Adaptive Environmental Monitoring and Alert Network (AEMAN)

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Abstract-This paper presents the design and implementation of an intelligent, multi-functional safety system titled "Smart AQI and Gas Leakage Detection System with IoT-Based Alert and Monitoring Network." The system utilizes an ESP32-S3 microcontroller to integrate real-time environmental monitoring, encompassing gas detection for harmful or combustible gases such as carbon monoxide, methane, ammonia, or liquefied petroleum gas (LPG), and precise Air Quality Index (AQI) calculation [1][2]. A key innovation is the adaptable, dual-mode operational framework (Home Mode and Industry Mode) that allows flexible application and specialized hazardous gas monitoring depending on environmental requirements [3]. For mission-critical response, the device employs Global System for Mobile communications (GSM) technology to deliver immediate phone calls and SMS alerts to three predefined contacts—the owner, the nearest fire station, and the local police station—ensuring rapid, non-internet dependent emergency notification [4]. Furthermore, the system incorporates a novel distributed AQI Network Mesh, utilizing peer-to-peer communication to facilitate large-scale, district-wise environmental mapping [5]. All collected data is managed and visualized via a centralized web portal, significantly enhancing domestic and industrial safety standards and providing a scalable solution for smart city environmental monitoring [6].

Keywords: Internet of Things, Air Quality Index, Gas Leakage Detection, Mesh Networking, ESP32- S3, Safety Automation, Environmental Monitoring, Smart Cities.

1. INTRODUCTION

The demand for robust safety solutions in both domestic and industrial environments has intensified, driven by increasing urbanization and the proliferation of complex chemical and energy infrastructure [7]. Traditional localized safety devices provide immediate alerts only to those in proximity and offer no mechanism for real-time spatial data analysis or proactive multi-agency alerting, resulting in fragmented response efforts and substantial delays in accident mitigation [8]. Environmental monitoring sensors deployed in distributed networks provide real-time data that helps manage pollution, detect hazards, and optimize resources in urban environments [9]. Contemporary environmental challenges necessitate the integration of multiple safety and monitoring functions into unified systems [10]. Smart cities increasingly require real-time detection of environmental hazards, enabling faster and more targeted intervention in critical situations [11]. This project develops an intelligent, multi-functional device capable of performing simultaneous environmental monitoring and executing immediate hazard response, serving as a cost-effective and scalable solution for enhancing both domestic and industrial safety [12].

2. LITERATURE REVIEW

Current Internet of Things (IoT) sensor networks generally utilize conventional star topologies, where all nodes connect back to a central hub [13]. While effective for localized data gathering, this architecture introduces potential single points of failure and limitations in coverage, particularly in complex or geographically expansive deployment scenarios [14]. In direct contrast, the proposed system utilizes a unique AQI network mesh system, which allows multiple devices to connect and share data with decentralized architecture that facilitates redundancy and enables area-wise, street- wise, and district-wise air quality mapping [15].

Mesh networks provide significantly superior advantages over star topologies for large-scale IoT deployments [16]. The nodes in a mesh network can act as repeaters, routing data through the network and creating multiple communication paths between every two nodes, improving network resilience and enabling nodes not within direct radio range to communicate through router nodes [17]. This redundancy ensures reliable data transmission and has high robustness and reliability as shown in Table 1 [18].

Table 1: Comparison

Feature / Criterion	Existing / Previous Generation Systems	Our Proposed IoT-Based System
Sensor Technology	Single gas sensor (usually LPG only), analog output, low accuracy	Multi-gas detection (LPG, VOCs, smoke, AQI), digital processing, higher precision
AQI Monitoring	Not available	Fully supported; computes AQI

