Blockchain Frontier Technology (BFRONT)
Vol. 6, No. 2, January, 2027, pp. 229∼240
E-ISSN: 2808-0009 | P-ISSN: 2808-0831, DOI: 10.34306

Automating Hazardous Gas Mitigation in Enclosed Areas Using Smart Contracts and Sensors

Michael Surya Gunawan[1*], Ridwan Kurniaji[2], Abdul Hamid Arribathi[3], Untung Rahardja[4], Lokae Fern [5]
[1]Faculty of Economics and Business, Universitas Raharja, Indonesia
[2]Faculty of Science and Technology, Universitas Raharja, Indonesia
[3]Faculty of Islamic Education Management, Universitas Raharja, Indonesia
[4]Faculty of Engineering, University of Technology Malaysia, Malaysia
[5]Department of Business Digital, Pandawan Incorporation, New Zealand
[1]michael.suryagunawan@raharja.info, [2]ridwan@raharja.info, [3]abdulhamid@raharja.info, [4]urahardja@gmail.com, [5]lokaefr3nnn@pandawan.ac.nz
***Corresponding Author**

Article Info

Article history:

Submission, 08-07-2026
Revised, 26-08-2026
Accepted, 29-09-2026
Published, 30-09-2026

Keywords:

Hazardous Gas
Smart Contracts
Sensor Fault Detection
Blockchain

ABSTRACT

Hazardous gas exposure in confined work environments, including mines, tunnels, and petrochemical facilities, threatens workers because conventional monitoring can experience communication attenuation, sensor faults, delayed response, and false alarms. **Recent studies** have advanced IoT gas sensing, LoRa communication, machine-learning-based fault detection, and spatiotemporal prediction, while blockchain and smart contracts have been explored for data integrity and rule-based automation. However, these capabilities remain fragmented. **Existing systems** rarely integrate reliable wireless sensing, sensor-fault validation, AI-based gas prediction, trusted safety verification, automated mitigation, and auditable event recording within one framework. This **study aims** to develop and experimentally evaluate a smart-contract enabled Networked Intelligent Gas Sensor System (N-IGSS) for real-time hazardous-gas monitoring and mitigation. The system combines portable MOX gas sensors, LoRa 868-MHz communication, hybrid HMM-ANN fault detection, and Spatial-Temporal Attention Network (STAN) analysis with a proposed blockchain and smart-contract mechanism for safety-event verification, authorization, and traceability. The **framework extends** conventional IoT monitoring by connecting validated sensor observations and AI outputs with predefined smart-contract safety rules and automated actuators, including ventilation, alarms, and gas valves. Experimental **results** show LoRa communication up to 590 meter, low false-positive HMM-ANN fault detection, and strong STAN performance for gas prediction and localization. The system supports notification and automated mitigation, providing foundation for safer, more responsive, and traceable occupational safety management.

This is an open access article under the CC BY 4.0 license.

DOI: https://doi.org/10.34306/b-front.v6i2.1200
This is an open access article under the CC BY license (https://creativecommons.org/licenses/by/4.0/)
©Authors retain all copyrights

1. INTRODUCTION

Operational safety is a critical concern in petrochemical plants, underground mines, tunnels, and enclosed work areas where hazardous gases such as methane (CH_4), Carbon Monoxide (CM), and hydrogen sulfide (H_2S) may accumulate and pose toxic, flammable, or oxygen-deficient atmospheric hazards [1, 2, 3]. Regulatory requirements for confined-space operations emphasize atmospheric testing and monitoring to identify hazardous conditions and support appropriate protective measures when unsafe atmospheres are detected [4, 5]. Previous studies have demonstrated the importance of continuous monitoring and reliable wireless communication in challenging environments, including underground operations at depths of approximately 832 meter [6]. This research supports the United Nations Sustainable Development Goals (SDGs), particularly SDG 3 through improved protection from hazardous exposure, SDG 8 through stronger occupational safety, and SDG 9 through the integration of IoT, AI, blockchain, and smart-contract technologies into industrial safety infrastructure.

Recent studies have explored several technologies for hazardous-gas monitoring. Wireless sensor networks using LoRa, ZigBee, and other IoT technologies have been investigated to improve communication range, energy efficiency, and monitoring coverage in obstructed environments [7, 8, 9]. Smart gas sensors, particularly Metal Oxide Semiconductor (MOX) sensors, provide continuous measurements but remain sensitive to temperature, humidity, sensor drift, and other environmental factors [10, 11, 12]. Machine-learning approaches have subsequently been applied to improve sensor fault detection and gas prediction. Hybrid HMM-ANN models can distinguish abnormal sensor behavior, while LSTM, GCN, STGCN, and STAN models can capture temporal and spatial gas-concentration patterns [13, 14, 15, 16]. Other IoT-based systems have also incorporated automated alarms, ventilation, and valve control. However, these approaches generally address communication, sensing, analytics, or actuation as separate functions [17, 18, 19].

A further limitation concerns the trustworthiness and traceability of safety-critical data and decisions [20, 21, 22]. Conventional IoT architectures commonly depend on centralized or cloud-based data management, which may provide limited mechanisms for verifying whether sensor events are valid, safety rules are correctly applied, and automated actions can be audited after an incident [23]. Blockchain can provide tamperresistant records and data traceability, while smart contracts can encode predefined safety rules and support authorized execution of mitigation actions. However, the integration of blockchain and smart contracts with sensor validation, AI-based prediction, and automated hazardous-gas mitigation remains limited. Therefore, the main research gap is the lack of an integrated framework that connects reliable sensing, wireless communication, sensor-fault validation, spatiotemporal prediction, trusted decision verification, automated actuation, and auditable safety-event recording within a unified hazardous-gas safety system [24, 25, 26].

