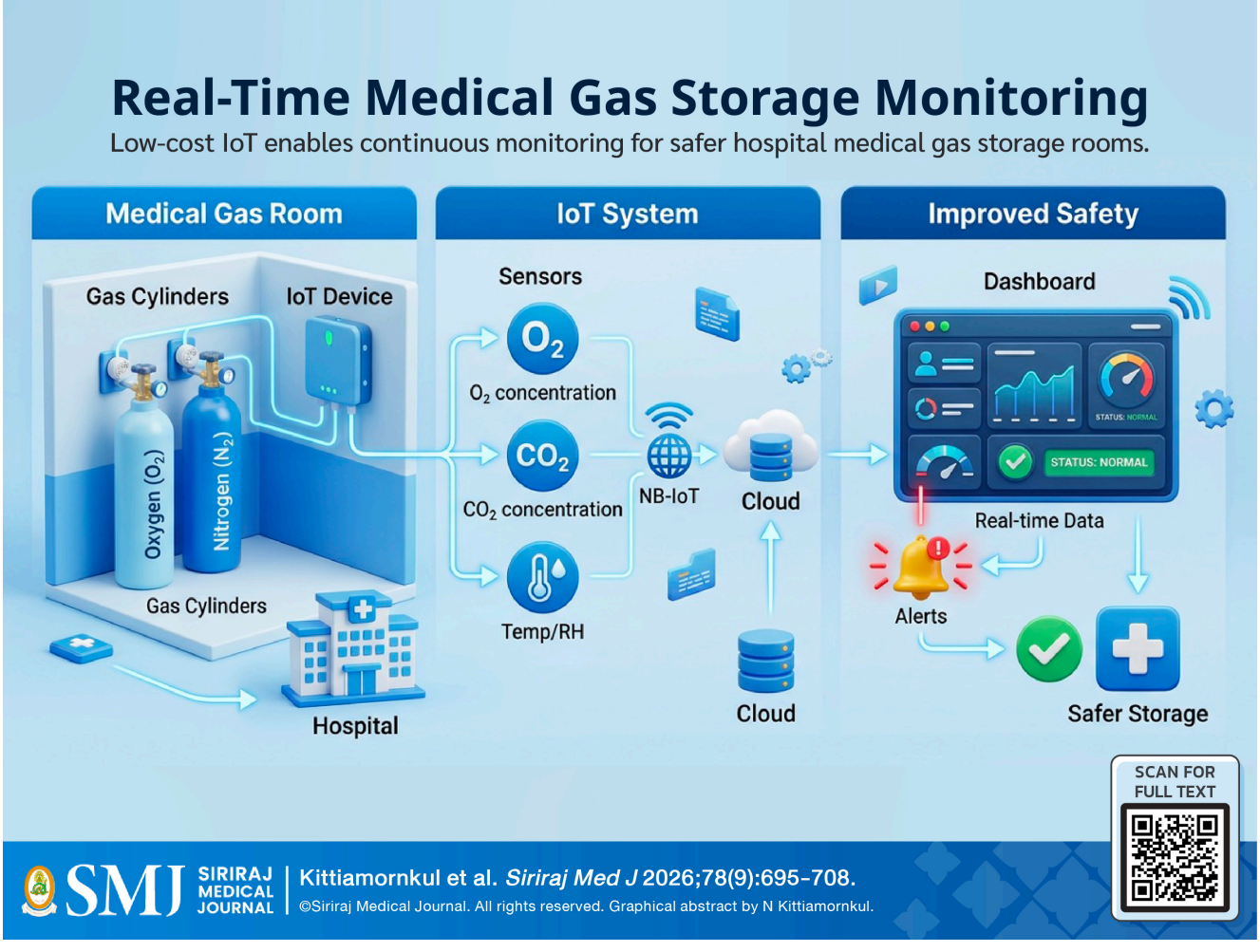
Design and Validation of a Low-Cost IoT-Based Medical Gas Monitoring System for Hospital Storage Rooms

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ABSTRACT

Objective: This study aimed to develop and evaluate a low-cost medical gas monitoring system to enhance safety in hospital gas storage rooms. Continuous monitoring of oxygen and carbon dioxide levels may help identify oxygen-deficient or oxygen-enriched conditions and elevated carbon dioxide concentrations that may pose occupational safety risks to healthcare personnel.

Materials and Methods: An Internet of Things (IoT)-based device was developed to monitor medical gases and environmental conditions, including oxygen, carbon dioxide, temperature, and relative humidity. The system enables real-time monitoring and online data visualization. Sensor performance was validated against standard reference equipment.

Results: The developed system demonstrated normalized root mean square differences (nRMSD) of 15.47%, 0.085%, 4.80%, and 5.39% for carbon dioxide, oxygen, temperature, and relative humidity, respectively, under ambient environmental conditions. The corresponding normalized mean bias differences (nMBD) were -9.70%, 0.283%, 2.54%, and -3.00%, respectively. However, validation was conducted over a narrow ambient concentration range and did not include controlled gas concentrations near the predefined alarm thresholds. Therefore, these results represent preliminary measurement agreement under ambient conditions and do not establish alarm performance or safety-monitoring performance across the intended decision range.

Conclusion: The proposed low-cost monitoring system (approximately USD 255) enables continuous real-time monitoring of oxygen, carbon dioxide, temperature, and relative humidity under ambient environmental conditions. The system may support environmental monitoring and improve occupational safety in hospital medical gas storage areas.

Keywords: Medical gas systems; carbon dioxide; internet of things; low-cost sensor (Siriraj Med J 2026;78(9):695-708)

INTRODUCTION

In hospital environments, improper levels of medical gases such as oxygen and carbon dioxide may pose significant health risks to healthcare personnel. Elevated carbon dioxide concentrations may cause adverse physiological effects, including respiratory acidosis, dizziness, and loss of consciousness, depending on exposure concentration and duration. In contrast, oxygen-deficient atmospheres may pose a direct risk of hypoxia, whereas oxygen-enriched atmospheres above 23.5%Vol increase the risk of accelerated combustion and fire.[1] Continuous monitoring is therefore essential to ensure occupational safety, particularly in confined medical gas storage areas. According to the Occupational Safety and Health Administration (OSHA), the permissible exposure limit for carbon dioxide is 5,000 ppm as an 8-hour time-weighted average, while short-term exposure to higher concentrations may cause adverse physiological effects.[2]

Medical gas systems are critical components of hospital infrastructure and are regulated by standards such as NFPA 99: Health Care Facilities Code, which provides requirements for the storage, distribution, alarm systems, and safe operation of medical gas systems according to the type of gas system and facility risk category.[3] These systems encompass the production, storage, distribution, and control of medical gases to ensure safe delivery for patient care. In addition to installed medical gas safety systems, continuous environmental monitoring of gas concentrations within storage areas may provide supplementary information on local environmental conditions and potential gas leakage.

