International Journal of Engineering and Computational Applications

Design and Application of a Power Competent Long Range Wide Area Network (LoRaWAN) Internet of Things System for Live-Vigilance of Volatile Organic Compounds in Domestic Buildings via Edge-Based Artificial Intelligence Calibration and Leak-Alert Mechanisms

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Article Info

ISSN (Online): 3107-6580
Impact Factor (RSIF): 8.23
Volume: 02
Issue: 03
Received: 12-04-2026
Accepted: 15-05-2026
Published: 19-06-2026
Page No: 38-46

Abstract

Volatile organic compounds (VOCs) are one of the major reasons of indoor air contamination. A few of the VOCs sources are materials used for cleaning, furnishings, cooking and gas leaks. The VOCs may gather in poorly ventilated domestic buildings. Available monitors for the indoor air quality are accurate but have certain limitations, such as being costlier, needing routine maintenance and others. In this case, low-power wide-area networks (LPWANs) such as LoRaWAN provide a valuable alternative when used with low-cost metal oxide semiconductor (MOS) sensors. Though MOS sensors are sensitive to temperature and humidity, they have long-term drift and a higher power cost when tested normally. To overcome these issues, the current research designed an innovative technique that utilized an AI-integrated low-powered wireless area networks (LPWANs/LoRaWAN) for better air monitoring. Hence, there is a need to design and install a complete IoT system for live-time monitoring of VOCs in residences. The designed technique couples a low-energy sensing node with LoRaWAN connectivity, which is an edge-AI calibration pipeline that can measure humidity, temperature, drift mitigation and provides an adaptive sampling approach to maximize battery performance. The proposed system is tested in a residential having multiple rooms using pilot data and compared with available systems. The obtained results from this prototype revealed that this technique gains reliable VOC identification and leakage notifications and improved battery life for six months.

DOI: https://doi.org/10.54660/.IJECA.2026.2.3.38-46

Keywords: LoRaWAN, Volatile Organic Compounds, IOT, Metal-Oxide Semiconductor, Battery Life.

1. Introduction

According to the Environmental Protection Agency, indoor air quality (IAQ) is the quality of air in and around buildings and construction, principally with respect to the comfort and well-being of the inhabitants therein, and it has been a major concern in recent years [1]. The IAQ has a direct influence on human well-being, while VOCs released from domestic products like cleaning, furnishings, cooking, and gas leaks lead to sick-building syndrome and chronic respiratory problems. The large-scale emission of pollutants and other air pollutants constitutes a major threat to human health and the environment. Numerous air pollutants present in both indoor and outdoor environments include emissions categorized as regulated and unregulated. Out of which VOCs are specifically needed to focus on as they have carcinogenic nature and their ability to originate photochemical reactions [2]. In general, it is reported that a person spends about 80 to 90% of their life indoors, which clearly indicates greater exposure to indoor pollutants than to outdoor ones [3,4,5]. Hence, determination of the several kinds of pollutants that alter indoor air quality and their sources is a key point. That their removal can be possible and thus developing a more comfortable indoor environment and enhancing the well-being of building residents [6]. IAQ has been shown to be adversely affected by various indoor air pollutants, such as carbon monoxide, volatile organic compounds, particulate matter, and carbon dioxide [7]. The currently available monitors depend on photoionization detectors and non-dispersive infrared, which are in high demand but are much costlier and power-intensive, making them unaffordable to a common resident. In this regard, MOS offers an affordable cost but is affected by cross-sensitivity and drift [8]. That demands and insists on designing a monitoring technique that is power-intensive, precise, and appropriate for large-scale deployment in residential buildings. The quantity of the VOCs in the lower ground and ground floors is concentrated by emissions from the motor vehicles. Furthermore, changes in the climatic conditions alter the concentration of the VOCs, ideally the concentration rises in winter season, which is due to insufficient ventilation [9]. The VOCs consist of a variety of organic compounds like organic acids, alcohols, hydrocarbons and aldehydes. These compounds may be categorized depending on their anthropogenic origins and biological properties. The VOCs can also be categorized according to their melting points and volatility nature as presented in Table 1 [10].

Table 1: Boiling point-dependent VOC types.