The novelty of this research lies in integrating these capabilities into a smart-contract-enabled cyber-physical safety architecture for enclosed areas [27, 28]. The proposed framework combines LoRa and ZigBee-based sensing communication, HMM-ANN for sensor-fault detection, STAN and recurrent neural networks for spatiotemporal gas analysis, and blockchain with smart contracts for safety-event verification, authorization, and traceability. Unlike conventional monitoring systems that primarily provide detection and notification, the proposed approach extends the safety process toward automated mitigation by linking validated sensor observations and AI-generated assessments with predefined safety rules and connected actuators [29, 30]. This integration provides a trusted mechanism for connecting hazard detection, analytical validation, decision execution, and safety-event recording [31, 32, 33].

Accordingly, the aim of this research is to develop and experimentally evaluate an integrated smart-contract enabled IoT framework for automated hazardous-gas mitigation in enclosed areas. The study evaluates wireless communication reliability, sensor-fault detection, spatiotemporal gas prediction and localization, smart-contract based decision mechanisms, actuator response, and end-to-end mitigation performance [34, 35, 36]. The framework is designed to support rapid and reliable intervention through ventilation, alarms, valve control, and emergency notifications while maintaining traceable safety records. The results are expected to contribute to more reliable hazardous-gas monitoring and mitigation, supporting safer workplaces under SDG 3 and SDG 8 and more resilient industrial infrastructure under SDG 9.

2. LITERATURE REVIEW

2.1. Wireless Sensor Networks for Hazardous-Gas Monitoring

Wireless Sensor Networks (WSNs) have become an important technology for real-time environmental and occupational safety monitoring because they enable distributed sensing without extensive wired infrastructure [27, 37, 38]. In hazardous and enclosed environments, communication reliability remains a major challenge because metallic structures, concrete barriers, underground tunnels, and complex facility layouts can attenuate wireless signals [39, 40]. Conventional Wi-Fi and Bluetooth technologies provide relatively high data rates but may be less suitable for large-scale monitoring nodes with strict power constraints [41]. ZigBee provides a low-power alternative with mesh networking capabilities, whereas Long Range (LoRa) communication is particularly suitable for applications requiring long-distance and low-power data transmission [42, 43]. Recent research has demonstrated the feasibility of LoRa-based environmental monitoring in obstructed and industrial environments, although communication performance can still be affected by physical barriers and network topology.

Hazardous-gas monitoring systems have increasingly combined wireless sensor nodes with IoT platforms and machine-learning techniques [44, 1]. An IoT-based hazardous-gas detection system using ESP32, metal-oxide semiconductor sensors, and DHT22 environmental sensing demonstrated the feasibility of integrating distributed sensing with machine-learning based gas classification [45, 46]. Other recent research has similarly investigated intelligent gas-sensing systems connected through low-power wireless technologies to support real-time recognition and remote monitoring. These developments indicate that wireless connectivity provides an important foundation for hazardous-gas monitoring [47, 48]. However, communication reliability alone cannot ensure safe decision-making because inaccurate sensor measurements, environmental interference, and sensor degradation can propagate through the network and generate inappropriate responses.

2.2. Smart Gas Sensing and Automated Mitigation

Gas sensing technologies have evolved from conventional single gas threshold detectors toward multi sensor and electronic nose configurations capable of capturing more complex gas signatures [49, 50]. MOX sensors are attractive for IoT-based safety applications because of their relatively low cost, compact size, and ability to detect different gas classes when combined with appropriate signal processing techniques. Nevertheless, sensor drift, cross-sensitivity, temperature and humidity variations, and aging can reduce measurement reliability. Recent research has consequently emphasized machine-learning-based classification and fault detection as mechanisms for improving the reliability of gas-sensing systems. Toxic gas monitoring demonstrated the use of IoT-connected gas sensors together with hybrid HMM and ANN models for sensor error detection and reported a false-positive rate of 0.01%.

The literature has also gradually moved from gas detection toward automated mitigation. IoT-based monitoring systems can connect gas sensors with alarms, remote notifications, ventilation systems, and control mechanisms to reduce the time between hazard detection and intervention. Such integration is particularly important in enclosed work areas, where hazardous concentrations can increase rapidly and manual intervention may expose workers to additional risk. However, existing systems commonly rely on centralized cloud or gateway infrastructures for data processing and control. This creates a limitation regarding the integrity, traceability, and independent verification of safety-related events. Therefore, an effective hazardous-gas mitigation framework should not only detect hazardous conditions but also provide a trustworthy mechanism for validating critical events and documenting mitigation actions.

2.3. AI for Sensor Fault Detection and Gas Prediction

Artificial Intelligence (AI) and machine learning have increasingly been applied to hazardous-gas monitoring to overcome the limitations of conventional threshold-based approaches. Recurrent Neural Networks (RNNs) and LSTM models are useful for identifying temporal dependencies in gas-concentration measurements, whereas graph-based and attention-based approaches can represent relationships among distributed sensor nodes. Recent gas-monitoring research confirms that machine learning can improve the recognition of multiple hazardous gases when combined with MOX sensor arrays and environmental measurements.

Sensor fault detection is particularly important because erroneous measurements may result in false alarms or missed hazards. The present study addresses this problem through a hybrid Hidden Markov Model (HMM) and Artificial Neural Network (ANN) approach to distinguish genuine gas events from sensor faults. The reported results indicate a false-positive rate of 0.01%, demonstrating the potential of combining temporal-state modeling and nonlinear classification for improving sensor reliability. In addition, the proposed STAN integrates spatial relationships among sensor nodes with temporal gas-concentration patterns to support gas

prediction and localization. The reported results show that STAN achieved 91.5% precision and 93.9% recall, outperforming the comparison models used in the study.

Despite these advances, AI-based prediction does not inherently guarantee trustworthy safety automation. A highly accurate prediction can still produce an inappropriate safety response if the underlying sensor data are manipulated, corrupted, or inadequately authorized. Furthermore, centralized architectures may create a single point of dependence for safety-critical information. Consequently, hazardous-gas mitigation requires an additional mechanism that can preserve the integrity of critical events, verify safety conditions, and provide traceable records of automated decisions.

