

WSN-Based Integrated Sensor System for Volcanic Activity Monitoring and Early Warning

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Article Information

Article Histories:

Submitted: 13 January 2026

Revised: 15 February 2026

Accepted: 3 March 2026

Keywords:

CO₂ Sensor

Integrated Sensor

IoT

SO₂ Sensor

Volcano Monitoring

WSN

ABSTRACT

This research presents the development of a WSN-based integrated sensor system designed to monitor ground vibrations, CO₂ concentration, and SO₂ concentration as early indicators of volcanic activity. The system integrates an ADXL335 accelerometer, MG-811 CO₂ sensor, and MQ-136 SO₂ sensor with an Arduino-based microcontroller, LoRa communication modules, and an Internet-of-Things (IoT) platform for real-time monitoring. Sensor calibration was carried out using controlled laboratory procedures, including drop tests for vibration measurement and gas exposure tests for CO₂ and SO₂ detection. The IoT layer, consisting of an MQTT-based web dashboard and automated Telegram notifications, successfully visualized sensor data and delivered early-warning messages during the outdoor test. The three-day outdoor simulation demonstrated stable operation of the sensor nodes, LoRa transmission, and solar-powered supply. Although the system has not yet been validated in a real volcanic environment, the prototype shows the feasibility of integrating multiple sensing modalities with low-power wireless communication and IoT-based data services. This indicates its potential for further development into a field-deployable volcanic monitoring and early-warning system.

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I. INTRODUCTION

Indonesia lies along the Pacific Ring of Fire and hosts 127 active volcanoes, making it one of the most volcanically active regions globally (PVMBG, 2022). Despite this high hazard potential, continuous monitoring is currently limited to fewer than 70 volcanoes (PVMBG, 2023). The high frequency of eruptions such as the 253 recorded in 2022, with Anak Krakatau contributing 88 events highlights the need for more distributed, low-cost, and autonomous monitoring technologies capable of delivering real-time information.

Previous research has explored various sensing approaches, such as accelerometer-based tremor detection (Hanwei Electronics, 2020), CO₂ measurement using the MG-811 sensor 811 (Winsen Electronics, 2021), and SO₂ detection using semiconductor devices such as the MQ-136 136 (Hidayat et al., 2020). Other studies have experimented with IoT-based gas monitoring platforms using WiFi modules like ESP8266 [6]. Although these works provide important building blocks, most focus on single parameters or remain limited to small-scale laboratory implementations.

In practice, multiple volcanic precursors tend to evolve simultaneously. Increasing tremor levels, elevated CO₂ flux, and rising SO₂ emissions often signal magma movement and pressure accumulation beneath the surface (Johnson & Malone, 2019). This motivates concurrent multisensor integration within a single device. The emergence of Wireless Sensor Network (WSN) technologies particularly LoRa, with its long-range and low-power characteristics and IoT-based platforms further strengthens the opportunity to build remote monitoring systems that are both scalable and energy efficient (Qodri, 2023).

This study develops and evaluates a multisensor WSN node that combines tremor, CO₂, and SO₂ monitoring. The system adopts LoRa for long-range communication and an IoT dashboard with automated alerts to enhance accessibility. Its performance is assessed through laboratory calibration and outdoor continuous operation tests, serving as an initial step toward a deployable early-warning platform for volcanic environments.

II. METHOD

2.1 System Design Overview

The system consists of two monitoring nodes and one server node. Each monitoring node integrates sensors for tremor (ADXL335), CO₂ (MG-811), and SO₂ (MQ-136). The server node receives, stores, and displays data through a web-based IoT dashboard. Figure 1 illustrates the overall architecture.

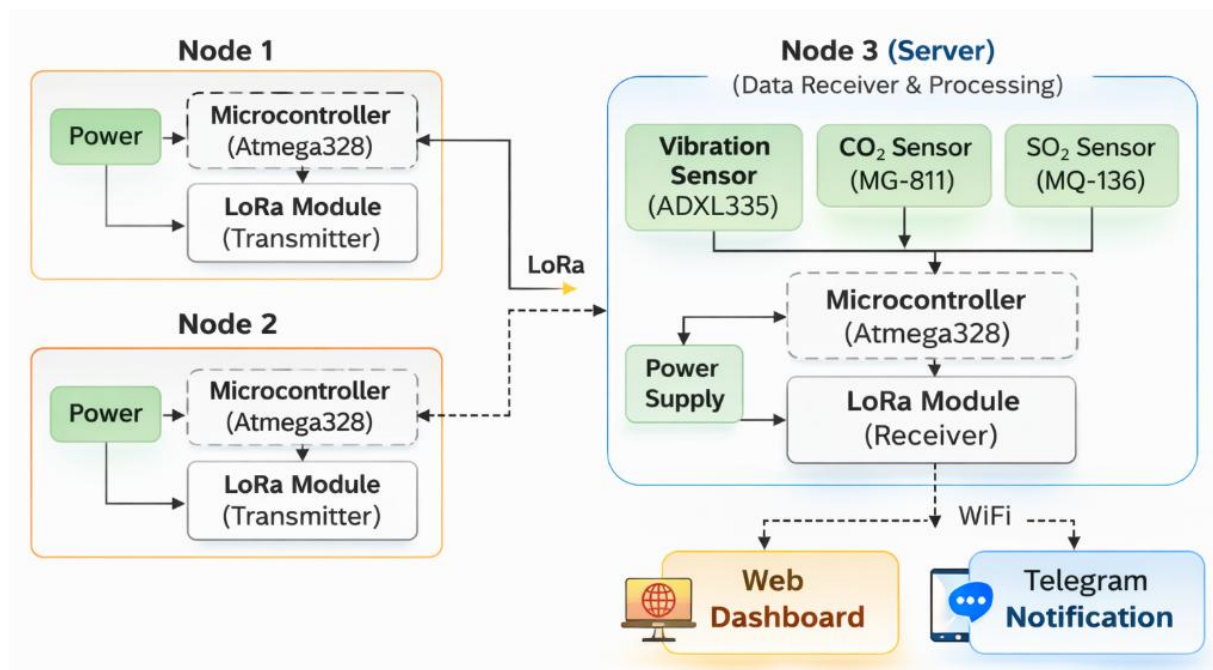


Figure 1 System architecture of the WSN based-integrated sensor

2.2 Hardware Components

2.2.1 Gas Sensors

The MG-811 CO₂ sensor operates on an electrochemical principle and produces a voltage proportional to CO₂ concentration. Its sensitivity characteristics are shown in Figure 2.