Occupational safety frameworks from the World Health Organization emphasize the importance of safe working environments and risk prevention strategies for healthcare workers, including engineering controls and environmental monitoring where hazardous exposure may occur. Previous research conducted at Siriraj Hospital has also highlighted the importance of monitoring hazardous medical gases in hospital environments by evaluating ethylene oxide exposure and determining safe contact periods for healthcare personnel, reinforcing the need for effective environmental gas monitoring systems.[4] Medical gas storage rooms are typically enclosed spaces with limited ventilation and contain large numbers of gas cylinders, including oxygen, nitrous oxide, carbon dioxide, and medical air. Biomedical engineers and maintenance personnel are required to enter these areas regularly to inspect equipment and monitor environmental conditions, often spending extended periods inside. In the presence of undetected gas leaks or abnormal gas concentrations, personnel may be exposed to hazardous conditions with potentially serious health consequences.

Medical gases, particularly oxygen and carbon dioxide, have well-documented physiological effects depending on concentration and duration of exposure. Oxygen deficiency may result in hypoxia and impaired physiological function, whereas oxygen-enriched atmospheres increase the risk of accelerated combustion and fire. Elevated carbon dioxide concentrations may cause respiratory acidosis and adverse neurological effects, including dizziness, impaired consciousness, and, at sufficiently high concentrations, loss of consciousness.[5,6]

Commercial gas monitoring instruments are available for various applications; however, their configurations, monitoring capabilities, certification requirements, and costs vary substantially. Recent studies have explored low-cost gas sensing technologies based on semiconductor, electrochemical, and non-dispersive infrared (NDIR) principles. However, most existing systems are limited to single-parameter measurements or lack real-time monitoring capability in confined hospital environments. Furthermore, the high cost of commercial devices limits their widespread implementation in routine hospital safety monitoring.[7-10]

Previous studies have primarily focused on the development and evaluation of individual gas sensing technologies or single-gas monitoring systems. In contrast, the proposed system was specifically designed for hospital medical gas storage rooms by integrating simultaneous monitoring of carbon dioxide, oxygen, temperature, and relative humidity with IoT-based real-time remote visualization and a visual warning function into a low-cost prototype. This integrated approach provides a practical solution for continuous environmental safety monitoring in confined hospital gas storage areas, thereby addressing an important gap in previous monitoring systems.

Therefore, this study aimed to develop and evaluate a low-cost prototype device for real-time monitoring of medical gas levels in hospital storage rooms using Internet of Things (IoT) technology. Recent studies have demonstrated the growing application of IoT technologies for hospital environmental and air quality monitoring, highlighting their potential to provide continuous surveillance, real-time alerts, and improved occupational safety in healthcare settings.[11] The proposed system enables continuous monitoring of oxygen, carbon dioxide, temperature, and relative humidity, with real-time data transmission and alert capability. This system is designed to improve safety and reduce the risk of hazardous gas exposure among healthcare personnel.

MATERIALS AND METHODS

Materials

The prototype system was developed to provide low-cost monitoring of medical gases and environmental conditions, including carbon dioxide (CO_2), oxygen (O_2), room temperature (T), and relative humidity (RH). Commercially available sensors and open-source microcontroller platforms were selected to reduce development cost while maintaining acceptable measurement performance.

An Arduino Mega 2560 microcontroller was used as the main controller for sensor data acquisition and system operation. The controller was selected because of its compatibility with multiple sensors, stable performance, and ease of programming.

For wireless data communication, an AIS NB-IoT module based on the Quectel BC95-B8 chipset with SubMiniature version A (SMA) connector was integrated into the system. This module enabled real-time transmission of measured data to the Magellan IoT cloud platform for remote monitoring and data visualization. NB-IoT communication was selected because of its low power consumption, wide network coverage, and suitability for long-term monitoring applications in hospital environments.

The controller unit and communication module were electrically connected to enable automatic data collection, processing, and online transmission, as illustrated in Fig 1.

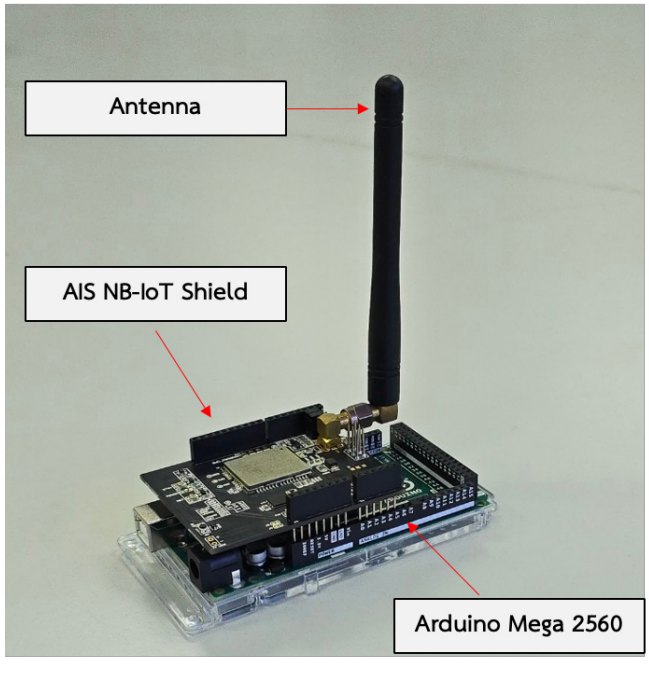


Fig 1. NB-IoT and Arduino Mega 2560 controller were used in this work.

The sensors were selected based on their commercial availability, low cost, suitable measurement range, and compatibility with the microcontroller platform. The selected components for monitoring carbon dioxide, oxygen, temperature, and relative humidity are summarized in Table 1.

The estimated total hardware cost of the developed prototype is presented in Table 2. The system was assembled using commercially available components to minimize cost while maintaining practical functionality for hospital monitoring applications.

Carbon dioxide concentration was measured using the MG-811 sensor, a metal oxide semiconductor sensor designed for CO_2 detection. The sensor was selected because of its wide measurement range and rapid response time, making it suitable for detecting changes in carbon dioxide concentration in enclosed environments.

Oxygen concentration was measured using the SEN0322 electrochemical oxygen sensor (DFRobot). This sensor provides stable oxygen measurements over a range of 0–25 %Vol with adequate resolution for environmental monitoring applications. Electrochemical sensing technology was selected because of its sensitivity and suitability for continuous oxygen monitoring.

Temperature and relative humidity were measured using the DHT22 sensor. This low-cost digital sensor integrates a thermistor and capacitive humidity sensing element, allowing simultaneous monitoring of environmental conditions relevant to gas storage room safety.

An OLED display (SSD1309) was incorporated into the prototype to provide real-time on-site visualization of measured parameters.