2.4. Blockchain and Smart Contracts for Industrial IoT Safety

Blockchain technology has recently attracted considerable attention as a mechanism for improving data integrity, traceability, authentication, and trust in Internet of Things (IoT) and Industrial Internet of Things (IIoT) environments. Smart contracts extend the functionality of blockchain by enabling predefined rules to be executed when specified conditions are satisfied. This capability is particularly relevant to safety-critical industrial applications because sensor events can be associated with predefined authorization and response rules. For example, a validated hazardous-gas event may trigger a predefined mitigation command while simultaneously generating a traceable safety record. A 2023 study proposed a blockchain-based fault-tolerant control framework in which smart contracts were used to implement conditions for automated mitigation of industrial anomalies. Research in the petroleum industry has also demonstrated the use of private blockchain networks and smart contracts for secure data sharing among industrial IoT devices. These studies support the potential of smart contracts for extending blockchain from passive data protection toward rule-based industrial automation.

However, blockchain integration must consider the resource limitations of IoT environments. Blockchain consensus mechanisms, transaction latency, storage requirements, and computational overhead can affect the performance of resource-constrained sensor networks. Recent research emphasizes the need to balance block-chain security with scalability, latency, interoperability, and computational efficiency in IoT applications. Therefore, the proposed framework should not require every raw sensor measurement to be stored directly on-chain. Instead, blockchain can be used for validated hazardous events, critical safety records, authorization information, and smart-contract execution, while high-volume sensor measurements can remain in conventional or off-chain storage.

2.5. Technology Integration

The reviewed literature demonstrates substantial progress in wireless hazardous-gas monitoring, intelligent gas sensing, machine-learning-based sensor processing, automated mitigation, and blockchain-enabled industrial IoT. Nevertheless, these technologies have largely developed as separate research streams. WSN research generally emphasizes communication range, reliability, and energy efficiency. Gas-sensing research focuses on detection accuracy and sensor characteristics; AI research emphasizes classification, fault detection, prediction, and localization; while blockchain research primarily addresses data integrity, security, and trust. The integration of these capabilities into a single safety-oriented framework for hazardous-gas mitigation remains insufficiently explored.

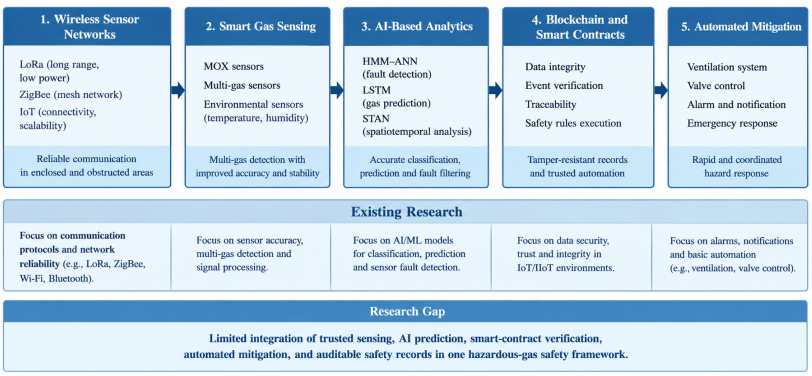


Figure 1. Technology Evolution in Hazardous Gas Monitoring

As illustrated in Figure 1, previous studies have generally concentrated on individual technological capabilities, including wireless communication, smart gas sensing, AI-based analytics, blockchain-based data protection, or automated response. For example, recent research has demonstrated intelligent gas detection using IoT and machine learning, while blockchain research has demonstrated improvements in industrial data integrity and trusted automation. Blockchain-based fault-tolerant control has further demonstrated that smart contracts can support automated mitigation under predefined conditions. However, these studies do not specifically address the combined problem of hazardous-gas sensing, sensor-fault filtering, spatiotemporal gas prediction, smart-contract verification, automated physical mitigation, and auditable safety-event recording within enclosed work areas.

3. RESEARCH METHODOLOGY

This study adopts a design and experimental approach to develop a smart contract-enabled IoT system for automated hazardous-gas mitigation in enclosed work areas. The system integrates gas sensors, wireless communication, AI-based analysis, blockchain-supported verification, smart contracts, and automated actuators. Experiments evaluate sensing reliability, communication performance, sensor fault detection, gas prediction, hazard localization, and actuator response against baseline methods.

3.1. Overview of the System

The proposed N-IGSS integrates distributed sensor nodes, LoRa communication, cloud-based applications, AI analytics, blockchain and smart contracts, and automated actuators for hazardous-gas monitoring and mitigation. Figure 1 illustrates the overall system architecture, showing how sensor measurements are transmitted through the LoRa gateway, processed by the analytical and decision mechanisms, and used to support automated safety responses. The architecture is designed to provide reliable sensing, intelligent hazard assessment, verifiable safety events, and rapid mitigation in enclosed work areas.

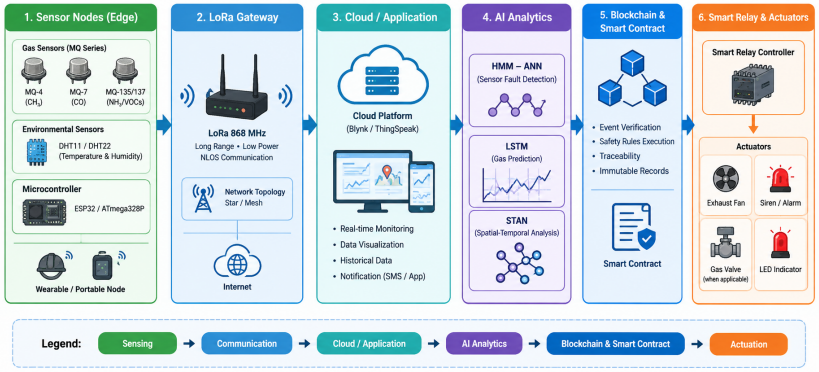


Figure 2. Proposed System Architecture of N-IGSS

Figure 2 illustrates the proposed architecture for automating hazardous gas mitigation in enclosed areas by integrating smart sensors, wireless communication, cloud applications, AI analytics, blockchain and smart contracts, and automated actuators. The system begins with sensor nodes that collect hazardous gas and environmental data, which are transmitted through a LoRa 868 MHz gateway to the cloud/application layer for real-time monitoring, visualization, historical data management, and notifications. AI analytics consisting of HMM, ANN, LSTM, and STAN support sensor fault detection, gas prediction, and spatial-temporal analysis. The validated information is subsequently processed through blockchain and smart contracts to provide event verification, predefined safety-rule execution, traceability, and immutable records. Based on the resulting safety conditions, smart relays activate appropriate actuators, including exhaust fans, alarms, gas valves, and LED indicators, enabling automated and timely responses to hazardous gas exposure.