		using multiple inputs
Alerts & Notifications	Local buzzer only	Buzzer + LED + GSM phone calls + SMS + online alerts
Connectivity	No connectivity (standalone)	Wi-Fi + GSM + optional LoRa mesh network
Data Logging	No data logging	Real-time cloud logging + history graph + dashboard
Remote Monitoring	Not available	View readings from anywhere via website/mobile
Emergency Response	User must manually check after alarm	Automatic SMS/call to owner, fire station, police
Operating Modes	Single mode only	Home Mode + Industry Mode + Mesh Mode
Coverage Area	Limited to 1 room (no networking)	Up to 100m (home), extended coverage using mesh
Scalability	Not scalable; only one device	Highly scalable; supports multiple interconnected nodes
Power Supply	Wall-powered only	Solar panel support + battery backup + 12V regulated supply
User Interface	No display, minimal indicators	Full LCD/OLED display + control buttons
Sensor Cross Verification	Not available	Multi-sensor verification to reduce false alarms
Mobile Application Support	None	Web dashboard + remote access available
Cost	Medium to high price, limited features	Low-cost with high functionality
Portability	Fixed installation	Portable design; supports IoT rover extension
Industrial Use	Limited or not suitable	Fully suitable for industry gas/leak monitoring
Environmental Monitoring	No temperature/humidity or AQI data	Includes temperature, humidity, AQI, toxic gas levels
System Intelligence	No processing, only threshold triggers	Intelligent thresholds + cloud analytics support
Network Integration	Not supported	Integrated AQI mesh system for area-wide mapping

3. PROPOSED SYSTEM ARCHITECTURE AND HARDWARE INTEGRATION

A. Scope and Contribution of the proposed work: The project scope encompasses the design, implementation, and functional testing of the complete connected safety system. The core objective is to deliver a functional prototype that enhances domestic and industrial safety while simultaneously contributing valuable data to a larger network of air quality monitoring systems. The paper details the utilization of the ESP32-S3 microcontroller as the central processing unit, the integration of multi-spectral sensors, and the deployment of both GSM and IoT platforms for comprehensive data handling and alerting [19].

B. Central Processing Unit Selection and Logic Flow: The architecture is founded upon the ESP32-S3 microcontroller, which serves as the central processing unit responsible for controlling all connected sensors and communication modules [1]. The ESP32-S3 is equipped with a dual-core 32-bit LX6 microprocessor with powerful dual-core processing capabilities essential for managing real-time data processing requirements, particularly the simultaneous execution of complex AQI calculation algorithms and rapid alert trigger logic [2]. The integrated Wi-Fi and Bluetooth capabilities simplify the implementation of both the IoT data upload mechanism and the peer-to-peer mesh communication required for the AQI network [3].

The system logic employs a prioritized operational flow where continuous sensor polling and initial data analysis are designated as high-priority, time-critical tasks [4]. The firmware structure must utilize efficient interrupt handling to ensure that non-critical functions are executed only after mission-critical checks are cleared, guaranteeing that minimal latency is achieved between critical level detection and the initiation of the GSM alert protocol as in Figure 1 [5].