Prototype design and system integration

All sensors were integrated with the microcontroller unit to enable simultaneous monitoring of carbon dioxide, oxygen, temperature, and relative humidity, as shown in Fig 2. Sensor outputs were acquired and processed by the Arduino Mega 2560 controller. The processed data were transmitted wirelessly through the AIS NB-IoT

TABLE 1. Selected low-cost sensors used in the prototype.

Sensor	Brand	Parameter	Measurement range
MG-811	Generic	Carbon dioxide (CO_2)	350-10,000 ppm
SKU:SEN0322	DFRobot	Oxygen (O_2)	0-25%Vol
DHT22	Aosong	Temperature (T)	-40°C to 80°C
DHT22	Aosong	Relative humidity (RH)	0-100%

TABLE 2. Estimated hardware cost of the developed prototype.

Component	Approximate cost (USD)
Arduino Mega 2560	51.49
NB-IoT module	37.14
CO_2 sensor (MG-811)	51.49
O_2 sensor (SEN0322)	84.77
Temperature/RH sensor (DHT22)	5.46
OLED display	9.05
Housing and accessories	15.60
Total estimated cost	255.00

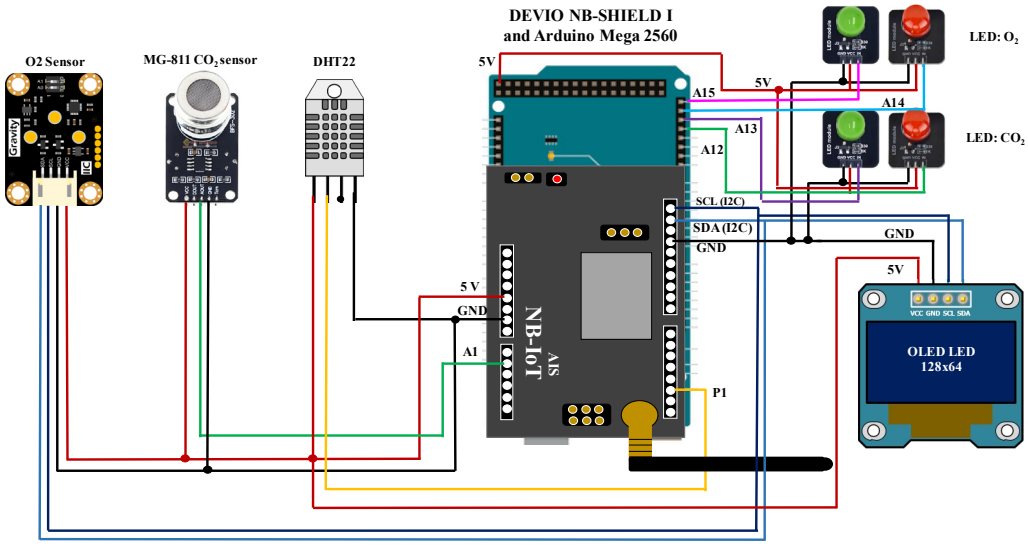


Fig 2. Three sensors were connected to the microcontroller and display system.

communication module based on the Quectel BC95-B8 chipset to the Magellan IoT cloud platform for remote monitoring and data visualization.

The sensing enclosure was designed using Tinkercad (Autodesk) and had external dimensions of 10 cm × 6 cm × 4 cm. The 3D model was subsequently prepared for 3D printing using FlashPrint 5 (Flashforge, USA). The enclosure was designed to accommodate the sensors and associated components. No dedicated ventilation holes were incorporated into the sensor enclosure. Ambient air could enter and exit through the cable-routing opening, allowing air exchange around the sensors. The control enclosure was a commercially available housing modified to accommodate the electronic components, display, cable connections, and antenna. The enclosure design and dimensions are shown in Fig 3.

The prototype was powered by a 12-V DC power supply. The Arduino Mega 2560 was programmed using Arduino IDE version 2.0. The firmware used the corresponding Arduino libraries for the CO_2, oxygen, temperature, and relative humidity sensors. For carbon dioxide measurement, the MG-811 sensor was interfaced using the CO2Sensor library with configuration parameters of 0.99 and 100, and the library calibration function was executed during system initialization. For oxygen measurement, the DFRobot SEN0322 sensor was operated using the manufacturer's I^2C library with a collection number of 10 measurements. Oxygen calibration was performed using ambient atmospheric oxygen concentration of 20.9%Vol as the reference value before the validation experiments.

The sensors acquired measurements at approximately 5-s intervals. The measurements were processed and

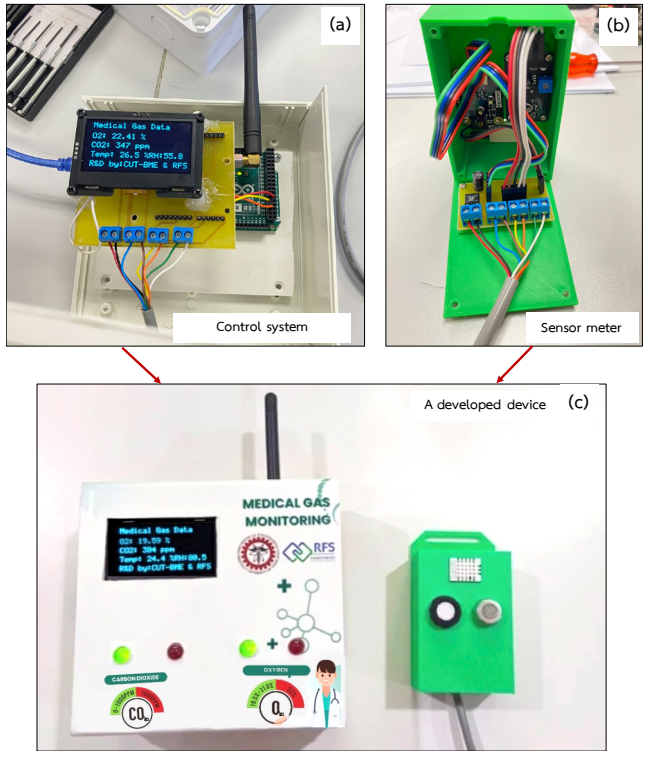


Fig 3. A low-cost device design; (a) inside of control box (b) inside of sensor box and (c) the successfully developed prototype.

averaged by the firmware over the reporting period and transmitted to the Magellan IoT cloud platform at approximately 1-min intervals. During normal operation, the system automatically attempted to reconnect when the NB-IoT connection was interrupted. Data that could not be transmitted during a network interruption were not locally buffered and were therefore lost. For comparative validation, the prototype data were subsequently averaged over 2-min intervals to match the recording interval of

the corresponding reference instrument. A total of 68 paired observations were obtained for the comparative analysis of carbon dioxide, temperature, and relative humidity. Thus, the 2-min interval represented a post-processing aggregation interval for temporal alignment with the reference instrument rather than the original sensor measurement interval.