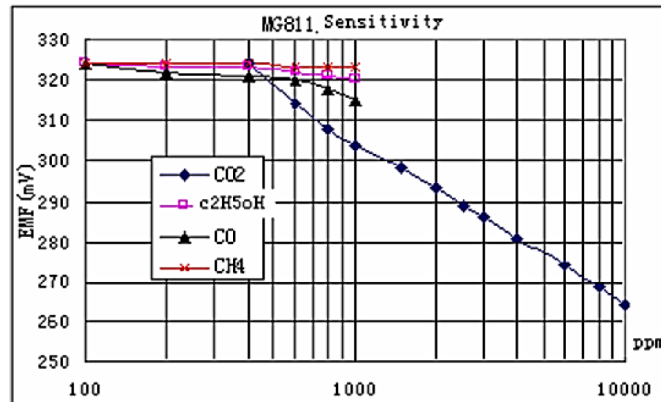


Figure 2 Sensitivity curve of the MG-811 CO₂ sensor

The MQ-136 SO₂ sensor uses a metal-oxide semiconductor that changes resistance when exposed to SO₂. Calibration is based on the R_s/R_o relationship (Figure 3).

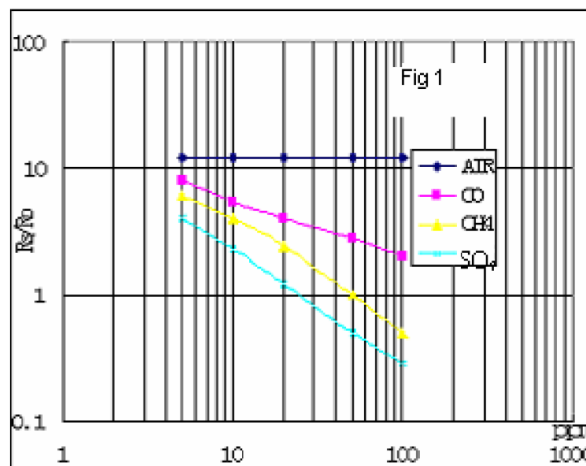


Figure 3 Characteristic response curve of the MQ-136 SO₂ sensor

2.2.2 Vibration Sensor (ADXL335)

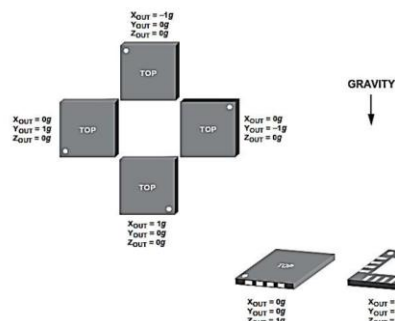


Figure 4 Operational axes of the ADXL335 accelerometer

Ground tremor is measured using the ADXL335 accelerometer. The sensor's working principle and 3-axis orientation reference shown in Figure 4 were used as the basis for interpreting acceleration changes and converting them to tremor magnitude.

2.2.3 Microcontroller

Each sensor node employs an Arduino ATmega328-based platform as the primary microcontroller for sensor signal acquisition and preprocessing. The microcontroller receives analog signals from the sensors, processes them, and prepares the data packets prior to wireless transmission.

2.3 Wireless Communication Architecture

2.3.1 LoRa Transmission

Low-power, long-range communication is implemented using LoRa modules as the primary backbone of the WSN. The topology and communication flow are included within the system block diagram in Figure 1.

2.3.2 IoT Integration

The system incorporates an Internet of Things (IoT) architecture that enables real-time data access, cloud-based storage, and automated alert delivery. The server node is equipped with an ESP8266 WiFi module that transmits the LoRa-received sensor data to a web server using standard TCP/IP communication. All incoming measurements (CO_2 , SO_2 , and ground vibration) are processed and visualized through an MQTT-based web dashboard, which displays the latest sensor values together with their associated status levels (normal, alert, or danger) based on predefined thresholds.

In addition to the web dashboard, the IoT system also provides an automated early-warning feature through Telegram. Whenever the processed data indicate a change in volcanic activity status, the server generates and sends a Telegram message using the Bot API. This mechanism allows stakeholders to receive immediate notifications on mobile devices without needing to monitor the dashboard continuously.

Through this IoT framework, the monitoring system forms a fully connected end-to-end architecture—ranging from sensor nodes, LoRa communication, WiFi transmission, cloud-based processing, and automated alert services—consistent with the implementation described in the original design.

2.4 Power System

To enable autonomous operation in remote volcanic regions, the system uses a 55 W solar panel connected to a Solar Charge Controller (SCC) and a 12 V lead-acid battery. The configuration and testing setup are shown in Figure 5.