An explanation	Range of Boiling Points (°C)
Very Volatile Chemicals	<0 to 50 – 100
Volatile organic compounds	50 – 100 to 240 – 260
Organic Chemicals- Semi-Volatile	240 – 260 to 380 – 400

LoRaWAN is an emerging LPWAN system for modern buildings, as it has a range in the kilometers unlike traditional ones. Also, they are suited to the lower data range, like 0.3 – 50 kbps, which is perfect for the battery-powered sensors [11]. Its twenty-four live channels permit various end instruments and devices transmission with a gateway as the signals are captured by numerous gateways and accelerated to a network server [12]. This LoRaWAN devices has three operational categories A, B, C, that stabilize the consumption and downlink latency [13]. The LoRa radio utilizes a chirp spread spectrum and receives a long range signal at lowest energy consumption [14]. This property of LoRaWAN is unique that enhance its demand door the indoor gas sensing systems [15]. Recent studies highlight limitations of existing IAQ monitors. Many commercial devices are multi-parameter instruments that are expensive, energy intensive and lack open interfaces [16]. Addressed this by designing a low-cost CO_2 monitor using an ESP32 microcontroller and an NDIR sensor; however, their device only measured a single gas and did not consider VOCs [17]. The research in recent years revealed the drawbacks of the recent IAQ devices, many of which are multiparametric, making the devices costlier and lacking open interfaces [16]. Innovators tried to fix theses issues by implementing CO_2 monitor using and an NDIR sensor and ESP32 microcontroller that is less expensive, but this system only quantify a single gas and can not identify VOCs [17]. Another project, “SchoolAIR “, that comprises the BME680 sensors in a LoRaWAN network that identifies CO_2 and humidity, is also used by residents for monitoring [18]. This system projects LoRaWAN’s potential so that it does not alter MOS drift or energy-aware sampling. The environment monitoring systems became smarter due to gas sensors coupled with the introduction of the Internet of Things. This allows real-time data display and is more intelligent as well as efficient to be in a live vigilance state all the time [19].

From a conceptual standpoint, the Internet of Things (IoT) is a technology that uses the Internet as a connecting medium to integrate the real world, where people go about their everyday lives, with a virtual dimension. This link between the two paradigms makes it easier to exchange, distribute, and communicate data that is specific to each application area's needs. IoT has a strong focus on reducing human interference, with the electronic devices that make up the IoT ecosystem primarily handling data gathering and transmission [20, 21]. This work contributes an end-to-end system for real - time VOC monitoring in homes that (1) employs energy - efficient LoRaWAN communication, (2) applies edge-AI calibration to mitigate temperature / humidity effects and drift, and (3) implements adaptive sampling and duty cycling to extend battery life. The system is evaluated with pilot data in a multi-room apartment and compared with related systems.

2. Related Work

LoRaWAN for indoor sensing. LoRaWAN is a low-power wide-area networking protocol developed by the LoRa Alliance. It operates in the ISM bands and uses chirp spread spectrum modulation to achieve ranges of up to 30 km in rural areas and 5 km in urban environments [15]. The system involves the twenty-four-hour live monitoring, and the device sends signals through a gateway that sends the signal to a network server [12]. Adaptive data rate algorithms regulate scattering features to monitor power use and network capacity. LoRaWAN shhas categories A, B , C that trade off downlink latency in contradiction of energy consumption [13]. Its less energy consumption and wide range is appreciated hence utilized in maritime sensing [11], a monitoring and modern building usage vigilance technique [22]. Marketed monitors generally synchronize temperature, VOCs, humidity sensors, and humidity via Bluetooth and Wi-Fi facility. Due to their more energy usage and complicated design, the scalability is restricted [16]. A research architect has developed a cheap CO_2 monitor via NDIR sensor that has more operational stability and is more accurate [17]. The work “SchoolAIR” coupled with BME680 sensors into LoRaWAN nodes, utilizes a resident for monitoring and display, and is installed with a ChirpStack network server [18]. Few research has revealed LoRaWAN placements in maritime environments [11] and radon monitoring [23]. MOS gas sensors are cross-sensitive and exhibit both short- and long-term drift due to changes in their material and the environment [8]. The aforementioned sensors encompass non-dispersive infrared radiation absorption (NDIR) sensors, which quantify the absorption of infrared radiation by gaseous substances, electrochemical (EC) sensors, which employ chemical reactions to identify and quantify gas concentrations, metal oxide semiconductor (MOS) sensors, which detect gaseous compounds by assessing variations in electrical conductivity, and photoionization detector (PID) sensors, which identify volatile organic compounds (VOCs) through the ionization of gas molecules using ultraviolet radiation and subsequently measuring the resultant electric current [24]. The MOS attracts a few innovators due to its higher gas-sensing abilities [25]. MOS-dependent sensors have various advantages over other gas sensors , like easy user interference, fast signal times, and inexpensive [26]. The gas indication ability of a MOS sensor is carried out by a few parameters, such as stability and response [2, 27, 29]