The visual warning logic was implemented using predefined concentration thresholds. Under normal conditions, the indicator light remained green. The indicator changed to red when the measured carbon dioxide concentration exceeded 5,000 ppm or when the measured oxygen concentration was below 19.5%Vol or above 23.5%Vol. These thresholds were implemented as warning criteria in the prototype; however, their alarm sensitivity and performance were not validated across the relevant concentration ranges.

Sensor data processing and calibration

The raw outputs from the sensors were processed using the manufacturers' recommended Arduino libraries. For carbon dioxide measurement, the MG-811 sensor was interfaced using the CO2Sensor Arduino library. The library converts the analog voltage signal into carbon dioxide concentration (ppm) using an embedded conversion algorithm based on the sensor response characteristics. Prior to data acquisition, the sensor was initialized using the library calibration function to establish the baseline response.

Oxygen concentration was measured using the DFRobot SEN0322 electrochemical oxygen sensor through the manufacturer's I^2C library. Oxygen concentration (%Vol) was obtained directly using the getOxygenData() function after sensor initialization. The sensor was calibrated according to the manufacturer's recommended procedure using ambient atmospheric oxygen concentration (20.9%Vol) as the calibration reference before the validation experiments.

Warning function verification

The warning function was functionally checked during prototype testing. For oxygen monitoring, oxygen gas was introduced into a closed chamber containing the prototype to observe the response of the visual indicator when the measured oxygen concentration increased. For carbon dioxide monitoring, the warning logic was checked by temporarily setting the CO_2 threshold to 1,000 ppm. Carbon dioxide concentration was increased using exhaled breath and combustion smoke, and the indicator changed from green to red when the measured concentration exceeded the temporary threshold.

These tests were performed only to confirm the basic operation of the visual warning logic and were not considered quantitative alarm validation. The use of exhaled breath and combustion smoke did not provide traceable or controlled CO_2 concentrations and may have introduced other environmental factors or interfering substances. Therefore, the response, sensitivity, and accuracy of the deployed 5,000-ppm CO_2 alarm threshold were not established in this study. Validation of alarm performance using certified CO_2 concentrations across the relevant operating range and at the 5,000-ppm threshold is required in future work.

Prototype validation

Prior to field deployment, the developed prototype was validated against standard reference instruments to assess measurement performance.

Oxygen concentration was evaluated separately using a $MaxO_2$+ AE oxygen analyzer (Maxtec, USA; model R217P72) as the reference instrument. The analyzer has a measurement range of 0–100% O_2 and a resolution of 0.1% O_2. According to the manufacturer's specifications, its total accuracy is ±3% of the actual oxygen level over the full operating temperature range, while accuracy and linearity are specified as ±1% of full scale under constant temperature, relative humidity, and pressure when calibrated at full scale. The analyzer uses a Max-250 series galvanic fuel-cell oxygen sensor and has a response time of approximately 15 s to reach 90% of the final value at 23 °C.

Before the validation measurements, the $MAXO_2$+ AE was calibrated to ambient air (20.9% O_2) using the instrument's one-touch calibration function, following the manufacturer's recommended procedure. No warm-up time was required according to the manufacturer's specifications. The prototype and reference analyzer were operated simultaneously, and their measurements were synchronized and compared at 1-min intervals.

Carbon dioxide concentration, temperature, and relative humidity were evaluated using an OIZOM Polludrone V6 air quality monitoring system (serial number N002P0001) available at Silpakorn University. The reference instrument was configured with the OZCO2_1, OZTEMP_1, and OZHUM_1 sensor modules for CO_2, temperature, and relative humidity measurements, respectively. According to the manufacturer's specifications, the CO_2 sensor uses non-dispersive infrared (NDIR) technology and has a measurement range of 0–5,000 ppm, a resolution of 1 ppm, a minimum detection level of 400 ppm, and a reported drift of ±5 ppm/year. The temperature sensor has a range of −40 to 125 °C with a resolution of 0.01 °C, while the

relative humidity sensor has a range of 0–100% RH with a resolution of 0.10% RH. The reference instrument was operated side-by-side with the prototype under ambient environmental conditions. For the instrument used in this study, raw measurements were recorded at 2-min intervals and transmitted to the manufacturer's cloud platform. The recorded data could also be downloaded as averaged datasets over longer intervals; however, the 2-min raw measurements were used as the reference observations in the present comparative analysis. The prototype measurements, originally acquired at shorter intervals, were subsequently aggregated to 2-min intervals to match the reference recording interval. Following temporal alignment, a total of 68 paired observations were included in the comparative analysis of CO_2, temperature, and relative humidity. These paired observations were obtained from a continuous validation sequence and were therefore treated as time-series paired observations rather than independent samples. The reference measurements covered ranges of 325.06–468.53 ppm for CO_2, 35.41–37.08 °C for temperature, and 57.34–61.65% RH for relative humidity. For oxygen validation, 11 paired observations were obtained from simultaneous measurements with the reference oxygen analyzer.

The validation was conducted under ambient environmental conditions to assess the agreement between the prototype and the reference instruments prior to practical deployment. Controlled validation using certified gas concentrations near the alarm thresholds was beyond the scope of the present study. Future studies will include controlled chamber experiments using certified gas concentrations to further evaluate the system under abnormal gas conditions.

The experimental setup for environmental parameter validation is shown in Fig 4.

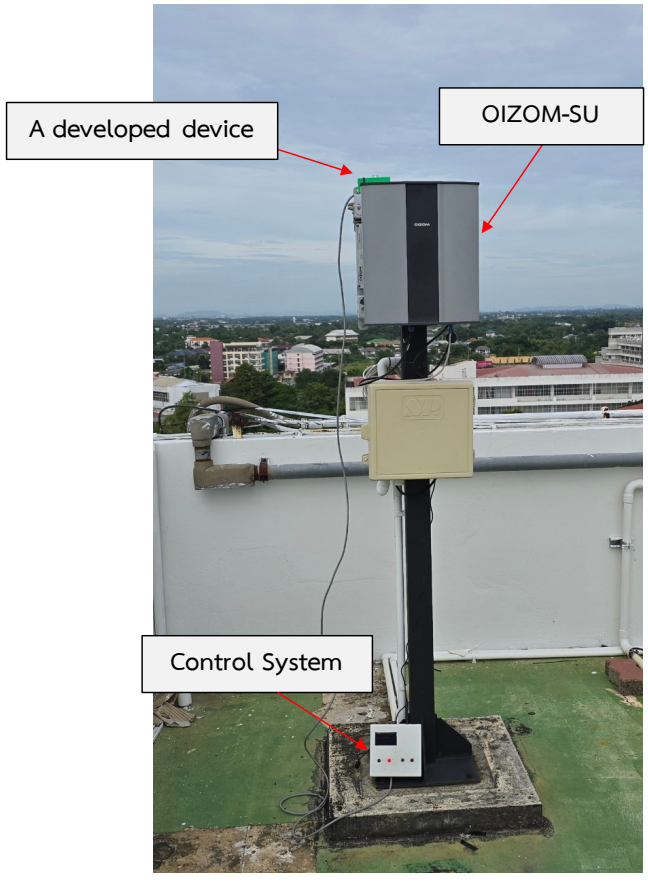


Fig 4. Experimental setup for side-by-side validation of carbon dioxide, temperature, and relative humidity measurements using the prototype and OIZOM reference instrument.