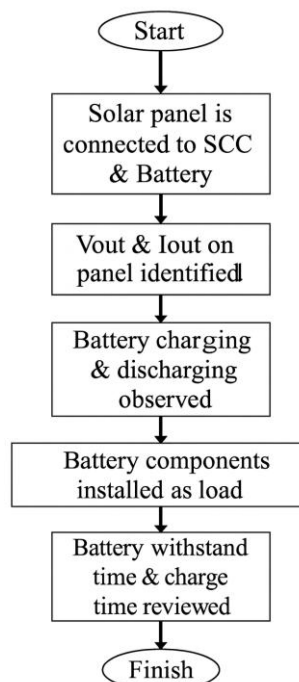


Figure 5 Solar power configuration used in the system

2.5 Sensor Testing and Calibration

2.5.1 Gas Sensor Calibration

CO₂ calibration was performed using controlled charcoal combustion, following the setup shown in Figure 6

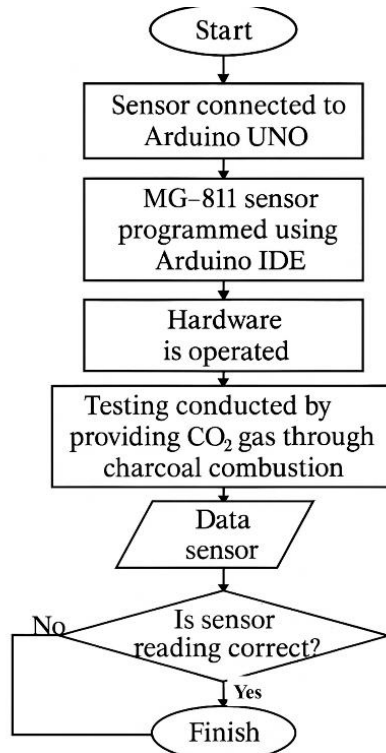


Figure 6 Calibration setup for the MG-811 CO₂ sensor

SO₂ calibration was performed using heated sulfur samples as depicted in Figure 7.

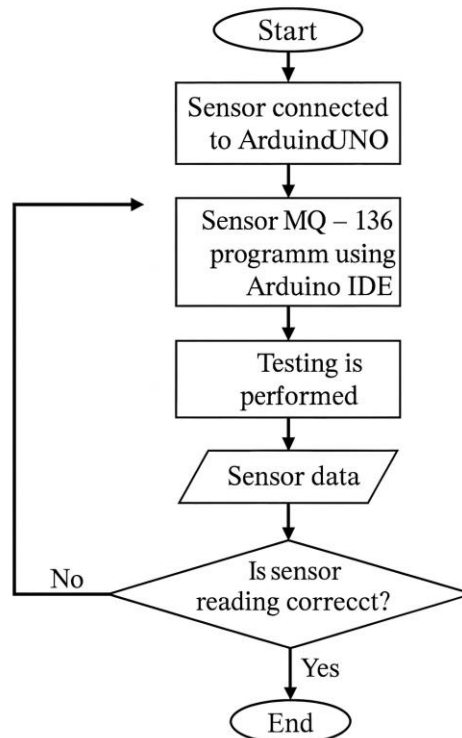


Figure 7 Calibration setup for the MQ-136 SO₂ sensor

2.5.2 Vibration Sensor Calibration

The ADXL335 was validated using drop tests of masses 1.0 kg and 1.5 kg from heights of 10, 20, and 30 cm. The calibration setup is illustrated in Figure 8.

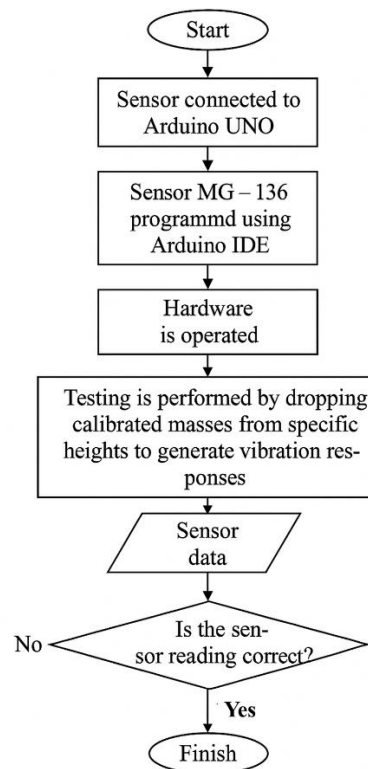


Figure 8 Calibration setup for the ADXL335 vibration sensor

2.6 Field Simulation Test

A three-day continuous monitoring test was conducted outdoors to evaluate the overall performance and stability of the system under real environmental conditions. During this period, all sensors operated continuously and produced time-series data for CO₂, SO₂, and ground vibration. The wireless communication link functioned reliably, with the LoRa modules successfully transmitting data from each monitoring node to the server node throughout the entire test.

The power system also performed stably, with the solar panel and battery configuration able to sustain system operation both during the day and at night. The prototype system remained functional over the full duration of the test, demonstrating its ability to perform basic monitoring tasks in an outdoor environment.

III. RESULT AND DISCUSSION

3.1 System Hardware Implementation

The complete hardware implementation of the WSN-based integrated sensor system is shown in Figure 9. The system integrates the MG-811 CO₂ sensor, MQ-136 SO₂ sensor, and ADXL335 vibration sensor with the Arduino-based processing unit and LoRa transceiver. The physical assembly demonstrated stable operation under outdoor environmental conditions, confirming that the system layout, wiring, and enclosure design provided sufficient robustness for field-like testing.

Power system evaluation using the solar panel and battery configuration Figure 5 showed that the 55 W panel was capable of maintaining the battery at operational levels throughout the day. The Solar Charge Controller effectively regulated charging and prevented over-discharge, demonstrating suitability for remote volcanic environments with limited power access.