C. Sensor Subsystem and Data Acquisition: The

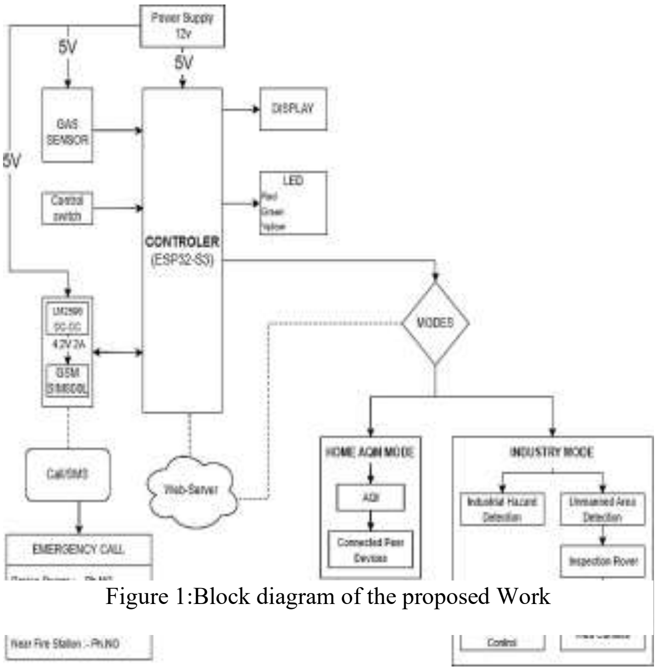

Figure 1:Block diagram of the proposed Work

device incorporates a specialized gas detection sensor capable of identifying harmful or combustible gases, including carbon monoxide, methane, ammonia, or LPG [6]. The MQ-series sensors are commonly employed for detecting multiple gas types including LPG, smoke, alcohol, propane, hydrogen, methane, and carbon monoxide [10]. Data acquisition is supplemented by temperature sensors which monitor ambient conditions [11].

For accurate Air Quality Index calculation, the raw electrical signals from the gas sensor must be converted into standardized pollutant concentration metrics, typically expressed in parts per million (PPM) as shown In Table 2 [12]. The Air Quality Index is calculated using pollutant concentration data, with AQI values of 50 or below representing good air quality, while AQI values over 300 represent hazardous air quality [13]. Crucially, the system utilizes data from the temperature sensor for dynamic thermal compensation [14].

Gas sensor performance, including sensitivity and measurement drift, is often influenced by operational temperature [15]. By integrating thermal data into the AQI calculation algorithms, the system performs dynamic calibration adjustments, thereby improving the overall accuracy and reliability of the gas readings across varying operational temperatures [16].

Table 2: Gas Readings

LISTS OF GASES	STANDARD VALUE	MODERATE VALUE	HAZARDOUS VALUE
CARBON MONOXIDE (CO)	0-50 PPM	50-100 PPM	>100 PPM
AMMONIA (NH3)	0-25 PPM	25-50 PPM	>50 PPM
SMOKE	0-10 PPM	10-50 PPM	>50 PPM
LIQUIFIED PERTOLEUM GAS (LPG)	0-1000 PPM	1000-5000 PPM	>5000 PPM
METHANE (CH4)	0-1000 PPM	1000-5000 PPM	>5000 PPM
PROPANE(C3H8)	0-1000 PPM	1000-5000 PPM	>5000 PPM
HYDROGEN(H2)	0-1000 PPM	1000-5000 PPM	>5000 PPM
CARBON DIOXDE (C02)	350-1000 PPM	1000-5000 PPM	>5000 PPM
BUTANE	0-1000 PPM	1000-5000 PPM	>5000 PPM

3.2 Power Management and Environmental Resilience

System robustness is significantly enhanced by its resilient power management architecture [17]. To ensure uninterrupted functionality and suitability for remote applications, the design incorporates solar panel support coupled with a battery backup [18]. IoT systems increasingly integrate solar power supply and battery backup mechanisms to maintain continuous operation in locations where grid power is unavailable [20]. This continuous power capability is fundamental to meeting the project's scalability and high-availability objectives [21].

3.3 Local User and Control Interface (LUI)

The Local User Interface (LUI) provides immediate, non-network dependent operational feedback [22]. A display module is integrated to show real-time AQI readings, temperature data, and alert messages [23]. Status is communicated visually through three indicator Light Emitting Diodes (LEDs): Green indicates a safe environment, Yellow signifies an alert status, and Red immediately indicates a danger requiring immediate intervention [24]. This unambiguous three-color indicator system ensures immediate status recognition [19].

International Journal of Scientific Research in Engineering and Management (IJSREM)
Volume: 09 Issue: 12 | Dec - 2025 SJIF Rating: 8.586 ISSN: 2582-3930

4. OPERATIONAL MODES AND ALERTING MECHANISMS

4.1 Dual-Mode Operational Framework

The system's flexibility is defined by its ability to operate in two distinct, user-defined configurations: Home Mode and Industry Mode [1]. In Home Mode, the device is configured as a household safety monitoring system, calibrated to cover an area of approximately 100 meters, focusing on detecting common residential hazards such as smoke and specific combustible gases like LPG leakage [2]. In contrast, Industry Mode configures the device for use in high-risk environments such as chemical plants and storage facilities where detection targets shift toward hazardous gases produced during chemical processing, and alert thresholds are substantially lowered to comply with industrial safety regulations[3] [4].