Statistical analysis

The measurement performance of the developed prototype was evaluated by comparing its measurements with those obtained from the reference instruments. Agreement between the prototype and reference measurements was assessed using the normalized root mean square difference (nRMSD) and normalized mean bias difference (nMBD). The nRMSD was used to describe the magnitude of overall measurement deviation, whereas the nMBD was used to describe systematic overestimation or underestimation relative to the reference measurements.

For each paired observation, xi represents the prototype measurement, yi represents the corresponding reference measurement, and N represents the number of paired observations. The root mean square difference (RMSD) and mean bias were calculated from the paired measurements. For normalization, the denominator was the arithmetic mean of the reference measurements ($\bar{y}$) for the corresponding validation dataset. Thus, nRMSD was calculated as RMSD divided by $\bar{y}$ and expressed as a percentage, while nMBD was calculated as mean bias divided by $\bar{y}$ and expressed as a percentage (as shown in Equations 1 and 2).[12] This normalization expresses the measurement deviation relative to the average reference measurement and allows comparison of relative measurement deviations across parameters with different units and scales.

Because the validation data were collected as time-series measurements under ambient conditions, the paired observations were not considered statistically independent. Therefore, nRMSD and nMBD were interpreted as descriptive measures of agreement rather than evidence of alarm performance. Uncertainty was estimated using a moving-block bootstrap procedure to account for temporal dependence in the paired observations, and 95% bootstrap confidence intervals were calculated for nRMSD and nMBD. The 95% limits of agreement

(LoA) were calculated from the paired measurement differences as the mean bias ± 1.96 standard deviations of the differences.

$$nRMSD = \frac{\sqrt{\frac{\sum_{i=1}^{N}(x_i - y_{i.})^2}{N}}}{\bar{y}} \times 100\% \quad (1)$$

$$nMBD = \frac{\frac{\sum_{i=1}^{N}(x_i - y_i)}{N}}{\bar{y}} \times 100\% \quad (2)$$

RESULTS

Validation of environmental parameters

Carbon dioxide, temperature, and relative humidity data were recorded at 2-min intervals and compared with measurements obtained from the OIZOM air quality monitoring system. Fig 5 illustrates the temporal variations and agreement between the developed prototype and the reference instrument.

The results presented in Fig 5 demonstrate that the developed prototype was capable of tracking temporal variations in environmental parameters with trends comparable to those of the reference instrument. Although some deviations were observed, particularly in carbon

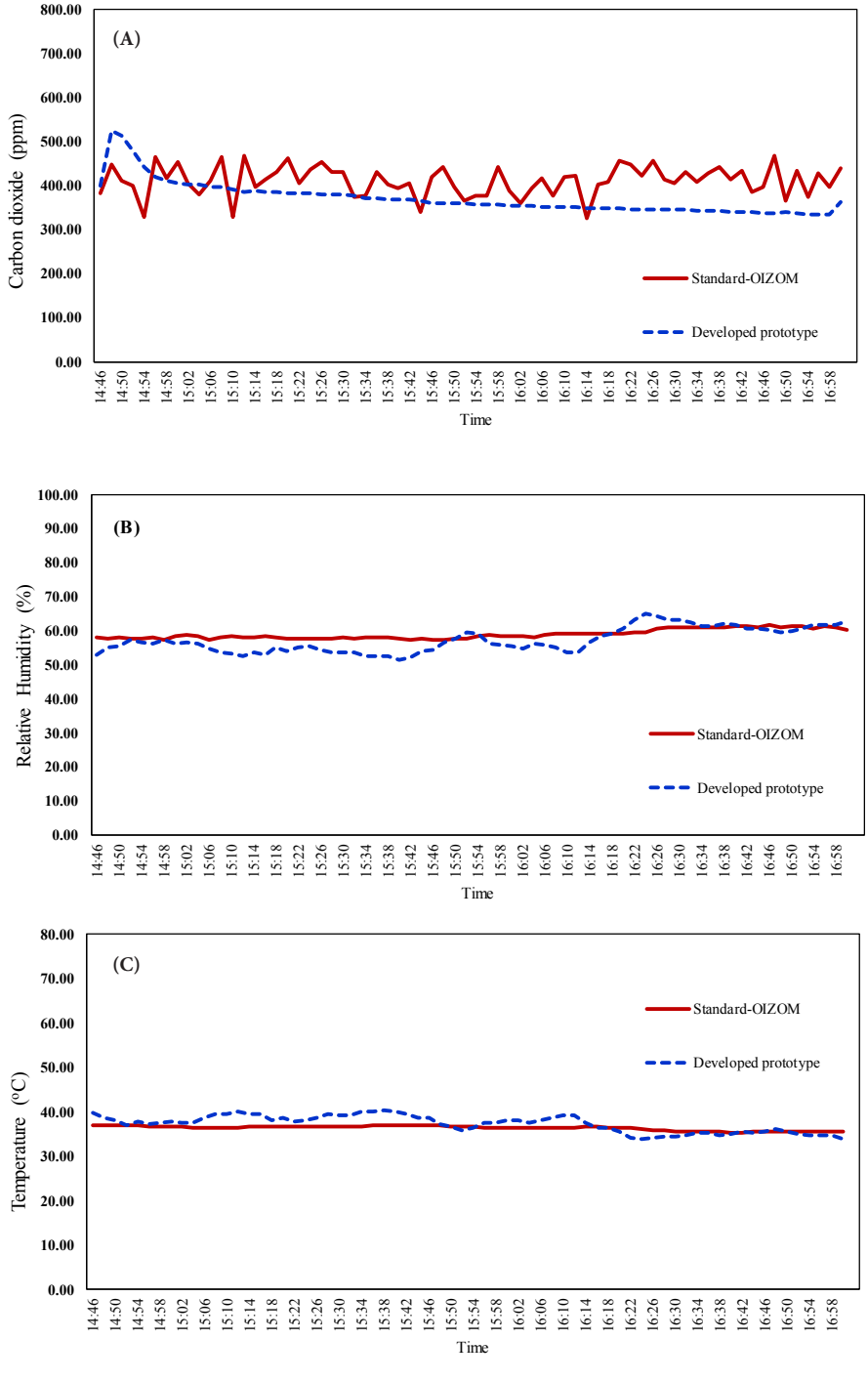


Fig 5. Comparison between prototype and OIZOM reference instrument for (A) carbon dioxide, (B) relative humidity, and (C) temperature.

dioxide measurements, the prototype showed consistent response behavior throughout the monitoring period.