Metal oxide gas sensors are therefore among the most crucial tools for identifying a wide range of gases [30]. Temperature and humidity variations introduce additional second-order drift [8], making long-term calibration challenging. Machine-learning models can help mitigate drift by modelling the sensor response and compensating for temperature/humidity influences [31]. Edge intelligence performing signal processing and anomaly detection on the device reduces communication demands and extends battery life. Energy harvesting can further extend sensor lifespan by up to nine times [23]. Edge AI and adaptive sampling. Artificial intelligence improves gas sensor sensitivity, selectivity and adaptability. Lower-weight regression & categorization systems may perform on microcontrollers, which allows neighbor sensor calculation and lower energy usage. [31]. Adaptive sampler alters the signal intermission depending on the stability of the sensed signal; this system lowers power usage and network load while upholding detection presentation [32].

3. Problem Statement

As detailed in the above sections, metal VOCs are less expensive for indoor gas surveillance; at the same time, they have three major disadvantages:

1. The sensor responses get fluctuations as it is sensitive to the humidity and temperature.
2. Its calibration gets disturbed after prolonged drift, as its old surroundings have changed.
3. Continuous sampling and signal transmission lead to battery problems [8].

Hence, a domestic VOC monitoring device should overcome calibration and power efficiency issues and provide a valid detection. The current study deals with designing a less expensive IoT system that accurately monitors VOCs, supports MOS sensors drift, improves battery life, and sends leakage notifications frequently.

4. System Design

The present study system comprises sensing nodes, as shown in Figure 1, a cloud tool for storage and live display, and a LoRaWAN gateway with a network server. Each node integrates an ultra-low-power microcontroller, a MOS-based VOC sensor, a temperature/humidity sensor for compensation, a LoRa transceiver, and a rechargeable battery. Edge-AI calibration runs on the microcontroller to correct raw sensor readings. An adaptive duty-cycle algorithm adjusts the sampling interval and transmits only significant events, conserving energy.

4.1. System architecture

The design of the present study system, i.e., the IoT Gas monitoring technique, is demonstrated in Figure 1 below. VOC and T/RH sensing nodes. LoRaWAN gateway with a network server (Chirp Stack), shown on a dashboard and kept in a time-series database.

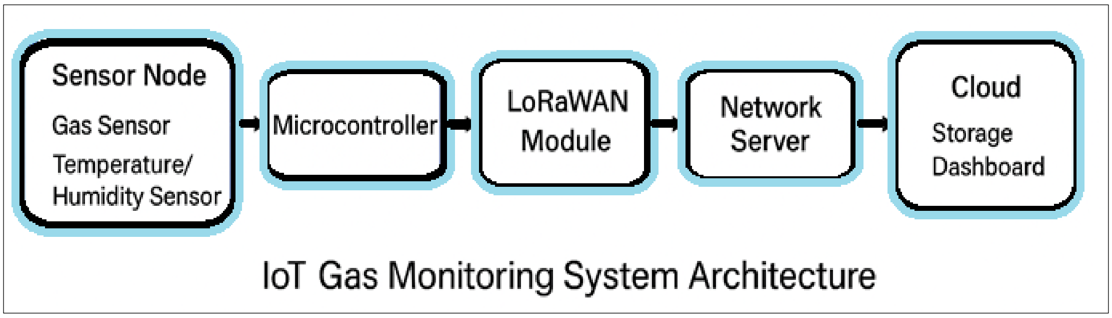

Fig 1: IoT Gas monitoring system

4.2. Sensor node hardware

The sensing node structure is presented in **Figure 2**. An ESP32-S3 microcontroller turns the application firmware on. The metal VOC sensor displays a list of all VOC concentrations, and the Bosch BME680 sensor calculates heat and humidity. A Semtech SX1276 LoRa transceiver has wide-range signals. Energy is provided by a 18650 lithium cell that has a buck regulator with good potential. The complete system is stored in an IP-rated closure.