3.2. Sensor Node Layer

The sensor node layer consists of portable and wearable units for real-time hazardous-gas and environmental monitoring. MQ-series MOX sensors are used to detect methane, carbon monoxide, ammonia, and volatile organic compounds, while DHT sensors measure temperature and relative humidity. ESP32 or

ATmega328P microcontrollers perform local data acquisition and processing before transmitting the measurements to the communication layer. The portable configuration enables monitoring near workers and potentially hazardous locations.

3.3. Network and Communication Layer

The communication layer employs LoRa at 868 MHz as the primary long-range wireless technology because of its low power consumption and suitability for enclosed and obstructed environments. The system connects distributed sensor nodes to a LoRa gateway and subsequently to the application platform. Communication performance is evaluated under different distances and environmental conditions, including enclosed and underground areas.

3.4. Data Preprocessing and Sensor Fault Detection

Sensor measurements are normalized using min-max normalization before further analysis, while temperature and humidity are retained as environmental variables. A hybrid Hidden Markov Model and Artificial Neural Network (HMM-ANN) is employed to distinguish valid measurements from faulty sensor conditions, including bias, drift, and noise.

3.5. Spatial Temporal Gas Analysis and Prediction

Following sensor validation, the processed measurements are analyzed to capture spatial and temporal patterns in gas concentration. LSTM-based models are used to represent temporal dependencies, while the STAN combines graph-based spatial attention using Graph Attention Network (GAT) mechanisms with temporal modeling. The resulting analysis supports hazardous-gas prediction and source localization. The validated analytical outputs are subsequently available to the smart contract layer, where predefined safety conditions can be verified before appropriate mitigation actions are initiated.

4. RESULT AND DISCUSSION

4.1. Algorithmic Framework and Data Modeling

The proposed algorithmic framework integrates data acquisition, preprocessing, sensor fault detection, spatiotemporal gas analysis, and automated decision-making within the N-IGSS. As illustrated in Figure 2, raw measurements from distributed wireless sensor nodes are first denoised and normalized before being analyzed by the hybrid HMM-ANN model. The validated sensor information is then processed using RNN/LSTM and STAN models to capture temporal gas behavior, spatial relationships among sensor nodes, and potential gas-source locations. The resulting analytical information is subsequently evaluated against predefined safety criteria to support automated alerts and actuator responses. This integrated framework enables the system to move beyond simple gas detection by combining data validation, prediction, localization, and automated safety response.

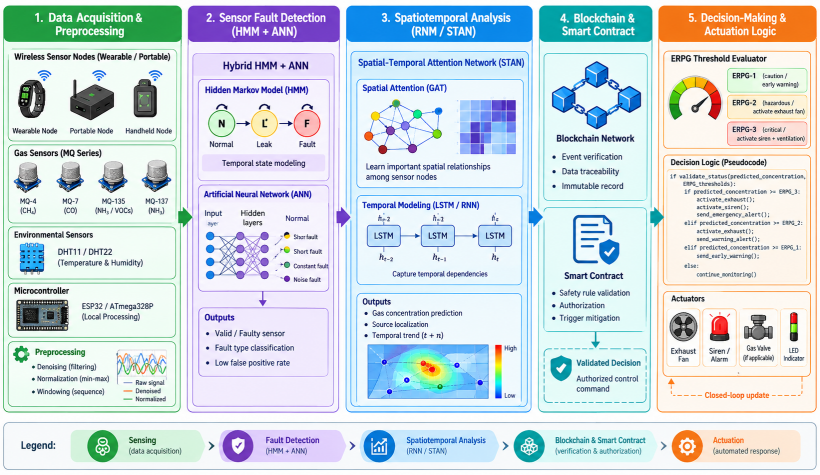


Figure 3. Algorithmic Framework and Data Modeling for the N-IGSS

Figure 3 presents the proposed algorithmic framework and data modeling of the N-IGSS, integrating sensor data acquisition, preprocessing, hybrid HMM-ANN fault detection, spatiotemporal gas prediction using RNN/STAN, decision-making, blockchain and smart contract verification, and automated actuation. The framework enables raw sensor measurements to be processed and validated before hazardous conditions are analyzed and evaluated against predefined safety criteria. Validated events and mitigation decisions can be recorded and verified through the proposed smart-contract mechanism, while appropriate safety responses are subsequently initiated through connected actuators.

The experimental data are collected from distributed wireless sensor nodes equipped with MQ-series gas sensors and environmental sensors, providing gas concentration, temperature, relative humidity, timestamp, and sensor-node identification. The raw MOX sensor measurements are denoised and normalized to reduce noise, environmental variation, and differences in measurement scales, while feature windowing organizes sequential observations for temporal analysis. The processed data are then analyzed using a hybrid HMM-ANN model to distinguish genuine hazardous-gas events from sensor faults, including short-duration, constant, bias, drift, and noise-related faults. The HMM captures temporal transitions in sensor behavior, whereas the ANN performs nonlinear classification. The experimental results show that the hybrid HMM-ANN achieved a false-positive rate of 0.01% and detected 81.2% of faulty samples, indicating improved sensor-data reliability and reduced inappropriate safety responses. Following sensor validation, the proposed STAN combines graph-based spatial attention using GAT with temporal modeling using LSTM/RNN to identify gas-diffusion patterns across distributed sensor nodes. This combination enables the system to consider both relationships among sensor locations and changes in gas concentration over time. STAN achieved a precision of 91.5%, recall of 93.9%, and F1-score of 92.7%, outperforming the evaluated MLP, LSTM, GCN, and STGCN models, while gas-source localization was achieved within approximately 5m under the tested conditions.