For carbon dioxide measurement (Fig 5A), the reference instrument recorded concentrations ranging from 325.06 to 468.53 ppm, with a mean concentration of 410.71 ppm, while the prototype measurements ranged from 333.02 to 525.29 ppm. The prototype exhibited greater measurement variability and larger deviations compared with the reference system. The nRMSD and nMBD were 15.47% and -9.70%, respectively, corresponding to an absolute RMSE of 63.52 ppm and a mean bias of -39.85 ppm. Using a moving-block bootstrap to account for temporal dependence, the 95% confidence intervals were approximately 12.96-17.66% for nRMSD and -14.17 to -5.30% for nMBD. The negative mean bias indicates that the prototype tended to underestimate carbon dioxide concentration relative to the reference instrument. These results indicate preliminary agreement under the observed ambient concentration range and should not be interpreted as validation of CO_2 alarm performance at the predefined 5,000-ppm threshold.

In contrast, relative humidity and temperature measurements (Fig 5B and Fig 5C) demonstrated relatively close agreement with the reference instrument. The lower normalized RMSD (nRMSD) and normalized MBD (nMBD) values suggest that the DHT22 sensor provided stable environmental monitoring performance under ambient operating conditions. Minor differences between the datasets may be attributed to sensor positioning, airflow variation, and differences in sensor response time between the prototype and the reference device.

For relative humidity, the normalized RMSD (nRMSD) and normalized MBD (nMBD) were 5.39% and -3.00%, respectively, corresponding to an absolute RMSE of 3.18 %RH and a mean bias of -1.77 %RH. The negative mean bias indicates a slight underestimation of relative humidity compared with the reference instrument.

For temperature, the normalized RMSD (nRMSD) and normalized MBD (nMBD) were 4.80% and 2.54%, respectively, corresponding to an absolute RMSE of 1.75 °C and a mean bias of 0.92 °C. The positive mean bias indicates a slight overestimation of temperature relative to the reference instrument.

Validation of oxygen measurement

Oxygen concentration data were recorded separately at 1-min intervals and compared with a standard oxygen analyzer. Fig 6 shows strong agreement between the developed prototype and the reference analyzer. The normalized RMSD (nRMSD) and normalized MBD (nMBD) were 0.085% and 0.283%, respectively, corresponding to an absolute RMSE of 0.017 %Vol and a mean bias of 0.056 %Vol.

The oxygen monitoring results shown in Fig 6 demonstrated very strong agreement between the developed prototype and the reference oxygen analyzer. The low normalized RMSD (0.085%) and normalized MBD (0.283%) values indicate good agreement between the prototype and the reference analyzer under ambient environmental conditions.

The measured oxygen concentrations remained close to ambient atmospheric levels with minimal fluctuation, and the prototype successfully reproduced these variations in a manner consistent with the reference instrument. These results suggest that the developed system has the potential for continuous oxygen monitoring under normal ambient conditions.

To further verify the response of the oxygen sensor under oxygen-enriched conditions, an additional functional verification was performed by introducing oxygen gas

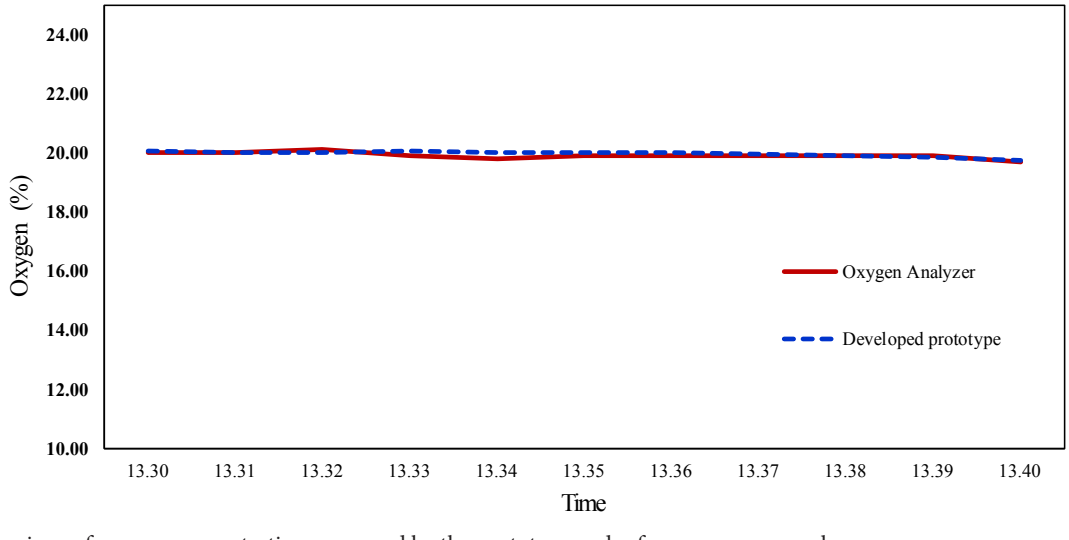


Fig 6. Comparison of oxygen concentration measured by the prototype and reference oxygen analyzer.

into a closed chamber. A total of 15 paired observations were compared with the reference oxygen analyzer. The prototype showed good agreement with the reference instrument, with a normalized RMSD (nRMSD) of 2.35%, a normalized MBD (nMBD) of -2.33%, an absolute RMSE of 0.512 %Vol, and a mean bias of -0.508 %Vol. However, the oxygen concentration did not exceed the upper alarm threshold of 23.5 %Vol, and no oxygen-deficient condition below 19.5 %Vol was tested. Therefore, these results demonstrate the prototype's ability to track increasing oxygen concentrations under the tested conditions but do not validate the upper or lower oxygen alarm thresholds or establish alarm sensitivity, response time, or false-negative performance.

Although the oxygen concentration did not exceed the upper alarm threshold (23.5 %Vol), the results confirmed that the prototype responded consistently to increasing oxygen concentrations under oxygen-enriched conditions.

The overall measurement performance of the developed prototype compared with the reference instruments is summarized in Table 3.

Table 4 summarizes the characteristics of the validation datasets and the agreement between the prototype and reference instruments. The table provides the observed reference measurement ranges, number of paired observations, reference instrument specifications, and 95% limits of agreement for each measured parameter. The results indicate that the validation data covered only ambient environmental conditions, with relatively narrow concentration ranges for carbon dioxide, temperature, and relative humidity, while the oxygen measurements were also obtained primarily under ambient conditions. These characteristics should be considered when interpreting the measurement agreement and the applicability of the results to conditions outside the tested ranges.