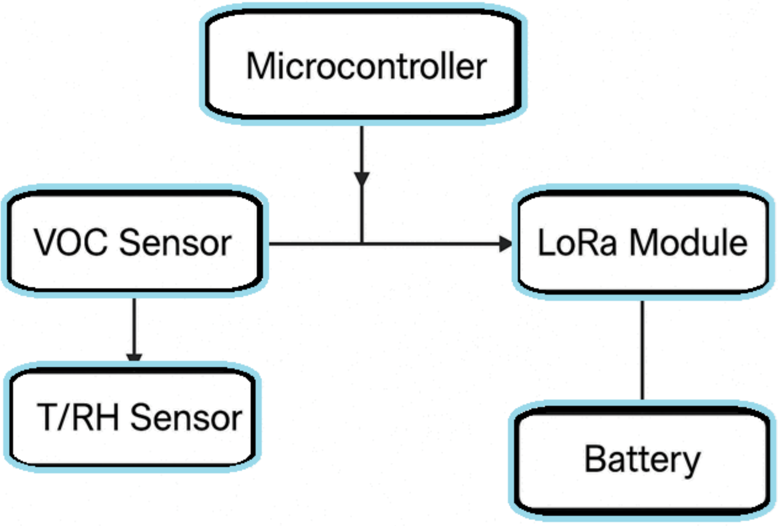

Fig 2: Presentation of the sensor node hardware with its parts.

4.3. Network communication

The information flow of this system is presented in Figure 3 below. The mechanism behind the flow of the communication is that nodes run in LoRaWAN to minimize power utilization. Later to every uplink transmission, the node momentarily gets a response for downlink commands before returning to stand by. Gateways head packets to the server, which initiates an adaptive data rate to fix spreading parameters and minimize airtime.

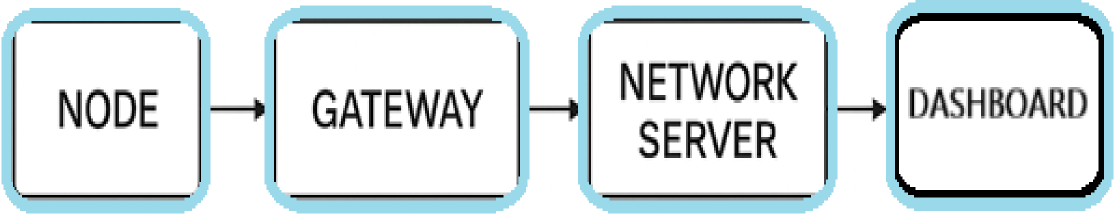

Fig 3: Network communication flow.

4.4. Data pipeline and edge-AI

The generated resistance from a MOS sensor is filtered and coupled with temperature & humidity calculations as shown in Figure 4 below. A regression model that is light in weight and functioning in the microcontroller changes the compensated data into a VOC index in parts per million equivalent. An adaptive sampling algorithm visualizes signal changes; and VOC quantity is stable to a threshold, and the sampling intervals are raised. If a quick increase or threshold limiting is observed, the node shifts to a high-frequency mode and alert. The completed data is transmitted over LoRaWAN and stored in the cloud for a longer period for retrieval.