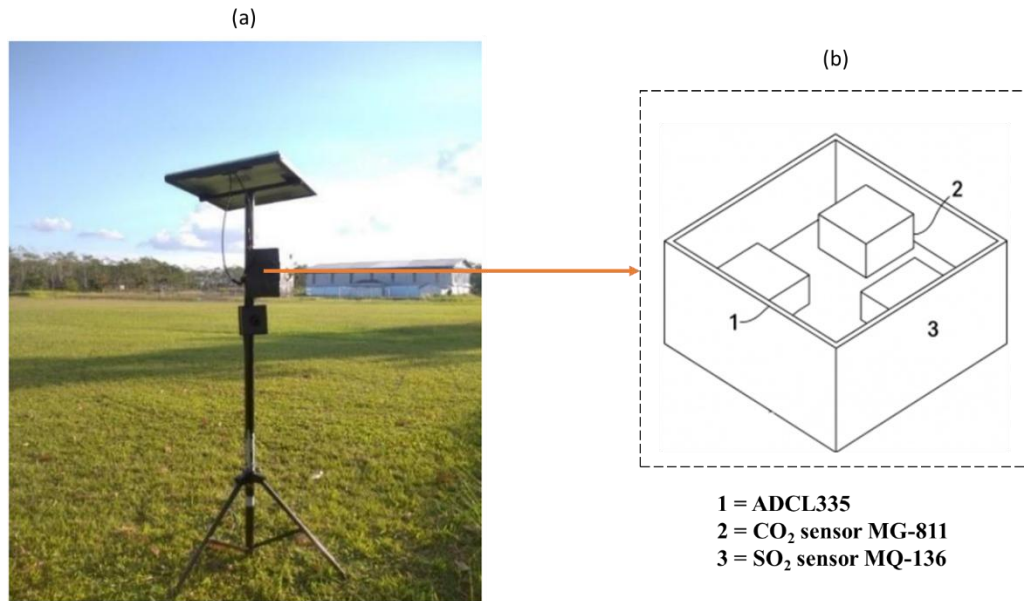


Figure 9 a) Hardware of the system b) integrated sensor

3.2 Gas Sensor Performance

3.2.1 CO₂ Sensor (MG-811)

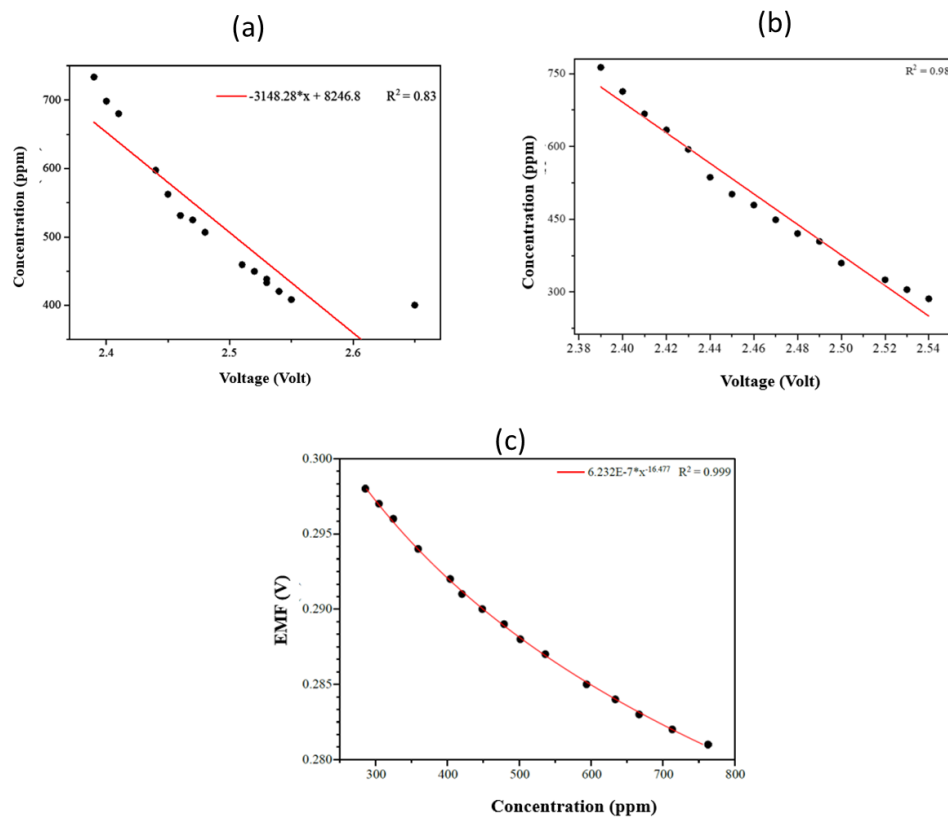


Figure 10 a) Calibration results of the MG-811 CO₂ sensor: Pre-calibration regression b) Calibration results of the MG-811 CO₂ sensor: Post-calibration regression c) Final sensitivity characteristic of the MG-811 sensor

The MG-811 sensor responded positively to increasing CO₂ concentrations produced from charcoal combustion. The voltage-to-ppm conversion curve used for calibration is shown in Figure 2.

Linear regression results from Figure 10(a), 10 (b) and 10 (c) demonstrate improved correlation after calibration, showing a sensitivity of MG-811 sensor is $-6,232 \times 10^{-7} X^{-16,477} V/ppm$, X is the CO₂ gas concentration.

This sensitivity aligns with the sensor's datasheet specifications and indicates that the MG-811 is capable of detecting CO₂ concentrations within the range required for volcanic degassing scenarios (400–10,000 ppm).

The system successfully classified CO₂ concentration ranges according to volcanic alert thresholds (normal, alert, danger) based on established PVMBG guidelines.