Field deployment in hospital environment

Following laboratory validation, the prototype was installed in a medical gas storage room at a practical hospital, as shown in Fig 7. The prototype was operated for approximately one week to demonstrate its performance under routine operating conditions. The sensing unit

TABLE 3. Normalized and absolute measurement errors of the developed prototype compared with the reference instruments.

Parameter	nRMSD (%)	nMBD (%)	RMSE	Mean Bias
Carbon dioxide (air)	15.47	-9.70	63.52 ppm	-39.85 ppm
Oxygen (air)	0.085	0.283	0.017%Vol	0.056%Vol
Oxygen (add gas)	2.35%	−2.33%	0.512%Vol	-0.508%Vol
Temperature	4.80	2.54	1.75°C	0.92 °C
Relative humidity	5.39	-3.00	3.18%RH	-1.77%RH

TABLE 4. Summary of validation data characteristics and agreement between the prototype and reference instruments.

Parameter	Reference measurement range	Paired observations (n)	Reference instrument specifications	95% limits of agreement
Carbon dioxide	325.06-468.53 ppm	68	0-5,000 ppm; resolution 1 ppm; drift ±5 ppm/year	-137.53 to 57.82 ppm
Oxygen	19.70-20.10%Vol	11	0-100% O_2; resolution 0.1% O_2; accuracy ±3% of actual O_2	-0.128 to 0.241 %Vol
Temperature	35.41-37.08 °C	68	-40-125 °C; resolution 0.01 °C	-2.00 to 3.85 °C
Relative humidity	57.34-61.65 %RH	68	0-100% RH; resolution 0.10% RH	-6.98 to 3.43 %RH

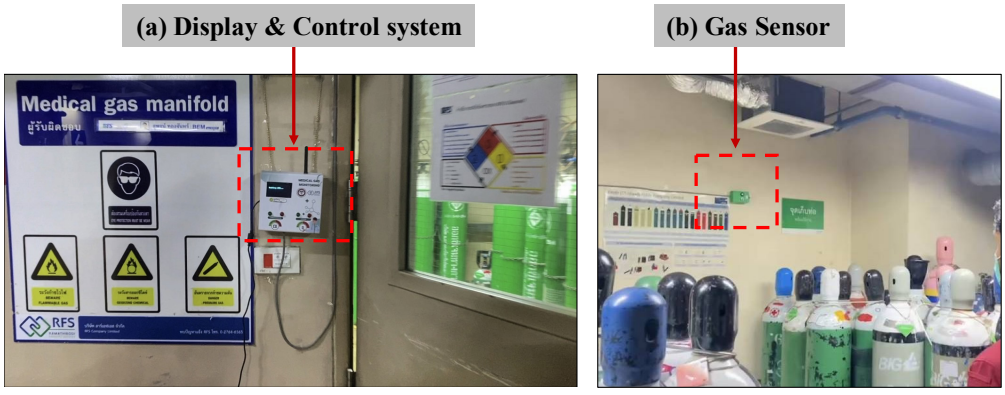


Fig 7. Installation of the developed monitoring system in a medical gas storage room at practical hospital.

was mounted on the wall at a height of approximately 1.8 m above the floor, close to the medical gas cylinder storage area. The location was selected as a practical monitoring point near the potential gas-release source while maintaining a fixed position that did not interfere with routine cylinder handling and storage operations. The storage room was a relatively enclosed space equipped with a single ventilation fan. The selected location was intended to provide representative monitoring of the local room environment; however, it was not intended to characterize spatial gas concentration gradients throughout the room. Gas distribution following a release may vary depending on the release location, cylinder arrangement, room geometry, and ventilation conditions. The placement was considered in the context of the need for ventilation and gas monitoring in enclosed medical gas storage areas. However, the present study did not evaluate spatial gas distribution or determine an optimal sensor location for the entire storage room. The deployment therefore demonstrated monitoring operation at the selected location rather than spatially resolved gas monitoring throughout the storage room.

The system successfully transmitted measurement data in real time via the NB-IoT network. Collected data were displayed on the Magellan IoT platform, allowing remote monitoring of carbon dioxide, oxygen, temperature, and relative humidity values (Fig 8). The platform also enabled historical data review and continuous observation of environmental conditions.

No reference instrument was operated alongside the prototype during the hospital deployment. Therefore, this phase of the study was considered an operational demonstration rather than field validation of sensor measurement performance. The purpose of the deployment was to demonstrate the practical operation of the proposed monitoring system, including real-time environmental monitoring and NB-IoT communication under routine hospital conditions. The prototype was operated for approximately one week and demonstrated measurement acquisition and transmission of environmental data to the cloud platform during the deployment period. As this deployment was intended primarily to demonstrate practical system operation rather than quantitative sensor validation, the measurements obtained during

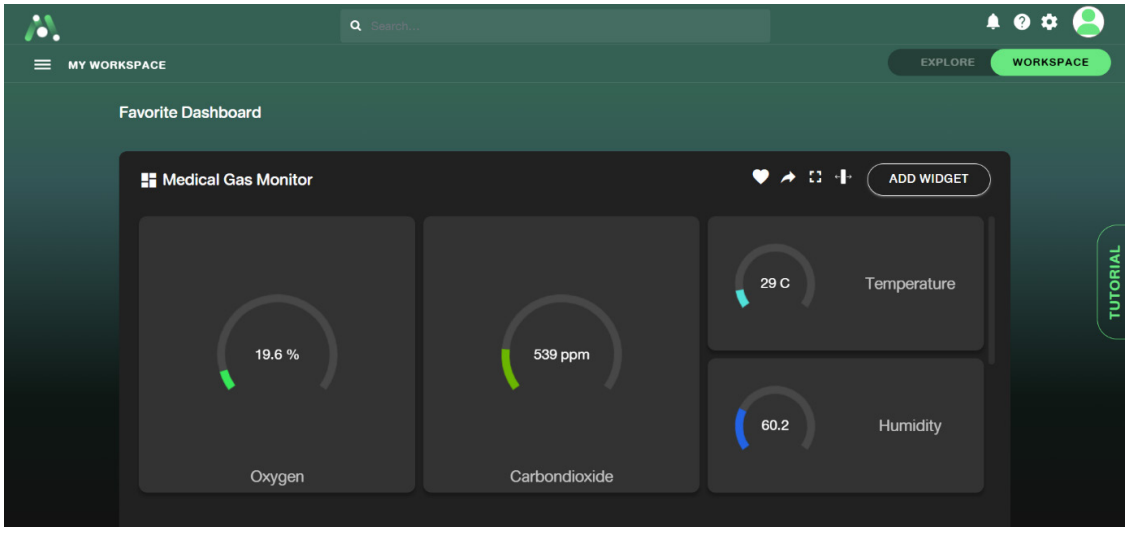


Fig 8. Real-time monitoring dashboard on the Magellan IoT platform.

this phase were not used for statistical comparison with a reference instrument. The hospital deployment therefore provides a preliminary demonstration of the feasibility of implementing the proposed monitoring system under routine hospital conditions.