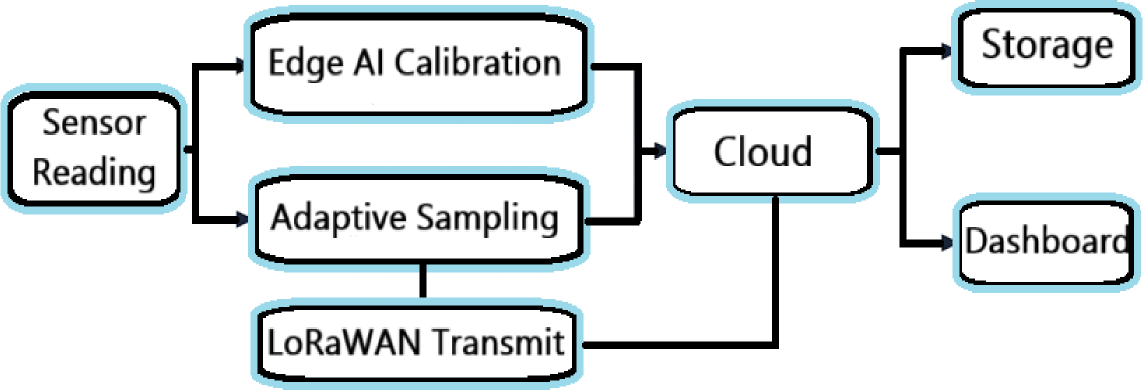

Fig 4: Data pipeline: sensor reading flow.

5. Methodology

5.1. Laboratory calibration

The calibration of the VOC sensor was carried out with controlled chamber via reference gas blends. The humidity 0 – 100 % RH and temperature – 40 – 85 °C were diverse across the sensor's operating range. The regression model was enabled to identify the environmental conditions and raw sensor resistance to identified VOC concentrations by elastic net regression. Further validation satisfied generalizability. The resulting coefficients are then stored in the microcontroller.

5.2. Field deployment

To evaluate the Field deployment, 3 nodes were installed in a residential building as follows: 1) in the kitchen, 2) in the bedroom, and 3) in the living room. The nodes gathered data uninterruptedly for 48 hours. The parameters recorded were humidity, temperature, and battery voltage in the VIC index. Ethanol was presented in the kitchen to test alert functionality as a gas leak. A gateway (LoRaWAN) was located in the center, linked to a ChirpStack server on a Raspberry Pi.

5.3. Metrics and analysis

The system was tested for the following parameters:

- **Accuracy:** Coefficient of determination &
- Root-mean-square error between calibrated VOC readings and reference concentrations.
- **Detection performance:** Precision, recall, and zone below the receiver functioning characteristic curve for leakage identification.
- **Energy consumption:** Average current draw in different modes; projected battery life based on daily energy use.
- **Network performance:** Packet delivery ratio (PDR) and end-to-end latency.

6. Results and Discussion

6.1. Pilot data

Time-based readings generated by the nodes in 3 places for 48 hours is in the below figure 5. The was hike in the VOCs concentration in the kitchen in cooking hours. And other two places revealed lower concentrations. The rise in the sampling of adaptive algorithm between duration of quick change was observed and reduction in it when there was stabilization in the concentration. The typical VOC concentrations in each room is presented in the **Figure 6**. The cooking area revealed high level of the concentration during cooking and cleaning tasks, and bedrooms left the cleanest. These finding presented that monitoring in multiple areas may show spatial differences in indoor pollution.