4.2 Automated GSM Emergency Alert Protocol

The effectiveness of the system in preventing accidents hinges on its automated emergency alert protocol[5]. When the system detects critical gas levels, it automatically triggers an immediate phone call and sends SMS alerts to three predefined external contacts: the owner, the nearest fire station, and the local police station[6]. This architecture reflects best practices in emergency notification systems where multiple notification pathways significantly enhance response effectiveness[7]. This robust and diversified alerting strategy significantly enhances the probability of rapid emergency service deployment[8].

5. DISTRIBUTED AQI MESH NETWORK AND DATA ANALYTICS

5.1 Mesh Communication and Peer-to-Peer Data Sharing

The system's unique distributed architecture utilizes mesh communication to allow multiple monitoring devices to connect and share environmental data dynamically[9]. This peer-to-peer data exchange enables the creation of a distributed AQI network capable of performing area-wise, street-wise, and district-wise air quality mapping[10]. The mesh protocol ensures that sensor data packets are efficiently transmitted across the network, even using multi-hop pathways, providing superior connectivity and coverage compared to centralized topologies [11]. By contributing to and sharing data across the network, the system facilitates data democratization where accurate environmental information is available across the service region [12].

5.2 Centralized IoT Platform and Visualization

All data collected by individual devices is continuously uploaded via IoT integration to a web-based dashboard and centralized web portal [13]. This platform provides comprehensive remote access, allowing authorized users to monitor environmental trends, analyze historical data, and check the status of multiple devices simultaneously as shown in Figure 2 [14]. A key analytical feature of the web portal is the graphical visualization of the AQI network mesh on a map format [15]. By enabling the visual overlay of real-time AQI data onto geographical coordinates, analysts can perform spatial-temporal analysis, allowing them to correlate observed AQI spikes geographically with potential sources [16].

Figure 2: Web Dash-Board

6. EXPANDED APPLICATIONS AND FUTURE DEVELOPMENT

6.1 Smart City Integration and Large-Scale Monitoring

Given its cost-effectiveness, scalability, and distributed data collection abilities, the system is highly relevant for large-scale smart city applications and environmental research [17]. The mesh network provides data density and resolution that often surpasses the capabilities of traditional, sparsely located governmental monitoring stations [18]. Smart cities are increasingly adopting IoT-based

environmental sensing systems that deploy networks of sensors across urban spaces to collect real- time data on factors like air and water quality, noise levels, and temperature [19]. The fine-grained

environmental data generated by the network provides crucial input for municipal planning, public health alerts, and localized policy implementation aimed at reducing air pollution [20].

6.2 Mobile-Controlled Inspection Rover Integration

A primary direction for future system flexibility and expansion is the integration of a mobile-controlled inspection rover designed to carry identical air and gas sensors[21]. This rover can be operated remotely to inspect areas that are unsafe for human personnel, such as leaking gas pipelines or

chemical storage tanks [22]. By transmitting both sensor data and live visual context, the rover allows emergency teams to conduct remote risk assessments before deploying human resources [23].

7. FUNCTIONAL VALIDATION AND PERFORMANCE METRICS

7.1 Validation Methodology

Validation of the system requires a comprehensive testing regime simulating both Home and Industry Mode scenarios using calibrated gas mixtures to simulate leakage events [24]. The methodology focuses on assessing the long-term reliability of the sensor readings, including linearity and calibration drift over time, particularly under fluctuating temperature conditions where thermal compensation algorithms are active. The test data is shown in Table 3[1].

Table 3: Testing of sensors.