Alert function performance

The developed system demonstrated the basic operation of the real-time visual warning function during prototype testing. Under normal test conditions, the indicator light remained green when the measured gas concentrations were below the predefined warning thresholds. When the measured values exceeded the programmed thresholds during functional testing, the indicator changed from green to red.

DISCUSSION

The present study demonstrated that the developed low-cost IoT-based monitoring system was capable of measuring oxygen, carbon dioxide, temperature, and relative humidity with good agreement with the reference instruments under ambient environmental conditions and was capable of real-time monitoring of oxygen, carbon dioxide, temperature, and relative humidity in hospital environments. Among all tested parameters, oxygen concentration showed the highest agreement with the reference instrument, whereas carbon dioxide measurements exhibited greater deviation but maintained similar temporal trends.

In practical hospital settings, monitoring temporal changes in gas concentration may provide useful supplementary information even when measurement accuracy is limited. Although the carbon dioxide sensor showed higher measurement error, its measurements followed temporal variations in concentration under the tested ambient conditions. However, its performance for quantitative monitoring near the 5,000-ppm alarm threshold was not established. This limitation is particularly relevant for enclosed medical gas storage rooms, where ventilation conditions and potential gas leakage may result in changes in indoor gas concentrations.

The high agreement observed for oxygen measurement under ambient environmental conditions suggests that the proposed system has the potential for continuous oxygen monitoring. However, additional validation under oxygen concentrations near and beyond the alarm thresholds is required before confirming alarm performance under abnormal oxygen conditions.

Conventional studies have reported the use of low-cost gas sensing technologies based on semiconductor, electrochemical, and non-dispersive infrared (NDIR) principles. Recent reviews have also highlighted the growing adoption of Internet of Things (IoT)-enabled environmental monitoring systems in hospitals, demonstrating their ability to provide continuous surveillance, remote data access, automated alerts, and improved environmental safety.[13,14] However, most reported systems have primarily focused on general indoor environmental monitoring (e.g., temperature, humidity, and indoor air quality) or single-parameter sensing, with limited attention to continuous monitoring of medical gas storage rooms where multiple gas and environmental parameters must be monitored simultaneously. In contrast, the present system integrates oxygen, carbon dioxide, temperature, and relative humidity sensing with real-time wireless data transmission through an IoT platform, providing a practical and low-cost solution for hospital safety monitoring.

The successful installation and operation of the prototype in a medical gas storage room at a practical hospital further demonstrate its practical feasibility. Real-time remote monitoring may facilitate continuous observation of environmental conditions and provide timely information to support safety management, improve response time, and strengthen occupational safety within hospital facilities.

The visual warning system may improve decision-making by providing immediate visual alerts when predefined alarm thresholds are exceeded before personnel enter enclosed storage areas.

In addition, the use of commercially available low-cost components may make this approach potentially attractive for hospitals in resource-limited settings, where access to conventional imported monitoring systems may be constrained by cost or procurement requirements. The estimated prototype component cost was lower than the listed prices of the commercial monitoring systems included in Table 5; however, these systems differ in sensor configurations, monitoring capabilities, certification, and procurement conditions. Therefore, the cost comparison should be interpreted as an indicative comparison of listed equipment prices rather than a like-for-like assessment of total system cost.

This study has several limitations. First, validation was conducted under ambient environmental conditions using side-by-side comparison with reference instruments rather than controlled gas concentrations. Consequently, the performance of the proposed system at carbon dioxide concentrations near the alarm threshold (5,000 ppm) and oxygen concentrations outside the normal environmental range (19.5–23.5%Vol) was not evaluated. Therefore, the present findings should be interpreted as evidence

TABLE 5. Approximate cost comparison between the developed prototype and commercially available systems.

System	Type of gas	Approximate Initial Cost (USD)	Real-time Monitoring
Developed prototype	CO_2, O_2, Temperature, RH	255	Yes
CO260 Carbon Dioxide Meter[15]	CO_2, CO	800	No
Sky2000 Multi Gas Detector[16]	CO_2 CO O_2 NH_3	10,000	No
Innova 1314 Multi-Gas Analyzer[17]	Multi-gas	40,000	No

Note: Prices shown are indicative listed prices obtained from the respective vendors or publicly available sources at the time of comparison and may vary according to sensor configuration, accessories, calibration, certification, shipping, installation, maintenance, and procurement conditions. The compared systems are not necessarily equivalent in terms of gas coverage, data logging, remote monitoring, certification, or service support.

of preliminary validation under ambient environmental conditions rather than comprehensive performance validation across the full operating range of the sensors. In addition, repeatability, response time, and long-term sensor stability were not investigated. Future studies should include controlled chamber experiments using certified gas concentrations to further evaluate alarm performance under abnormal environmental conditions.

Future studies should focus on improving carbon dioxide sensor calibration, evaluating long-term field performance, integrating automated alert systems such as mobile notifications, and expanding the platform to monitor additional medical gases.

CONCLUSIONS

The developed low-cost IoT-based medical gas monitoring system demonstrated preliminary measurement agreement with reference instruments for oxygen, carbon dioxide, temperature, and relative humidity under ambient environmental conditions. The prototype also demonstrated the feasibility of real-time data transmission and environmental monitoring in a hospital medical gas storage room. However, validation was limited to ambient conditions and did not cover the predefined alarm thresholds or the full intended decision range. Therefore, the present findings support the feasibility of the prototype as a low-cost environmental monitoring platform but do not establish its suitability as a safety alarm device. Further validation using controlled and certified gas concentrations, including concentrations around the relevant alarm thresholds, is required before safety-related deployment can be established.

Data Availability Statement

The data that support the findings of this study are not publicly available due to institutional and safety considerations. However, the data are available from the corresponding author upon reasonable request.

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Conflict of Interest

The research team declares no conflict of interest in this study.

Registration Number of Clinical Trial

Not applicable.

Author Contributions

Conceptualization and methodology, P.C and N.K.; Investigation, T.S and S.B.; Formal analysis, Visualization and writing – original draft, N.K. and P.C; Writing – review

and editing, S.B.; Supervision, P.C. All authors have read and agreed to the final version of the manuscript.

Use of Artificial Intelligence

During the preparation of this manuscript, the authors used ChatGPT to improve the language and readability of the manuscript. The authors subsequently reviewed and edited the generated content as necessary and take full responsibility for the final version submitted for publication.

Institutional Review Board Statement

This study was approved by the Human Research Ethics Committee of Christian University of Thailand (Approval No. น. 08/2568).

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