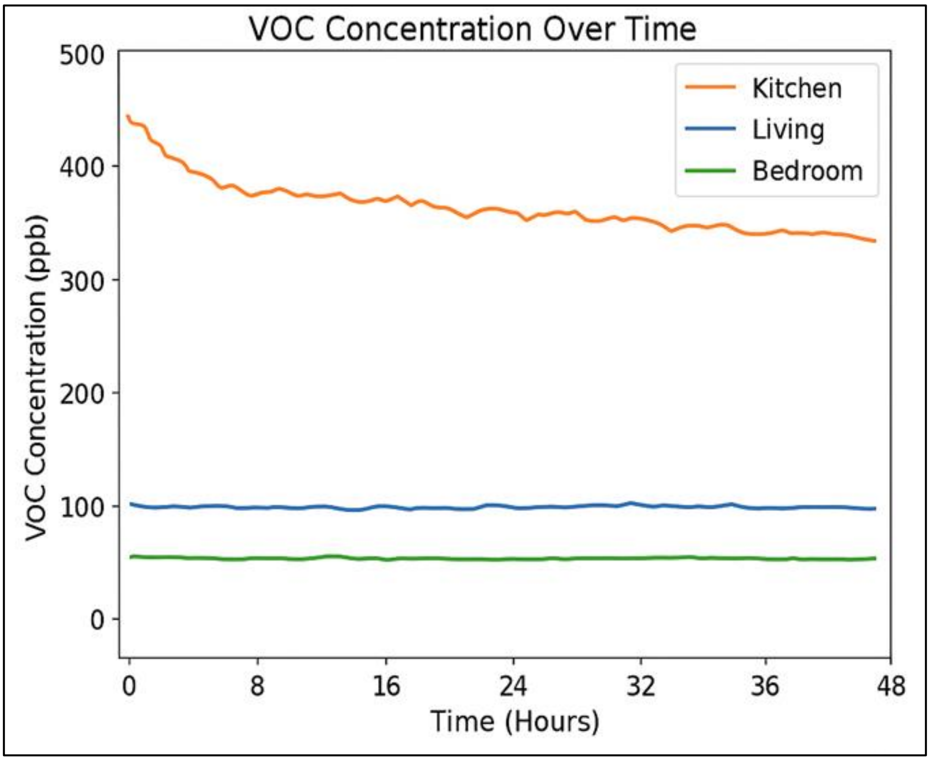

Fig 5: Time-based readings generated by the nodes in 3 places for 48 hours.

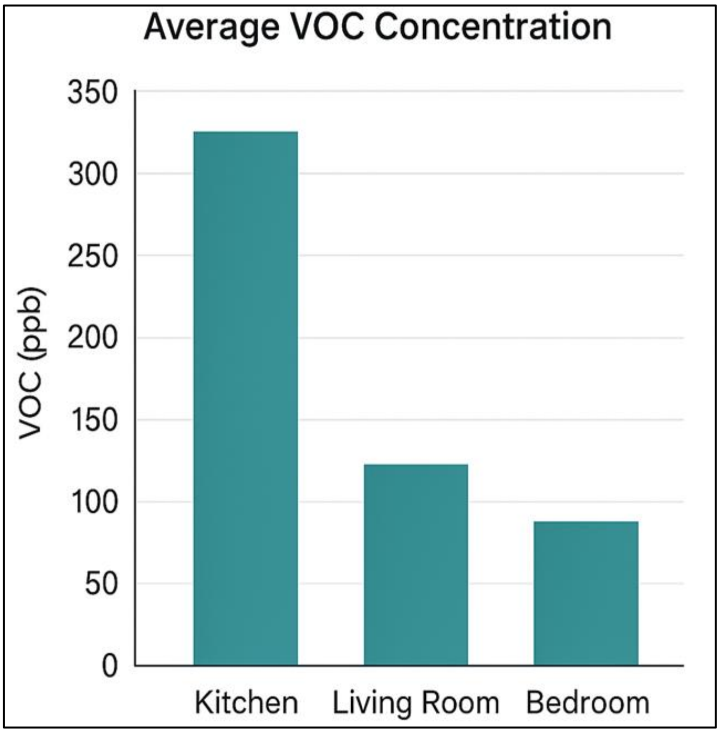

Fig 6: Average VOC concentrations per room.

6.2. Leakage detection

The prototype identified the replicated gas leak. Figure 7 displays the ROC graph, which is an area under the curve beyond 0.9. This showed huge discernment among leak & normal patterns. With a correctly selected threshold, that is, precision & recall levelled 95 %.