3.2.2 SO₂ Sensor (MQ-136)

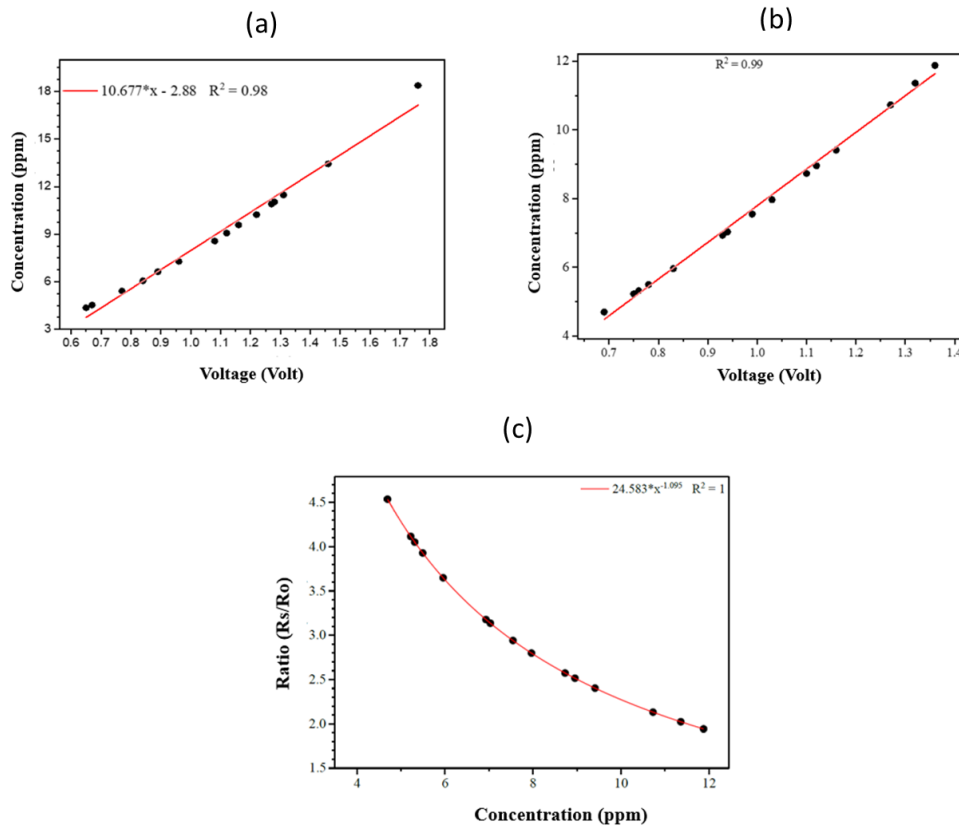


Figure 11 a) Calibration results of the MQ-136 SO₂ sensor: Pre-calibration regression b) Calibration results of the MQ-136 SO₂ sensor: Post-calibration regression c) Final sensitivity characteristic of the MQ-136 sensor.

The MQ-136 sensor demonstrated consistent response to SO₂ generated by heated sulfur, with R_s/R_o values mapped using logarithmic calibration curves shown in Figure 3.

The calibration and regression results in Figure 11 show a clear inverse relationship between gas concentration and R_s/R_o value, confirming the expected behavior of metal-oxide semiconductor sensors.

The final regression model demonstrated a sensitivity of approximately: $2,453X^{-1.095} (R_s/R_o)/ppm$. This performance confirms the MQ-136's suitability for detecting SO₂ levels relevant to volcanic emissions, particularly in the range of 20–40 ppm where alert-level degassing is typically observed.

3.3 Vibration (Tremor) Measurement Performance

The ADXL335 accelerometer was evaluated using drop tests with 1.0 kg and 1.5 kg masses at 10, 20, and 30 cm heights. The test setup is shown in Figure 12, and Figure 13 illustrate the comparison between ADXL335 output and a reference microtremor device.

Figure 12 shows the comparison between the ADXL335 accelerometer and the reference microtremor instrument during drop tests using a 1.0 kg mass from heights of 10 cm, 20 cm, and 30 cm. The responses along the x- and y-axes are presented in subfigures (a–f).

At a drop height of 10 cm, both instruments record low-amplitude vibration signals immediately after impact. The general waveform patterns are similar, and the peak responses occur at nearly the same

time. Although small differences in amplitude are observed, the overall signal trend remains consistent between the two devices.

When the drop height increases to 20 cm and 30 cm, the peak amplitudes increase accordingly. This indicates that the ADXL335 responds consistently to increasing excitation energy. The similarity in signal shape and timing suggests that the accelerometer can detect relative changes in vibration intensity reliably.

These results indicate that for a 1.0 kg mass, the ADXL335 performs consistently in detecting variations in vibration magnitude.