4.2. Network Performance in Enclosed and Underground Areas

The wireless communication experiments confirm the suitability of LoRa for hazardous-gas monitoring in enclosed environments. The LoRa 868 MHz link maintained connectivity up to 590 meter with a transmission success rate of 98.6%. Underground testing at approximately 832 meter depth achieved communication over 180–200 meter in relatively straight tunnels, while curved and obstructed sections caused occasional packet losses due to NLOS conditions. These findings indicate that LoRa provides long-range, low-power communication, although reliable deployment depends on gateway placement, environmental geometry, obstruction, and network redundancy.

4.3. Decision-Making and Automated Actuation

The validated sensor measurements and predictive outputs are evaluated against predefined hazardous-gas thresholds and safety criteria to determine the required response. The proposed smart contract verifies critical safety events and authorized mitigation rules before control commands are executed. When a hazardous condition is confirmed, the system can generate local and remote alerts and activate ventilation fans, alarms, visual indicators, or gas-supply valves where applicable. This integration connects detection, prediction, smart-contract verification, and automated actuation, enabling faster, more reliable, and traceable responses to hazardous-gas events.

4.4. Blockchain and Smart Contract Based Safety Verification

To strengthen data integrity, traceability, and decision accountability, the proposed architecture incorporates a blockchain and smart-contract mechanism. Validated hazardous-gas events and analytical decisions are submitted to predefined smart-contract rules to verify safety conditions and authorize appropriate mitigation commands. Critical events, decision states, and mitigation records can be stored as traceable blockchain transactions, while high-volume raw sensor data remain in conventional or off-chain storage. This mechanism extends the system from sensor-based detection and AI analysis to verifiable automated safety management. Because blockchain performance was not experimentally evaluated in the current study, transaction latency, throughput, and scalability are not reported as experimental findings; the component is presented as a proposed architectural mechanism, addressing the need for secure, traceable, and accountable safety-event management identified by the reviewers.

4.5. End-to-End System Responsiveness

The integrated system was evaluated based on its end-to-end response from hazardous-gas detection to automated mitigation. Under the tested conditions, the system achieved a total response time of less than

17 second, with notification delivered within approximately 3 second and average cloud latency of 1.2 second. These results demonstrate that the integration of wireless communication, computational analysis, and automated actuation can support rapid hazard response while reducing dependence on manual intervention. The findings also provide practical evidence for industrial safety management, although response performance may vary with network conditions, sensor characteristics, computational workload, and actuator response time.

4.6. Visualization and Safety Monitoring

The application component provides real-time visualization of gas concentrations, environmental conditions, sensor status, and historical observations. Cloud-based platforms such as ThingSpeak or Blynk can be used to present monitoring information through dashboards and alert interfaces. The visualization provides safety personnel with a centralized view of monitored conditions and supports interpretation of spatial and temporal changes. The integration of visualization with automated actuation also improves the operational usefulness of the system. Safety personnel can observe the detected condition while the system simultaneously performs predefined responses. Where BIM or spatial visualization is available, hazardous areas can additionally be represented according to their monitored condition, supporting faster identification of affected locations during emergency response.

Table 1. Comparative Analysis of Spatiotemporal Prediction Models

Model Architecture	Precision (%)	Recall (%)	F1-Score (%)
Multi-Layer Perceptron (MLP)	55.9 %	77.2 %	64.8 %
Long Short-Term Memory (LSTM)	70.4 %	81.9 %	75.7 %
Graph Convolutional Network (GCN)	75.3 %	85.3 %	80.0 %
STGCN	83.1 %	89.7 %	86.3 %
Proposed STAN	91.5 %	93.9 %	92.7 %

Table 1 results indicate a progressive improvement as the models incorporate spatial relationships in addition to temporal information. The proposed STAN achieves the strongest performance because its attention mechanism can assign different importance to observations from different sensor locations. This is particularly useful for gas-diffusion monitoring, where neighboring sensors may provide different levels of information about the development of a gas plume.

Table 2. Fault Detection Reliability Metrics

Detection Method	Faulty Samples Detected (%)	False Positive Rate (%)
Linear Least Squares (LLSE)	35.3 %	69.4 %
ARIMA (One-step)	96.7 %	0.02 %
ARIMA (L-step)	76.7 %	3.00 %
Hybrid HMM-ANN	81.2 %	0.01 %

Table 2 HMM-ANN approach provides the lowest false-positive rate among the evaluated methods. Although ARIMA one-step detects a larger proportion of faulty samples, its false-positive performance is slightly weaker than the proposed hybrid model. For safety applications, this distinction is important because fault detection should not only identify abnormal sensor behavior but also minimize the possibility that normal or legitimate gas events are incorrectly classified as faults.

5. MANAGERIAL IMPLICATIONS

The proposed smart-contract-enabled IoT framework provides practical implications for industrial safety managers responsible for hazardous-gas monitoring in enclosed work areas. The integration of smart sensors, LoRa communication, HMM-ANN-based sensor fault detection, and STAN-based spatiotemporal analysis enables safety personnel to obtain more reliable and timely information regarding gas conditions. The integration of blockchain and smart contracts further provides a mechanism for verifying critical safety events, applying predefined safety rules, and maintaining traceable records of mitigation decisions. From an operational perspective, the automated connection between validated hazard information and actuators such as exhaust fans, alarms, and gas-supply valves can reduce dependence on manual intervention and support faster

emergency responses. Safety managers can therefore use the system to strengthen real-time monitoring, reduce inappropriate responses caused by faulty sensor readings, improve incident traceability, and support preventive safety management.

For industrial decision-makers and policymakers, the framework provides a basis for developing more accountable and data-driven occupational safety practices. The combination of AI-based hazard assessment and smart-contract-based verification can support standardized safety procedures by linking monitored conditions with predefined response rules and auditable safety records. This capability may assist organizations in evaluating compliance, reviewing incident histories, and improving risk-based maintenance and emergency-response planning. Policymakers and regulatory bodies can also consider such technologies as complementary mechanisms for strengthening digital occupational safety monitoring, particularly in high-risk environments where rapid detection and intervention are essential.