Sensor	Test Gas / Source	Baseline Value	Peak Value	Response Time	Recovery Time
MQ-2	LPG (unlit stove release)	150	620	2–3 sec	15–20 sec
MQ-2	Smoke (incense stick)	130	540	1–2 sec	18–25 sec
MQ-7	CO (burning paper/matchstick smoke)	80	260	4–6 sec	20–30 sec
MQ-7	Low-CO test (warm breath)	80	120	2 sec	10–15 sec
MQ-135	VOCs (perfume/sanitizer)	90	480	1–2 sec	20–30 sec
MQ-135	CO_2 (human breath)	100	250	2–3 sec	25–35 sec

7.2 Communication Latency Analysis

The efficacy of the device as a critical safety system is directly dependent on the speed of alert delivery[2]. Communication latency must be quantitatively measured across two distinct channels: Alert Latency, which measures the time delay from sensor reading exceeding the preset critical threshold to the successful initiation of the GSM phone call and SMS alerts[3], and Data Latency, which evaluates the end-to-end time required for sensor data to traverse the network and be rendered on the centralized web portal[4].

7.3 Reliability and Cost Efficiency

System reliability is ensured by the hardware redundancies engineered into the design, specifically the continuous operation provided by the solar power supply and battery backup, and the fault tolerance provided by the dual communication paths (GSM and IoT) [5]. Redundancy in wireless sensor networks is recognized as an effective solution to overcome node failures and ensure reliability[6]. The mesh network further enhances reliability by ensuring data can be rerouted dynamically[7].

8. RESULTS

The results of the system evaluation show that the proposed device performs effectively when compared with existing commercial solutions such as the Ventis Pro5, Alpha Web Monitor, and LoRa-based air quality transmitters. While industrial products offer high-precision electrochemical sensing, the developed model provides reliable detection of LPG, smoke, VOCs, CO, and other gases within a practical ppm range using low-cost MQ sensors. The system also successfully measures temperature, humidity, and AQI, and supports P2P communication through ESP-NOW for local network monitoring. Additionally, features such as multi-mode operation, live dashboard monitoring, and real-time alerts make the prototype functionally comparable to professional systems while maintaining affordability and suitability for home, lab, and educational applications Table 4.

Table 4: Comparison with other devices

FEATURES	REAL WORLD PRODUCT	OUR PRODUCT
MULTI GAS MONITORING	VENTIS PRO5 : - O2: ±0.1% vol - CO: ±2 ppm or ±10% - H2S: ±2 ppm or ±10% - LEL: ±3% LEL or ±10% - CO2: ±50 ppm or ±5%	Alpha Web Monitor: - 10-Gas Detection: NH3, Benzene, Toluene, Smoke, Alcohol, CO, H2, LPG, Propane, Butane. - Range: 10ppm ~ 10,000ppm (Variable per gas) - Sensor: MQ Sensor Array (Resistive)
AQI MONITORING	LoRa Indoor Air Quality Transmitter CO2: 0 ~ 2,000ppm, Temperature:-10°C ~ 60°C, Humidity: 0 ~ 95%RH	Smart Home Hub: - AQI: Composite Smoke/VOC Index (0-100+) - Temp: 0°C ~ 50°C (±2°C) - Humidity: 20% ~ 90% RH (±5%) *(Based on DHT11 specs)*
P2P CONNECTION	LoRa Indoor Air Quality Transmitter -frequency: 862 ~ 932MHz	ESP-NOW Mesh Network: - Frequency: 2.4 GHz (Wi-Fi Band) - Topology: Decentralized Peer-to-Peer - Feature: Real-time "Area AQI" averaging
GAS MONITORING MULTIMO	GrayWolf IAQ multi-gas meters Probe modes,	Dual-Mode System: - HOME Mode: Safety focused

DE FEATURE S	Platform modes	(LPG/Smoke/AQI) - INDUSTRY Mode: Specific Gas Targeting (NH3, Benzene, etc.) - Interface: Web Dashboard Control

9. CONCLUSION

The project successfully delivers an innovative and integrated safety and environmental monitoring system, effectively combining robust sensor technology[8], resilient wireless communication[9], decentralized networking through the AQI mesh[10], and comprehensive cloud data analytics[11]. The device provides necessary real-time air quality monitoring, calculates the Air Quality Index, and ensures immediate, automatic, and network-independent emergency notification through its GSM protocol to multiple public safety stakeholders[12].