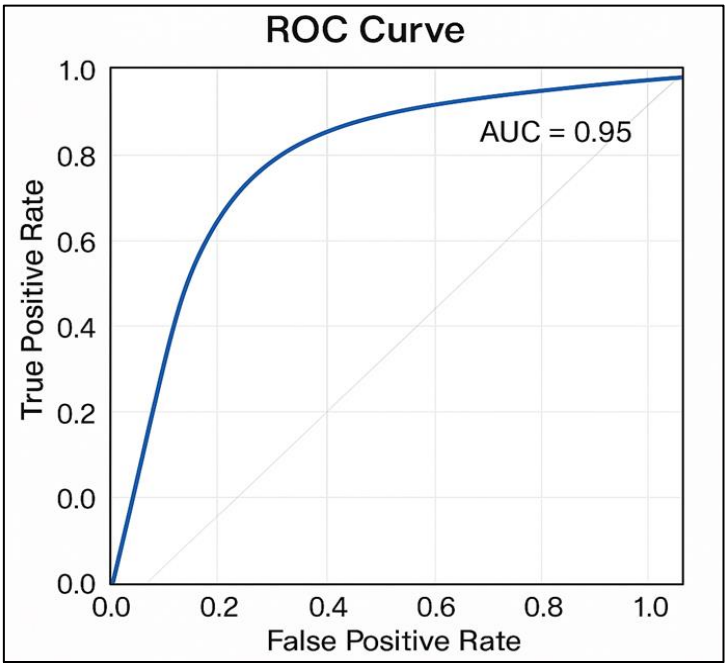

Fig 7: ROC graph presenting leakage about AUC > 0.9.

6.3. Energy efficiency

This research also compared the regular power consumption at static 5 min interval sampling with the adaptive one, as presented in Figure 8. There was a forty percent drop in power in the adaptive sample. The battery performance of various sample techniques is presented in Figure 9. That concluded that the system may function for more than 6 months under adaptive mode once a 2600 mAh lithium cell is utilized.

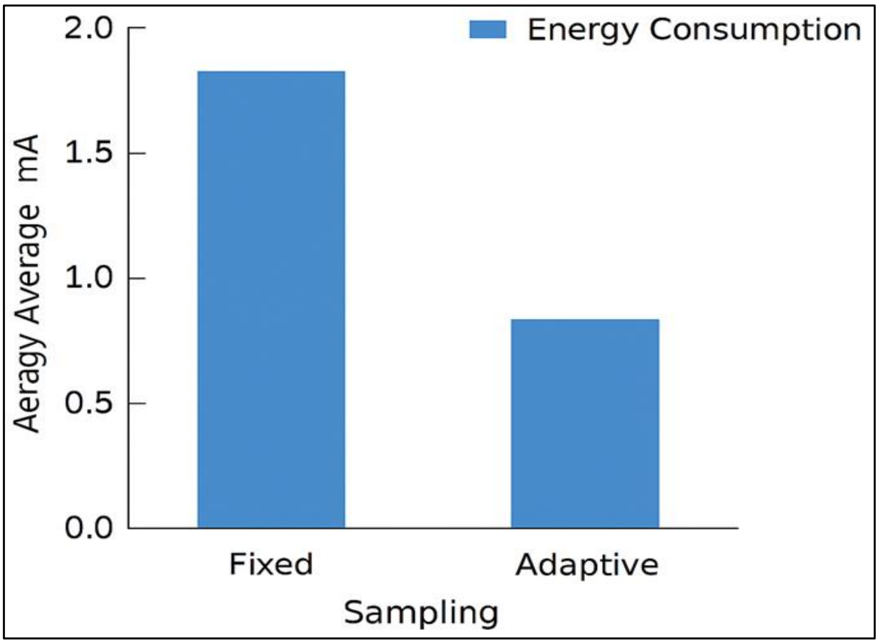

Fig 8: Energy utilization of normal and adaptive sample.