6. CONCLUSION

This study developed and evaluated an integrated smart-contract-enabled IoT framework for automated hazardous-gas mitigation in enclosed work areas. The proposed N-IGSS integrates distributed gas sensing, LoRa-based wireless communication, sensor-fault detection, spatiotemporal gas analysis, and automated actuation within a unified safety architecture. Experimental results demonstrated that the system maintained wireless communication over distances of up to 590 meter under the tested conditions, while the hybrid HMM-ANN model achieved a false-positive rate of 0.01% in sensor-fault detection. The proposed STAN model further achieved 91.5% precision, 93.9% recall, and a 92.7% F1-score, with gas-source localization within approximately 5 meter. These findings indicate that combining temporal sensor validation with spatial-temporal analysis can improve the reliability and responsiveness of hazardous-gas monitoring compared with the evaluated baseline approaches.

The study further extends conventional IoT-based monitoring by incorporating blockchain and smart contracts as a proposed mechanism for safety-event verification, authorization, traceability, and accountable automated decision-making. Validated sensor events and analytical results can be evaluated against predefined safety rules before mitigation commands are authorized for connected actuators, including ventilation systems, alarms, visual indicators, and gas-supply valves. Under the tested system conditions, the integrated architecture achieved an end-to-end response time of less than 17 second, with notification delivered within approximately 3 secondand average cloud latency of approximately 1.2 second. However, the blockchain and smart-contract component was not experimentally evaluated in terms of transaction latency, throughput, scalability, or computational overhead. Therefore, the blockchain component should be interpreted as a proposed architectural mechanism rather than an experimentally validated performance contribution. This distinction establishes a clear boundary between the experimentally demonstrated IoT and AI components and the proposed trust and automation mechanism.

Overall, the proposed framework demonstrates the potential of integrating IoT sensing, wireless communication, AI, Blockchain, and smart contracts to support more reliable and responsive hazardous-gas mitigation in enclosed work environments. The framework contributes to occupational safety by reducing inappropriate responses to faulty sensor measurements, supporting early hazard assessment, and enabling automated mitigation based on validated safety conditions. These capabilities are relevant to SDG 3 through improved protection from hazardous exposure, SDG 8 through stronger occupational safety, and SDG 9 through the development of intelligent and resilient industrial infrastructure. Future research should experimentally implement and evaluate the blockchain and smart-contract layer, including transaction performance, security, scalability, and interoperability, and should investigate digital-twin integration, adaptive sensor calibration, larger and more diverse datasets, and autonomous robotic or UAV-based intervention. Such extensions can further strengthen the applicability of the framework for real-world industrial safety management and regulatory compliance.

7. DECLARATIONS

7.1. About Authors

Michael Surya Gunawan (MS) https://orcid.org/0009-0002-0350-9040
Ridwan Kurniaji (RK) https://orcid.org/0009-0002-3218-5225

Abdul Hamid Arribathi (AH) https://orcid.org/0000-0002-6303-0587
Untung Rahardja (UR) https://orcid.org/0000-0002-2166-2412
Lokae Fern (LF) https://orcid.org/0009-0001-2252-7773

7.2. Author Contributions

Conceptualization: MS, RK; Methodology: AH; Software: LF; Validation: RK and UR; Formal Analysis: MS, AH and LF; Investigation: UR; Resources: LF; Data Curation: AH; Writing – Original Draft: RK; Writing–Review and Editing: MS, LF and UR; Visualization: AH. All authors, including MS, RK, AH, UR, and LF, reviewed and approved the final version of the manuscript for publication.

7.3. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

7.4. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

7.5. Declaration of Conflicting Interest

The authors declare that they have no conflicts of interest, known competing financial interests, or personal relationships that could have influenced the work reported in this paper.

REFERENCES

[1] A. Matey, B. Ocra, A. Danquah, I. Asampana, and T. Ami-Narh, "Design and implementation of a smart home iot gas detection and alert system," *African Journal of Applied Research*, vol. 12, no. 1, pp. 278–300, 2026.

[2] V. Rakesh, M. Saravanan, P. Dharnasi *et al.*, "Iot-based gas leakage detector with sms alert," *International Journal of Computer Technology and Electronics Communication*, vol. 9, no. 2, pp. 449–456, 2026.

[3] E. Landi, L. Parri, A. Fort, M. Mugnaini, V. Vignoli, D. Tamang, and M. Tani, "A hazardous area personal monitoring system for operators in gas depots and storage tanks," *Chemical Engineering Transactions*, vol. 91, pp. 121–126, 2022.

[4] Occupational Safety and Health Administration, "Permit-required confined spaces," 29 CFR 1910.146, U.S. Department of Labor, Washington, DC, USA, occupational Safety and Health Standards.

[5] S. S.-Y. Lai and M. A. Mirza, "Smart construction safety platform: Integrating ai and iot for proactive hazard management," in *International Conference on Wireless Sensor Networks, Ubiquitous Computing and Applications*. Springer, 2026, pp. 1–13.

[6] G. Thirumalaiah and M. Khan, "Smart self-powered wireless sensor network for industrial monitoring," *Smart Chips for Smart Devices: VLSI Design for Next-Generation IoT Solutions*, pp. 141–178, 2026.

[7] M. Balu, J. Govindaraj, V. Sivamurugesan, R. Shali, N. Nagarajan, and J. S. J. Lawrence, "Intelligent hazardous gas detection and drainage blockage reduction system: An iot-based approach," in *AIP Conference Proceedings*, vol. 3341, no. 1. AIP Publishing LLC, 2026, p. 020070.

[8] G. Karuna, R. R. Kumar, S. Gopaldas, V. Parvathaneni, and T. Lokesh, "Air quality and hazardous gas detection using iot for household and industrial areas," in *E3S Web of Conferences*, vol. 391. EDP Sciences, 2023, p. 01146.

[9] A. Olayiwola, O. Osifeko, K. Olaniyi, A. Oluwaleke, and O. Adizua, "Development of an iot based smart gas leakage monitoring system," *Scientia Africana*, vol. 24, no. 2, pp. 119–128, 2025.

