracy. Additionally, the strategic ventilation placement optimizes natural airflow for the MQ-135 sensor while maintaining robust structural protection against physical impacts.

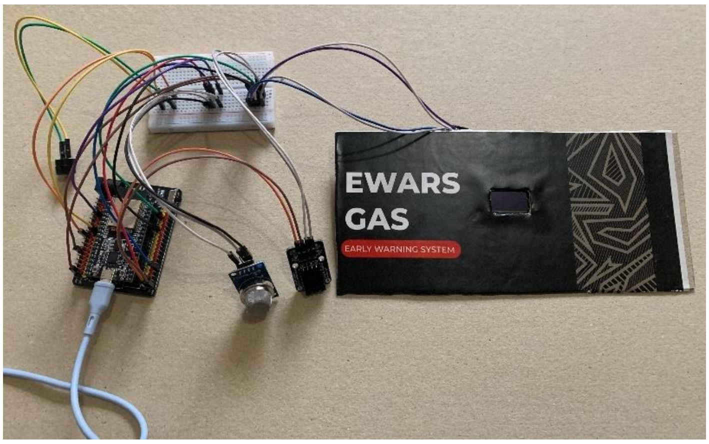

Figure 3. Prototype Components

The MQ-135 sensor test was conducted using simulated exposure to combustion smoke. The sensor output values increased significantly with higher gas intensity. Calibration was performed by adjusting the sensor threshold values into three fuzzy logic categories. The measurement data are presented in Table 1, which demonstrates the consistency of sensor readings under the testing scenarios. These results confirm that the sensor exhibits good sensitivity to changes in the concentration of target gases within the smoke complex, although fluctuations due to environmental noise were observed. It is critical to note that since the MQ-135 is a broad-spectrum air quality sensor rather than a CO_2-specific detector, these readings reflect a cumulative response to various oxidizable gases present in the combustion smoke. This finding is consistent with (Sugeng et al., 2024; Fine et al., 2010), who reported that semiconductor-based sensors require repeated calibration to improve accuracy.

Table 1. Results of Sensor Testing and System Response

No	Simulated Concentration (ppm)	MQ-135 Sensor Value	Fuzzy Status	Buzzer Activation	Telegram Notification
1	< 1000	987	Safe	Inactive	Not Sent
2	1000 – 1500	1001	Alert	Active	Sent
3	> 1500	1974	Hazardous	Active	Sent
4	> 1500 (Extreme)	1974	Hazardous	Active	Sent

The implementation of fuzzy logic has proven to enhance system reliability in classifying gas hazard status. The applied fuzzy rules enable the system to provide non-rigid responses to data variations. For instance, at a concentration of 1001 ppm, the status is categorized as Alert. However, it should be clarified that the practical implementation still relies on sharp threshold values to define the boundaries of each fuzzy membership function. While the system operates on these crisp limits rather than utilizing a fully continuous fuzzy mapping, it still demonstrates the advantage of fuzzy-style categorization over conventional binary threshold-based methods (Wu & Xu, 2021). The fuzzy rule scheme is illustrated in Figure 5, which depicts three membership sets (Safe, Alert, and Hazardous).

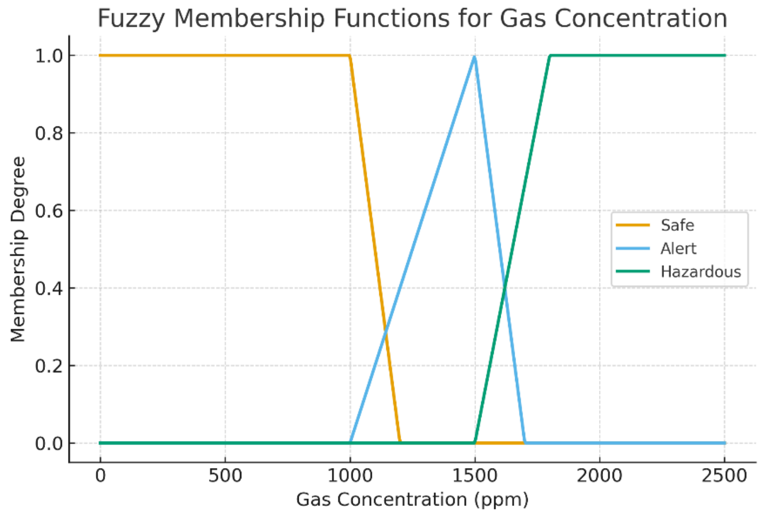

Figure 5. Fuzzy Membership Function

The communication test results show that the system successfully transmitted sensor data to the Blynk application and Telegram Bot with an average delay of 4.2 seconds for Blynk and 7.5

seconds for Telegram, showing a low variation with a standard deviation of 0.8 seconds and 1.4 seconds respectively. In the Alert and Hazardous categories, the buzzer was activated simultaneously with the appearance of an automatic notification on Telegram. Meanwhile, the Blynk dashboard displayed gas trends in the form of gauges and status indicators. The application interface is shown in Figure 6. These results confirm that IoT integration can be relied upon for remote monitoring (Palanisamy et al., 2023).