The system's strong potential lies in its architectural resilience, exemplified by the distributed AQI Network Mesh, which transforms individual safety readings into a collective, region-wide environmental map, fostering community-driven air quality awareness [13]. The adaptable Home and Industry operational modes ensure suitability for diverse high-risk environments[14]. By integrating these critical features, the device enhances safety standards in domestic, industrial, and public settings, making it highly relevant for large-scale environmental research and Smart City initiatives [15]. Future research will focus on the deployment and practical validation of the mobile- controlled inspection rover, alongside continued refinement of the mesh network's data fusion algorithms [16].

REFERENCES

[1] M. Janardhan, N. Rakshitha, E. Sravani, D. M. Afroz, and N. Supriya, “IoT and ML for Air Pollution Monitoring with Real Time Data and Prediction of Health Advisory,” *Proc. 5th Int. Conf. Trends Mater. Sci. Inven. Mater. ICTMIM 2025*, pp. 1082–1087, 2025, doi: 10.1109/ICTMIM65579.2025.10987928.

[2] P. K. Kumar, L. Priyanka, and S. Deepika, “Wireless Sensor Network Based on IoT for Air Pollution Monitoring,” *2024 3rd Int. Conf. Power Electron. IoT Appl. Renew. Energy its Control. PARC 2024*, pp. 195–198, 2024, doi: 10.1109/PARC59193.2024.10486812.

[3] B. Sudantha, M. Manchanayaka, C. Y. Yang, C. Premachandra, M. Firdhous, and K. Sumathipala, “IoT Empowered Open Sensor Network for Environmental Air Pollution Monitoring System in Smart Cities,” *Proc. ICITR 2023 - 8th Int. Conf. Inf. Technol. Res. Next Evol. Digit. Transform.*, pp. 1–5, 2023, doi: 10.1109/ICITR61062.2023.10382893.

[4] A. Ali, “A Framework for Air Pollution Monitoring in Smart Cities by Using IoT and Smart Sensors,” *Inform.*, vol. 46, no. 5, pp. 129–138, 2022, doi: 10.31449/inf.v46i5.4003.

[5] J. Dutta, F. Gazi, S. Roy, and C. Chowdhury, “AirSense: Opportunistic crowd-sensing based air quality monitoring system for smart city,” *Proc. IEEE Sensors*, vol. 0, pp. 1–3, 2016, doi: 10.1109/ICSENS.2016.7808730.

[6] G. Morgado, O. Postolache, and J. D. Pereira, “Smart City Air Quality Monitoring supported IoT ecosystem,” *Proc. Int. Conf. Sens. Technol. ICST*, 2023, doi: 10.1109/ICST59744.2023.10460781.

[7] M. Patel, A. Mehta, and N. C. Chauhan, “Design of Smart Dashboard based on IoT Fog Computing for Smart Cities,” *Proc. 5th Int. Conf. Trends Electron. Informatics, ICOEI 2021*, pp. 458–462, 2021, doi: 10.1109/ICOEI51242.2021.9452744.

[8] D. P. More and D. L. Bhuyar, “Automated Road Accident Detection and Location Tracking Using GSM and GPS,” vol. 10, no. 01, pp. 167–176, 2025, doi: 10.5281/zenodo.15751577.

[9] R. Alena, R. Gilstrap, J. Baldwin, T. Stone, and P. Wilson, “Fault tolerance in ZigBee wireless sensor networks,” *IEEE Aerosp. Conf. Proc.*, pp. 1–15, 2011, doi: 10.1109/AERO.2011.5747474.

[10] H. Gusdevi, A. Setya P, and P. Handini Zulaeha, “Prototype of LPG gas leakage detector using flame sensor and MQ-2 sensor,” *Comput. Sci. Inf. Technol.*, vol. 1, no. 1, pp. 32–38, 2020, doi: 10.11591/csit.v1i1.p32-38.

[11] A. M. Anika, M. N. Akter, M. N. Hasan, J. F. Shoma, and A. Sattar, “Gas Leakage with Auto Ventilation and Smart Management System Using IoT,” *Proc. - Int. Conf. Artif. Intell. Smart Syst. ICAIS 2021*, pp. 1411–1415, 2021, doi: 10.1109/ICAIS50930.2021.9395774.