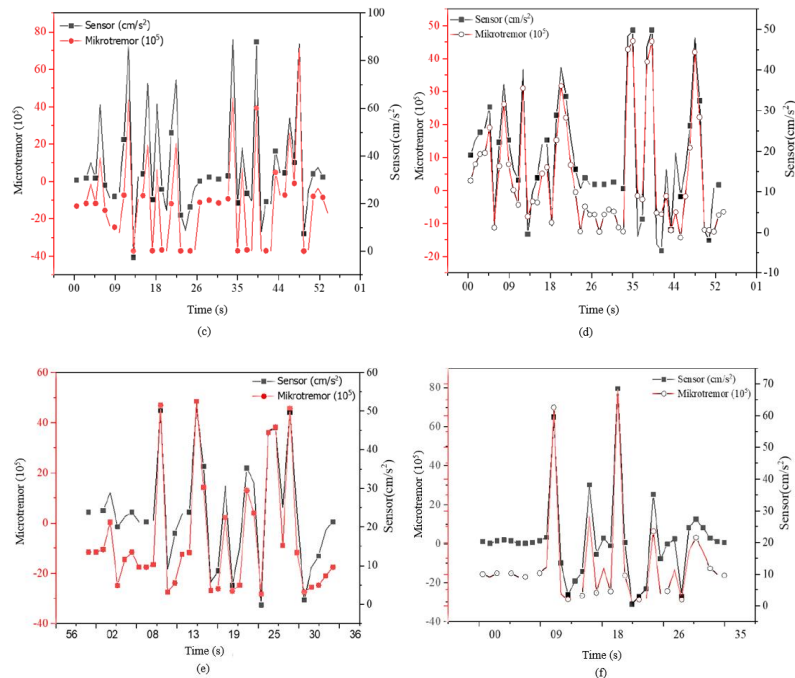


Figure 12 Comparison between ADXL335 output and reference microtremor instrument during vibration testing using a 1.0 kg mass: (a–b) drops from 10 cm (x and y axes), (c–d) drops from 20 cm (x and y axes), (e–f) drops from 30 cm (x and y axes).

Figure 13 presents the vibration responses using a 1.5 kg mass under the same drop height variations. Compared to the 1.0 kg test, higher amplitudes are observed due to the larger impact force produced by the heavier mass.

At all drop heights, both the ADXL335 and the reference instrument show similar waveform patterns. As the drop height increases, the peak amplitude also increases. This proportional response confirms that the sensor output follows the expected trend of increasing excitation energy.

Although minor amplitude differences exist between the two instruments, the overall pattern and signal behaviour remain comparable. This indicates that the ADXL335 is capable of detecting relative vibration changes under different loading conditions.

Overall, the results from Figures 12 and 13 indicate that the ADXL335 accelerometer provides stable and consistent responses under different impact intensities. The calibration results show a proportional relationship between acceleration and sensor output, demonstrating the sensor's ability to follow the expected vibration trend. Although quantitative statistical validation was not performed, the graphical comparison confirms that the calibrated sensor is adequate for detecting relative variations in low-amplitude tremor for early-warning monitoring applications.

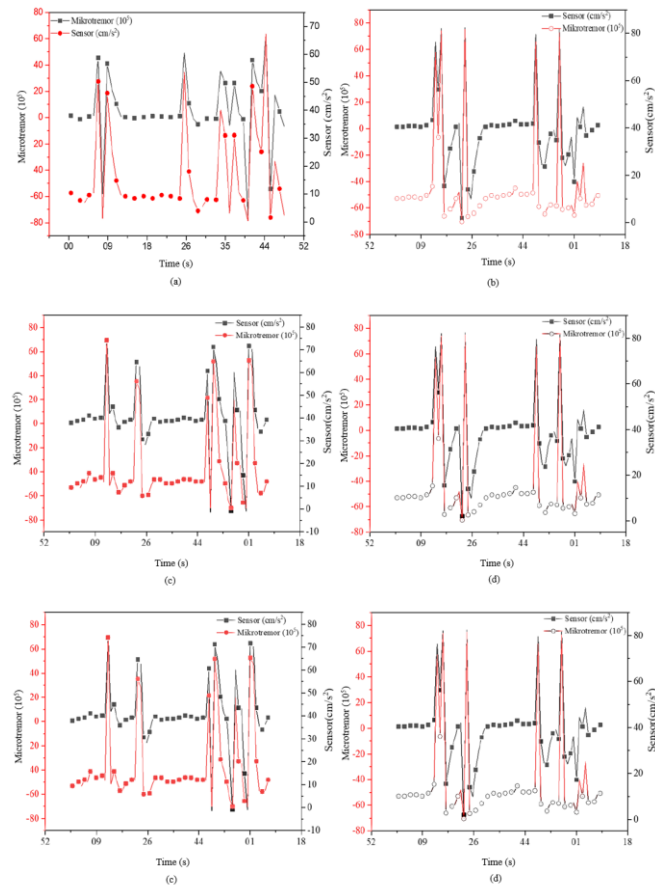


Figure 13 Comparison between ADXL335 output and reference microtremor instrument during vibration testing using a 1.5 kg mass: (a–b) drops from 10 cm, (c–d) drops from 20 cm, (e–f) drops from 30 cm

3.4 Field Simulation and System Stability

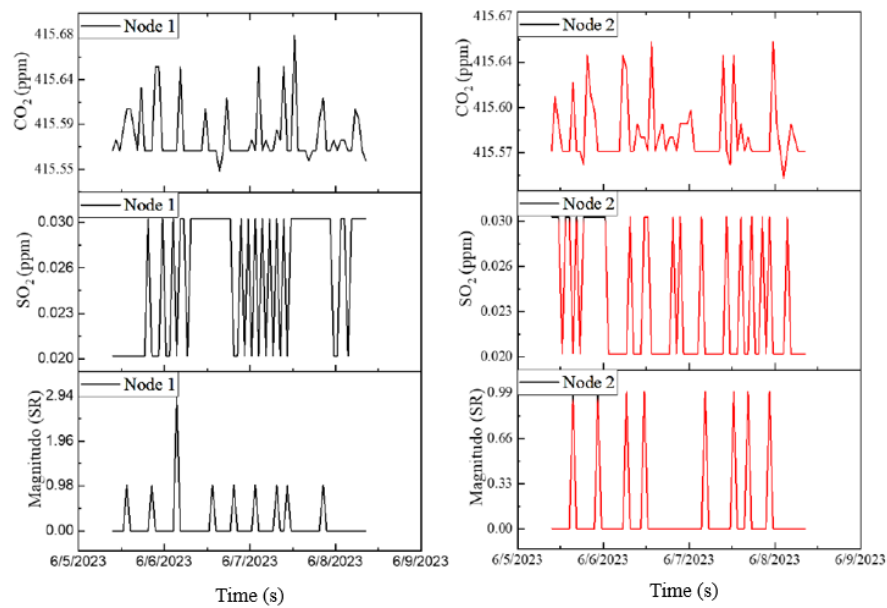


Figure 14 Three-day outdoor monitoring results

A three-day outdoor simulation test was conducted to assess basic system functionality under continuous operation. The recorded time-series data for CO₂, SO₂, and tremor are shown in Figure 14.