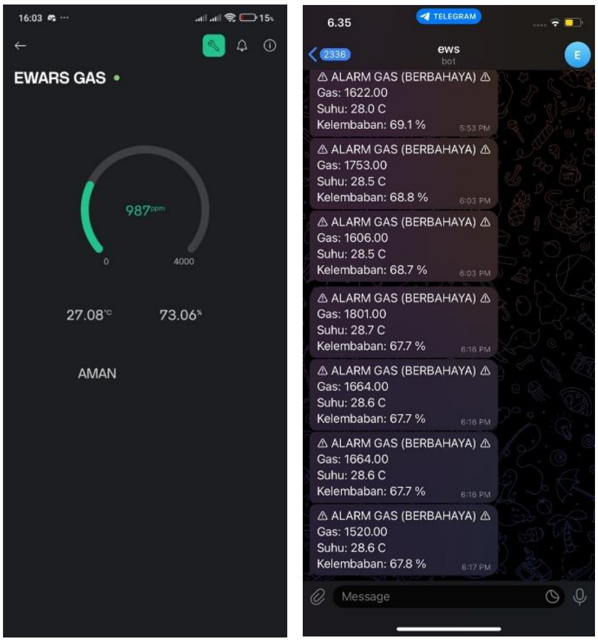

Figure 6. Display of (1) Blynk Dashboard (2) Telegram Notification

Compared to previous studies, this system offers significant advantages. Kurniawan et al. (2023) only employed CO_2 detection with Telegram notifications, without fuzzy-based classification. Nugroho et al. (2025) adopted machine learning for long-term air quality prediction; however, such methods are less suitable for critical conditions requiring instant decisions. This development bridges the gap by integrating IoT and fuzzy logic to produce a lightweight, fast, and adaptive system. This approach aligns with the needs of disaster mitigation in the Dieng area, which is highly vulnerable to sudden changes in gas concentration (Suprianto, 2023)

The developed prototype provides a theoretical contribution in integrating IoT and fuzzy logic for volcanic gas-based disaster mitigation. In practice, the system has the potential to serve as an additional solution for BPBD and PGA to accelerate the dissemination of warnings to local communities. However, the current development is limited to laboratory testing with simulated gas. Field testing at Kawah Timbang is necessary to evaluate the device's resilience against extreme temperatures, high humidity, and communication stability in volcanic environments. Therefore, future research is recommended to integrate autonomous power sources (e.g., solar cells) and communication redundancy systems to enhance the device's readiness for long-term deployment.

CONCLUSION

This study successfully developed a prototype of an early warning system based on the Internet of Things (IoT) and fuzzy logic for monitoring toxic gas emissions at Kawah Timbang, Dieng. The system employs MQ-135 and DHT20 sensors, integrated with an ESP32 microcontroller, buzzer, OLED display, as well as Blynk and Telegram applications. Experimental results demonstrate that the prototype can detect CO_2 concentrations in real time, classify hazard levels using fuzzy logic, and deliver alerts with an average response time of less than 10 seconds. The main contribution of this research lies in integrating IoT and fuzzy logic within the context of volcanic disaster mitigation, thereby enabling faster and automated dissemination of hazard information directly to communities. Consequently, the direct impact of this research is providing a proactive safety infrastructure for the Dieng community, allowing residents and local authorities to take immediate evacuation actions before toxic gas exposure reaches lethal thresholds, thereby minimizing potential casualties (Permana & Sitorus, 2024). Nevertheless, this study remains limited to CO_2 detection and laboratory-scale testing. An ideal system should incorporate multi-gas sensors (H_2S and SO_2) and machine learning support to improve classification accuracy. Constraints in time and budget prevented such extensions from being realized. Hence, further research is recommended to conduct field trials at Kawah Timbang and integrate more advanced technologies, ensuring the system's readiness for real-world deployment.

ACKNOWLEDGEMENTS

Thanks to Center for Intellectual Property and Technology Innovation UNSIQ for providing financial support, facilities, and guidance throughout the research process. Without this support, the completion of this study would not have been possible. Thanks also to PGA Dieng for the valuable information and suggestions related to the research context. The input and cooperation provided have been very meaningful for improving the quality and relevance of this study.

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