[10] K. Kumar, S. N. Chaudhri, N. S. Rajput, A. V. Shvetsov, R. Sahal, and S. H. Alsamhi, "An iot-enabled e-nose for remote detection and monitoring of airborne pollution hazards using lora network protocol," *Sensors*, vol. 23, no. 10, p. 4885, 2023.

[11] S. I. Al-Hawary, J. R. N. Alvarez, A. Ali, A. K. Tripathi, U. Rahardja, I. H. Al-Kharsan, R. M. Romero-Parra, H. A. Marhoon, V. John, and W. Hussian, "Multiobjective optimization of a hybrid electricity generation system based on waste energy of internal combustion engine and solar system for sustainable environment," *Chemosphere*, vol. 336, p. 139269, 2023.

[12] D. A. Purser and J. L. McAllister, "Assessment of hazards to occupants from smoke, toxic gases, and heat," in *SFPE handbook of fire protection engineering*. Springer, 2026, pp. 2271–2352.
[13] T. Babu, R. R. Nair *et al.*, "Enhancing gas leak detection with iot technology: An innovative approach," *Procedia Computer Science*, vol. 235, pp. 961–969, 2024.
[14] J. Praveenchandar, D. Vetrithangam, S. Kaliappan, M. Karthick, N. K. Pegada, P. P. Patil, S. G. Rao, and S. Umar, "Iot-based harmful toxic gases monitoring and fault detection on the sensor dataset using deep learning techniques," *Scientific Programming*, vol. 2022, no. 1, p. 7516328, 2022.
[15] Y. Zhao, L. Yang, Q. Duan, Z. Zhao, and Z. Wang, "Research on detection methods for gas pipeline networks under small-hole leakage conditions," *Sensors*, vol. 25, no. 3, p. 755, 2025.
[16] A. S. Naik, S. K. Reddy, and M. G. Raj, "Rtepms: Real-time environmental parameters monitoring system using iot-based lora 868-mhz wireless communication technology in underground mines," *IEEE access*, vol. 12, pp. 7430–7455, 2024.
[17] T. Vasundharadevi, R. Jayaraman, K. Mahima, M. Yugandhar, P. Sahithi, and S. Fathima, "Real-time remote monitoring of toxic environments in mining sites using esp and lora," in *2026 8th International Conference on Intelligent Sustainable Systems (ICISS)*. IEEE, 2026, pp. 732–737.
[18] M.-H. Lin, R. Sivaraman, Z. Nan, U. Rahardja, I. Muda, F. S. Fahim, B. S. Bashar, L. Li, and I. Husein, "Capacity optimization design of hybrid energy power generation system." *Mathematical Modelling of Engineering Problems*, vol. 10, no. 4, 2023.
[19] R. E. A. A. Alsalhi, Y. Mustapha, and M. F. Hilmi, "Entrepreneurial and inclusive leadership in enhancing employee innovation in the uae oil and gas sector," *Aptisi Transactions on Technopreneurship (ATT)*, vol. 8, no. 1, pp. 114–124, 2026.
[20] C. V. Royal, K. Dhanalaxmi, M. Priya, A. S. A. Shaik, D. Tirkey, and B. Venkatesu, "Smart gas leak detection system using wireless sensor networks and embedded technology," *Research Digest on Engineering Management and Social Innovations (p-ISSN: 3117-4418 e-ISSN: 3117-4426)*, vol. 2, no. 4, pp. 517–525, 2026.
[21] U. Rahardja, P. A. Sunarya, N. Lutfiani, M. Hardini, and S. N. Sari, "Transformation of green economic recovery based on photovoltaic solar canopy," *Transformation*, vol. 7, no. 2, 2022.
[22] J. B. Rahmad, S. Suwandi, C. K. T. Soedaryono, L. F. D. Aryanti, and D. Aprialiasari, "Analysis of the effect of community's role in csr activities on the image of the company of minarak brantas gas, inc." *ADI Journal on Recent Innovation*, vol. 3, no. 2, pp. 153–171, 2022.
[23] E. F. Ladeira and B. M. Silva, "A machine learning-based platform for monitoring and prediction of hazardous gases in rural and remote areas," *Ieee Access*, vol. 13, pp. 20 297–20 315, 2025.
[24] P. Kanjalkar, J. Kanjalkar, D. Ghuge, K. Ghodake, V. Godase, and S. Halbe, "An integrated ammonia gas detection and monitoring system for industrial safety and environmental health," in *International Conference on Smart Health and Intelligent Technologies (ICSHit-2024)*. Atlantis Press, 2025, pp. 64–75.
[25] N. K. A. Dwijendra, I. Vaslavskaya, N. V. Skvortsova, T. P. Rakhlis, U. Rahardja, M. H. Ali, A. H. Iswanto, L. Thangavelu, and M. M. Kadhim, "Application of experimental design in optimizing fuel station queuing system," *Industrial Engineering & Management Systems*, vol. 21, no. 2, pp. 381–389, 2022.
[26] G. Ramesh, S. Bojjawar, N. Swapna, and K. Uday, "An iot system for monitoring and alerting safety in coal mines," in *E3S Web of Conferences*, vol. 616. EDP Sciences, 2025, p. 03001.
[27] B.-K. Chew, A. Mahmud, and H. Singh, "Autonomous hazardous gas detection systems: a systematic review," *Sensors*, vol. 25, no. 21, p. 6618, 2025.
[28] L. Paul, R. D. Mohalder, and K. M. Alam, "An iot based smart waste management system for the municipality or city corporations," *arXiv preprint arXiv:2411.09710*, 2024.
[29] B. Halubanza, A. Chulu, and M. Namuchile, "Design and implementation of a dual-mode iot-based gas leakage detection and alert system for residential safety in resource-constrained environments," in *Proceedings of International Conference for ICT (ICICT)-Zambia*, vol. 7, no. 1, 2025, pp. 314–321.
[30] P. Ojo, T. Adejumo, L. Oyinkanola, S. Adejuwon, I. Aderibigbe, and K. Akano, "Iot-based gas leakage detection and monitoring system," *Journal of Science and Information Technology*, vol. 19, no. 1, pp. 284–290, 2025.
[31] A. F. Eriyawan and C. A. Utama, "The effect of greenwashing on firm performance with multiple directorships as moderating variable," *Aptisi Transactions on Technopreneurship (ATT)*, vol. 8, no. 1, pp.