During the test, all sensors were able to record data continuously, and the LoRa communication link successfully transmitted data to the server node without interruption. The power system also remained stable, with the solar panel and battery maintaining adequate operating levels across the test period.

Although the test did not include measurements in an actual volcanic environment, the outdoor simulation provides preliminary evidence that the system can operate continuously and handle basic monitoring tasks under uncontrolled environmental conditions.

3.5 IoT Dashboard and Alert Evaluation

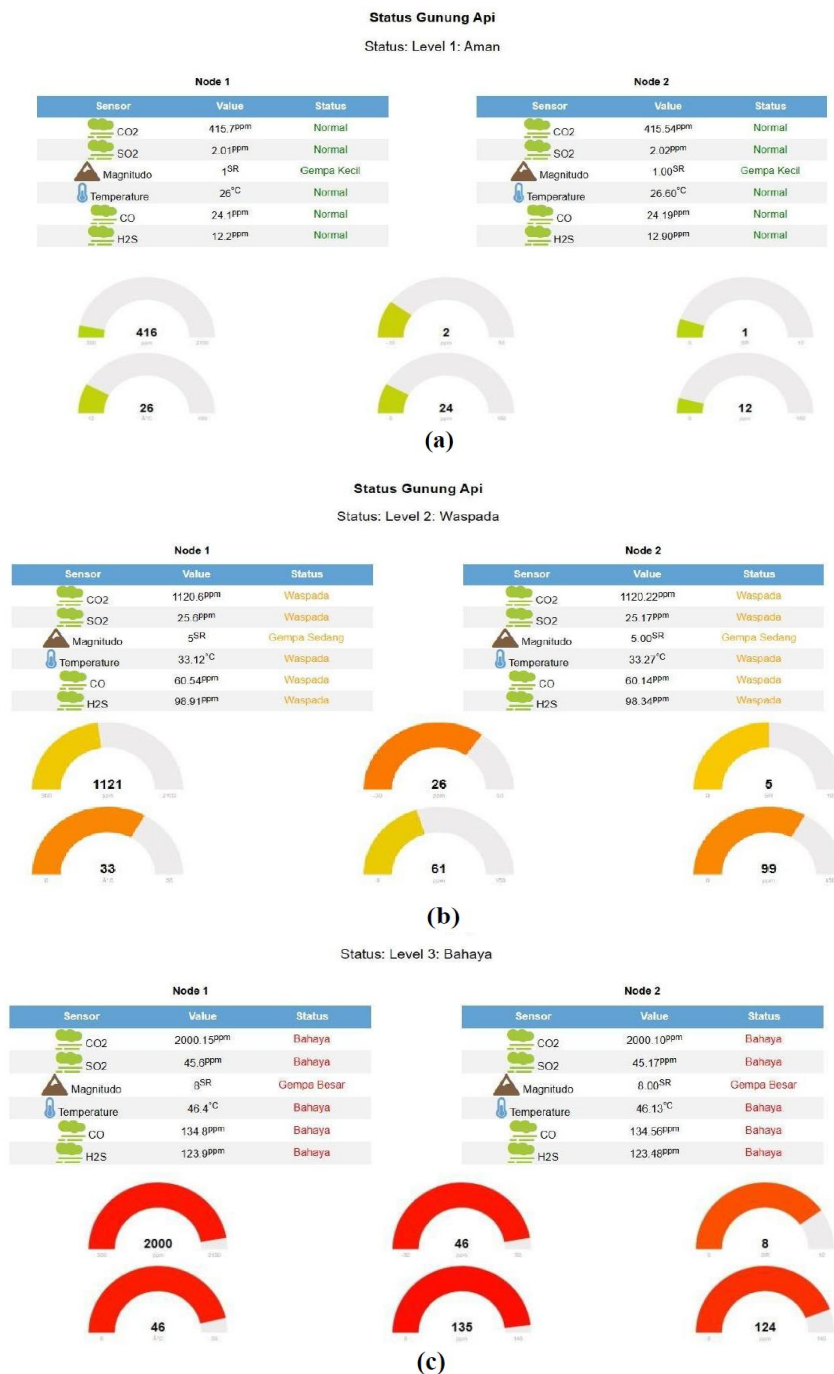


Figure 15 a) Web-based IoT dashboard displaying real-time CO₂, SO₂, and vibration values under Normal conditions b) Web-based IoT dashboard under Alert conditions c) Web-based IoT dashboard under Danger conditions

The IoT platform implemented in this system provides real-time visualization and automated alert delivery based on the data received by the server node. During the three-day outdoor simulation, the ESP8266 WiFi module successfully forwarded LoRa-received sensor data to the web server via TCP/IP, and the MQTT-based dashboard displayed the incoming CO₂, SO₂, and vibration measurements in real time.

The interface of the web dashboard, shown in Figure 15, presents time-series plots for each parameter along with the corresponding status levels (normal, alert, or danger). This visualization confirms that the IoT data pipeline from the sensor nodes through LoRa transmission to web-based monitoring operated correctly throughout the test period.

In addition to the dashboard, an automated early-warning mechanism was implemented using the Telegram Bot API. When the server node detected a change in status based on the predefined thresholds, the system automatically delivered notification messages to the designated Telegram channel. An example of this alert message is shown in Figure 16, demonstrating the successful integration of messaging functionality into the IoT workflow.