[12] J. Wu and X. Ding, “Using Wireless Sensor Network to Remote Real-Time Monitoring and Tracking of Logistics Status Based on Difference Transmission Algorithm,” *J. Sensors*, vol. 2021, 2021, doi: 10.1155/2021/4084288.

[13] R.-T. S. Processing and in E. Systems,

"Real-Time Stream Processing in Embedded Systems," no. September, 2017.

[14] F. Li, W. Liu, W. Gao, Y. Liu, and Y. Hu, "Design and Reliability Analysis of a Novel Redundancy Topology Architecture," *Sensors*, vol. 22, no. 7, 2022, doi: 10.3390/s22072582.

[15] V. Singh and D. Singh, "Reliability of Wireless Mesh Networks and Smart Grids: A Review," *2023 3rd Int. Conf. Intell. Technol. CONIT 2023*, pp. 1–6, 2023, doi: 10.1109/CONIT59222.2023.10205552.

[16] A. Raja Basha, "A Review on Wireless Sensor Networks: Routing," *Wirel. Pers. Commun.*, vol. 125, no. 1, pp. 897–937, 2022, doi: 10.1007/s11277-022-09583-4.

[17] A. N. Upadhyaya, K. Muthukumar, N. R. R. Paul, and S. Ravikanth, "Advancing Safety: IoT-Based Multi Sensor System for Real-Time Multiple Hazards Detection and Alarming," *Proc. 4th Int. Conf. Smart Electron. Commun. ICOSEC 2023*, pp. 404–410, 2023, doi: 10.1109/ICOSEC58147.2023.10276128.

[18] Z. H. C. Soh, S. A. C. Abdullah, M. A. Shafie, and M. N. Ibrahim, "Home and industrial safety IoT on LPG gas leakage detection and alert system," *Int. J. Adv. Soft Comput. its Appl.*, vol. 11, no. 1, pp. 131–145, 2019.

[19] R. Mateos-Rodriguez *et al.*, "Scalable IoT Solution for Real-Time Air Quality Assessment in Urban Environments," *IOP Conf. Ser. Earth Environ. Sci.*, vol. 1524, no. 1, pp. 1–10, 2025, doi: 10.1088/1755-1315/1524/1/012012.

[20] A. Morchid *et al.*, "Fire detection and anti-fire system to enhance food security: A concept of smart agriculture systems-based IoT and embedded systems with machine-to-machine protocol," *Sci. African*, vol. 27, no. June 2024, p. e02559, 2025, doi: 10.1016/j.sciaf.2025.e02559.

[21] M. A. Rahman, H. Ahmed, and M. M. Hossain, "An Integrated Hardware Prototype for Monitoring Gas Leaks, Fires, and Remote Control via Mobile Application," *Int. J. Adv. Comput. Sci. Appl.*, vol. 13, no. 10, pp. 833–840, 2022, doi: 10.14569/IJACSA.2022.0131099.

[22] Charles Antony Raj, "Innovations in Real-Time Operating Systems (RTOS) for Safety-Critical Embedded Systems," *J. Comput. Sci. Technol. Stud.*, vol. 7, no. 3, pp. 791–797, 2025, doi: 10.32996/jcsts.2025.7.3.86.

[23] M. N. A. Ramadan, M. A. H. Ali, S. Y. Khoo, M. Alkhedher, and M. Alherbawi, "Real-time IoT-powered AI system for monitoring and forecasting of air pollution in industrial environment," *Ecotoxicol. Environ. Saf.*, vol. 283, no. April, p. 116856, 2024, doi: 10.1016/j.ecoenv.2024.116856.

[24] V. S. Kashyap, "Scalable Cloud Computing Architecture for IoT Data Processing," *Comput. Eng. Technol. Innov.*, vol. 1, no. 1, pp. 52–59, 2024, [Online]. Available: https://doi.org/10.48314/ceti.v1i1.26