74–84, 2026.
[32] N. K. A. Dwijendra, U. Rahardja, N. B. Kumar, I. Patra, M. M. A. Zahra, Y. Finogenova, J. W. G. Guerrero, S. E. Izzat, and T. Alawsi, "An analysis of urban block initiatives influencing energy consumption and solar energy absorption," *Sustainability*, vol. 14, no. 21, p. 14273, 2022.
[33] L. Chiominto, G. D'Emilia, P. Esposito, G. Ferri, E. Natale, D. Polverini, P. Spinozzi, V. Stornelli, and L. Chiavaroli, "A new and smart gas meter with blockchain validation for distributed management of energy tokens," *Eng*, vol. 6, no. 11, p. 290, 2025.
[34] B. Shingan, M. Pujari, and A. K. Aarya, "Advancing environmental safety in city gas distribution: sustainable solutions and infrastructure resilience," *Sustainable and Resilient Infrastructure*, vol. 11, no. 1, pp. 55–78, 2026.
[35] S. Sukardi, S. Wahyuni, and R. Rachmawati, "Entrepreneurship capability by triple series innovations in building competitive resilience within the airline industry," *Aptisi Transactions on Technopreneurship (ATT)*, vol. 7, no. 3, pp. 957–972, 2025.
[36] F. A. Almalki and A. Rajaram, "Optimizing gas efficiency and enhancing security in ethereum smart contracts through integrated clustering and anomaly detection," *International Journal of Information Security*, vol. 24, no. 3, p. 145, 2025.
[37] L. Sulistyowati, M. Z. Hamzah, and N. Ratnawati, "Macroeconomic and price of oil and gold on liabilities of hajj fund management agency," *Aptisi Transactions on Technopreneurship (ATT)*, vol. 7, no. 2, pp. 676–686, 2025.
[38] A. A. Nair, C. N. S. Niteesha, G. Sharma, and S. Nalinakshan, "Monitoring and leak detection of hazardous gas using internet of things," in *2025 3rd International Conference on Intelligent Data Communication Technologies and Internet of Things (IDCIoT)*. IEEE, 2025, pp. 739–744.
[39] C. Alarcon, S. Alarcon, A. Hoffer, and B. Pavez, "Hydrogen 5.0: interdisciplinary development of a proof-of-concept smart system for green hydrogen leak detection," *Processes*, vol. 13, no. 3, p. 639, 2025.
[40] F. Syafariani, M. S. Lola, S. S. S. Abd Mutalib, W. N. F. W. Nasir, A. A. K. A. Hamid, and N. H. Zainuddin, "Leveraging a hybrid machine learning model for enhanced cyberbullying detection," *Aptisi Transactions on Technopreneurship (ATT)*, vol. 7, no. 2, pp. 371–386, 2025.
[41] J. Famaey, O. L. López, R. A. Pérez, G. Callebaut, L. De Strycker, E. Katranaras, J. Liao, R. K. Singh, M. Ashraf, A. Azarbahram *et al.*, "A survey on ambient iot: Use cases, standardization, enabling technologies, and research directions," *IEEE Communications Surveys & Tutorials*, 2026.
[42] M. A. Kadhem and H. Al-Libawy, "Lora mesh for large-scale networks: A systematic review of routing, energy, coverage distance, and open research challenges," in *2026 18th International Conference on Electronics, Computers and Artificial Intelligence (ECAI)*. IEEE, 2026, pp. 1–6.
[43] R. Giuliano, S. A. I. Mocci De Martis, A. Tomeo, F. Terlizzi, M. Gerardi, F. Fallucchi, L. Felli, and N. Dall'Ora, "A hybrid lora/zigbee iot mesh architecture for real-time performance monitoring in orienteering sport competitions: A measurement campaign on different environments," *Future Internet*, vol. 18, no. 2, p. 105, 2026.
[44] M. Priyanka and S. Sameer, "A machine learning-based platform for monitoring and prediction of hazardous gases in rural and remote areas," *Research Digest on Engineering Management and Social Innovations (p-ISSN: 3117-4418 e-ISSN: 3117-4426)*, vol. 2, no. 4, pp. 889–896, 2026.
[45] A. M. B. Ratnayake, H. Suhaimi, and P. E. Abas, "Transforming beekeeping through technology: A systematic review of precision beekeeping," *Sci*, vol. 8, no. 4, p. 87, 2026.
[46] A. B. Jadhav, S. S. Kamble, D. M. Rushikesh, M. Kumar, and S. B. Khadake, "Iot-enabled gas leakage detection system using esp32," 2026.
[47] H. Qin, C. Jin, T. Zhou, and W. Zhou, "A lora-based multi-node system for laboratory safety monitoring and intelligent early-warning: Towards multi-source sensing and heterogeneous networks," *Sensors*, vol. 25, no. 21, p. 6516, 2025.
[48] D. N. Barreto, D. d. S. Sousa, L. Walter, R. K. d. O. A. Cardoso, F. Al-Seba'ey, D. Gache, J. F. d. S. Petruci, and B. Mizaikoff, "A compact multiplexed hazardous gas sensing platform for real-time monitoring in mining scenarios," *ACS Measurement Science Au*, vol. 6, no. 3, pp. 736–742, 2026.
[49] Q.-K. Zou, Y.-T. Wang, P.-L. Gan, X.-Z. Lin, and X. Guo, "Adaptive real-time electronic-nose system for multi-gas monitoring," *Sensors and Actuators B: Chemical*, vol. 466, p. 140277, 2026.
[50] A. Jaya, Q. Aini, A. Rizky, R. Evans *et al.*, "Self supervised transformers for high dimensional time series anomaly detection," *Blockchain Frontier Technology*, vol. 6, no. 1, pp. 25–37, 2026.