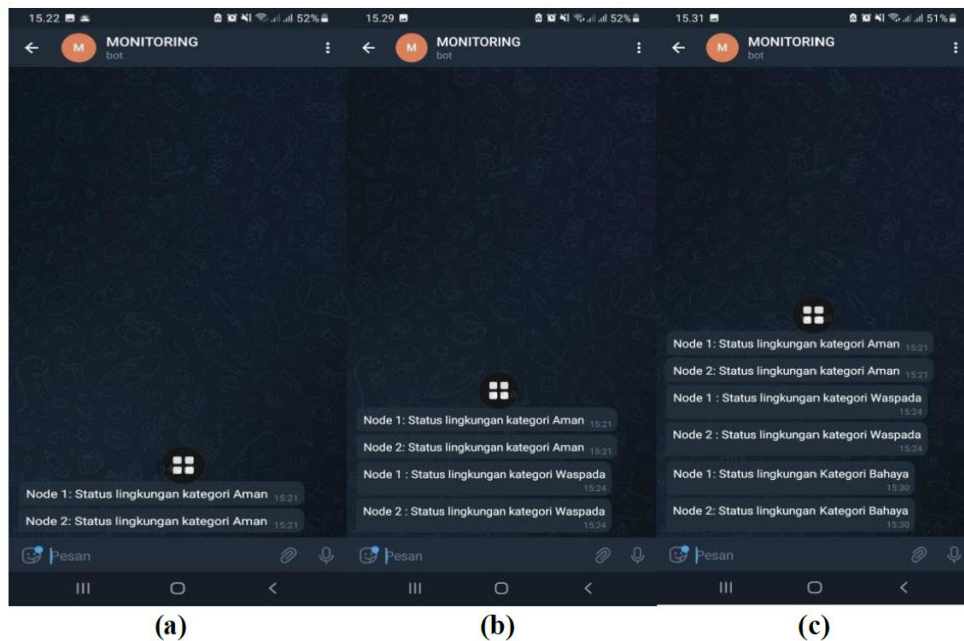


Figure 16 a) Telegram notification generated during Normal conditions b) Telegram notification generated when the system enters an alert condition c) Telegram notification sent during Danger conditions

These results indicate that the IoT layer of the system functioned reliably during the outdoor simulation, supporting remote monitoring and alert dissemination under environmental conditions consistent with the system's intended field usage. Although further evaluation is needed in an actual volcanic setting, the IoT implementation shows practical potential for supporting early-warning applications.

3.6 Discussion

The integration of tremor, CO₂, and SO₂ sensing within a single wireless node demonstrates the feasibility of combining multiple volcanic precursors into one monitoring platform. Each sensor exhibited stable behavior during laboratory and outdoor testing, and the LoRa-based communication reliably delivered data within the operational range of the prototype. These findings align with similar multisensor WSN implementations reported in previous studies, which indicate that combining gas and seismic indicators can improve the reliability of eruption forecasting systems.

The IoT layer, consisting of the MQTT-based web dashboard and Telegram alert system, also functioned effectively during testing. This integration confirms that low-power wireless communication combined with cloud-based processing can support real-time monitoring and early-warning functions in remote environments.

Despite these promising results, the system has not yet been validated in an actual volcanic environment. Gas sensors such as MG-811 and MQ-136 may exhibit different behaviors when exposed

to high-temperature volcanic gases, humidity fluctuations, or acidic aerosols. Similarly, LoRa performance may vary over long distances and in complex topographical conditions. Further field deployment is required to evaluate long-term durability, communication reliability, threshold accuracy, and overall system resilience under real volcanic conditions.

IV. CONCLUSION

This research presents the development of a multisensor wireless monitoring system designed to observe three early indicators of volcanic activity: ground vibration, CO₂ concentration, and SO₂ concentration. The system integrates the ADXL335 accelerometer, MG-811 CO₂ sensor, and MQ-136 SO₂ sensor with an Arduino-based microcontroller and LoRa communication modules. Laboratory testing showed that each sensor produced consistent output trends in accordance with their characteristic curves. The vibration sensor responded proportionally to impact variations, while the gas sensors demonstrated expected changes under controlled CO₂ and SO₂ exposure.

The outdoor simulation test further demonstrated that the sensor nodes, LoRa communication link, and solar-powered supply were able to operate continuously for three days under natural environmental conditions. The IoT layer of the system comprising an MQTT-based web dashboard and an automated Telegram alert mechanism also functioned reliably. The dashboard successfully visualized real-time sensor data and status classifications, while the Telegram bot delivered automatic notifications whenever threshold changes were detected. These results confirm that the proposed architecture is capable of supporting remote monitoring and automated alert dissemination for volcanic indicators.

However, the system has not yet been evaluated in an actual volcanic environment. Gas sensor performance may vary under high temperatures, acidic conditions, or high humidity commonly found near active vents. Likewise, LoRa communication may behave differently across long distances and complex terrain. Future work should therefore include field deployment in volcanic areas, extended durability testing, optimization of threshold values, and evaluation of long-range communication performance.

Overall, the prototype demonstrates the feasibility of integrating seismic and gas sensor measurements with low-power wireless communication and IoT-based monitoring into a single platform. With further refinement and field validation, the system has strong potential to be developed into an effective early-warning tool for volcanic monitoring applications.

ACKNOWLEDGEMENTS

The authors would like to express their gratitude to the Department of Science, Institut Teknologi Sumatera, for the support provided during the execution of this research. This work was funded through the Hibah Penelitian Jurusan Sains Institut Teknologi Sumatera Tahun Anggaran 2023 under contract number 8355/IT9.3.1/PT.01.03/2023. The authors also thank all laboratory staff and students who contributed to the system assembly, testing, and data collection processes.

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