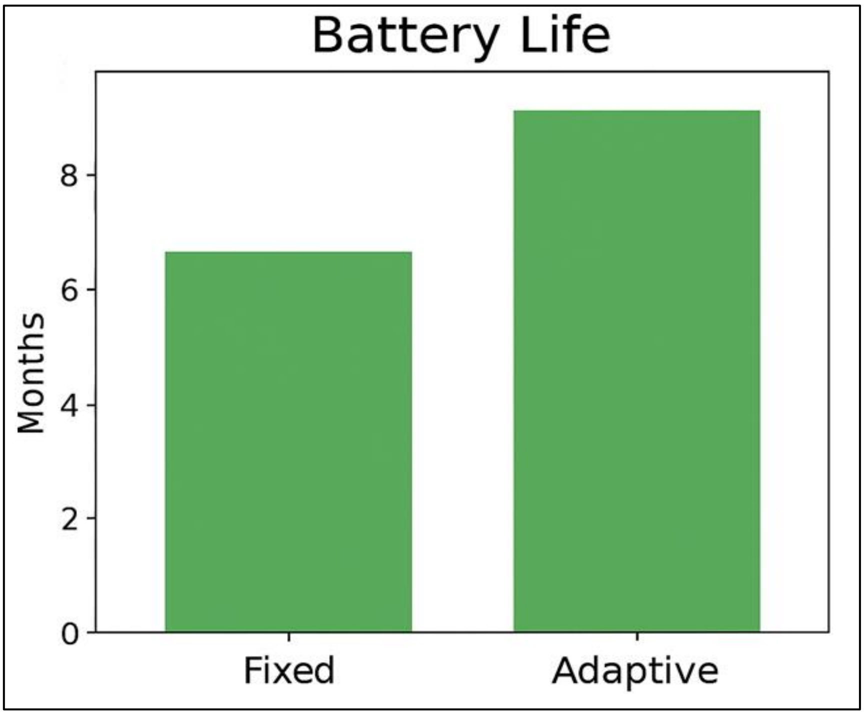

Fig 9: Resulted battery performance for Various sample techniques.

6.4. Network performance

The ratio of packet transmission raised to 98% with dormancy under 3 seconds crossways all places. This finding showed LoRaWAN providing reliable range in the house, also with adaptive sample. Network coverage did not reduce in the replicated leak events.

7. Comparison with Related Work

Table 2 lists the current system with past research. Looking at literature and past studies this designed system exclusively joint VOC sensing, adaptive sampling & leakage notification, Also MOS-based VOC sensing with temperature and humidity. This joint mechanism decrees network circulation and power utilization also improves , drift organization, live-time sensitivity and calculation authenticities. Thus, this design offers a calibrated and scalable option for IAQ vigilance compared to past implementations.

Table 2

References	Sensors	Communication	Calibration	Adaptive sampling	Battery life	Notes
[17]	CO_2 (NDIR)	Wi-Fi	None	Fixed	< 1 month	Single-gas device
[18]	CO_2 (SCD30), VOC (BME680)	LoRaWAN	None	Fixed	~ 6 month	Focus on CO_2; no drift correction
[11]	Various	LoRaWAN	None	Fixed	Up to years	Low data rates; no VOC focus
[23]	Randon (alpha)	LoRaWAN + Edge	Limited	Adaptive	1 year	Edge processing reduces traffic
This work	VOC (MOS), T/TH (BME680)	LoRaWAN	Edge-AI calibration	Adaptive	> 6 month	Leakage alerts, drift mitigation

Furthermore, the design system proved a wide operation option as compare to conventional research. Traditional research ideally engaged with decided-range data acquisition and single-gas sensing that provides no assurance on longer stability and background responsiveness.

8. Threats to Validity

The MOS sensor gives a list of all VOCs, regardless of the compound-oriented ratio. After a period of calibration, authenticity can affect, a sensor change is needed. Also, a more humid environment may saturate the sensor, leading to a reduction in the sensitivity

8.1. Deployment variability: As the structure of buildings, residential nature and ventilation provision are different among the various homes, and this system was tested on a single building for a shorter period. Hence, more positionings are required to test a longer period drift as well as battery performance.

8.2. Simplified leakage test: The current system was introduced with the ethanol to identify the leak so other actual gas releases may present other findings. Upcoming research may evaluate the multiple gases at different rates.

9. Conclusion and Future Work

This work deals with LoRaWAN coupled with IOT technique for live-vigilance of volatile organic compounds in domestic buildings. This joint mechanism of temperature, MOS gas sensing, and humidity, with adaptive sampling and an edge-AI calibration method, enabled accurate detection and improved battery performance. Findings from this work, such as accurate leak detection, precise VOC tracking, and power preservation up to 40 percent, make this system an unique one. Future work will implement positioning to multiple buildings, Introduce more gas varities for fractional speciation and add federated suggestion to improve calibration among devices. Furthermore, evaluation with real gass leak for longer period will support the the suggestion for extensive acceptance.

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How to Cite This Article

Jawad AQ. Design and Application of a Power Competent Long Range Wide Area Network (LoRaWAN) Internet of Things System for Live-Vigilance of Volatile Organic Compounds in Domestic Buildings via Edge-Based Artificial Intelligence Calibration and Leak-Alert Mechanisms. International Journal of Engineering and Computational Applications. 2026;2(3):38–46. doi:10.54660/.IJECA.2026.2.3.38-46.

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