Development and Evaluation of a Portable Dilution-Based Gas Mixer System for On-Site Calibration of Low-Cost Sensors in Ambient Air Monitoring

Rudi Anggoro Samodro[1,*], Gigin Ginanjar[1], Yonan Prihhapso[1],
Muhammad Rizky Mulyana[1], Miftahul Munir[1], Dinar Nurcahyono[1],
Bondan Dwisetyo[1]

[1]Research Center for Equipment Manufacturing Technology, National Research and Innovation Agency of Indonesia (BRIN), Tangerang Selatan, Indonesia 15314

*Author to whom correspondence should be addressed:
E-mail: rrud001@brin.go.id

(Received May 28, 2025; Revised January 08, 2026; Accepted March 10, 2026)

Abstract: Low-cost sensors are increasingly being used to measure various fields, including environmental monitoring. However, their accuracy relies on regular calibration using known gas mixture concentrations. This study presents the development and evaluation of a portable dilution-based gas mixture (DGM) system designed for on-site calibration of low-cost oxygen sensors. The system utilizes 99.999 %mol/mol oxygen and nitrogen gases blended via two portable mass flow controllers, operated by a LabVIEW interface. Calibration was performed at 30 %mol/mol, 60 %mol/mol, and 90 %mol/mol oxygen concentrations, and validated using certified reference gas mixtures. The observed measurement errors were 0.046 %mol/mol, –0.002 %mol/mol, and –1.952 %mol/mol, respectively. These results confirm high accuracy and repeatability, aligning with the Indonesian standard SNI 9178:2023. This system provides a cost-effective, traceable, and field-deployable solution for sensor calibration, which is particularly beneficial for expanding the monitoring of ambient air quality in resource-limited settings.

Keywords: calibration; dilution; gas mixture; low-cost sensor; SNI 9178:2023

1. Introduction

Low-cost sensors or microsensors are affordable devices designed to measure various fields. These sensors are increasingly being applied in environmental monitoring1), home and building automation2), agricultural system automation3), wearable technology for health monitoring4), and Internet of Things (IoT) systems5). For instance, a low-cost methane sensor has been demonstrated for industrial safety monitoring and gas leak detection applications6). In addition, UAV-based low-cost sensors have been developed to assess structural reliability, avionics performance, and component lifetime7,8). Combined with Android applications, these sensors have also been developed to support survey and mapping work9,10). Low-cost sensors play a significant role in enabling real-time data acquisition11). They also consume low power12), making them a perfect solution for mobile deployment13) in environmental monitoring and energy management14). Their energy-efficient architecture facilitates deployment in remote areas powered by batteries or renewable sources, i.e., solar panels, allowing long-term autonomous operation with low maintenance15,16). In smart building systems, these sensors support Heating, Ventilation, and Air Conditioning (HVAC) optimization, contributing to reduced energy waste17,18). Moreover, in renewable energy systems, they monitor key atmospheric variables that influence the performance of solar and wind technologies19,20). As part of smart city infrastructures, low-cost sensors assist in tracking air pollutants and climate indicators, supporting energy-efficient and environmentally conscious urban planning21,22). In agriculture and industry, their utility extends to real-time irrigation optimization and emissions control, enabling more sustainable resource use23,24).

Recently, these low-cost sensors have been studied, and several limitations have been pointed out, namely sensors cross sensitivity or limited sensors selectivity, temperature and humidity interferences, long-term stability, or sensor drift. To address this limitation, different methods are being developed, like the adoption of machine learning on the monitoring data25,26). Another study used a nano-material approach to develop a new type of sensor to

Cite: R. Samodro et al., "Development and Evaluation of a Portable Dilution-Based Gas Mixer System for On-Site Calibration of Low-Cost Sensors in Ambient Air Monitoring". Evergreen, 13 (01) 387-395 (2026). https://doi.org/10.5109/7411073.

improve the selectivity based on thermal effects[27], while other research focuses on the quality assurance of the sensor readings and the framework used to evaluate the low-cost sensor[28,29]. Despite their widespread adoption due to affordability, scalability, and deployment flexibility, low-cost air quality sensors exhibit inherent limitations in accuracy, stability, and response characteristics, necessitating calibration strategies ranging from data-driven algorithmic approaches[30,31] to controlled and metrologically grounded calibration frameworks[32,33]. The reliability of low-cost sensors is often compromised by sensor drift, environmental interference, and manufacturing variability. Therefore, selecting these sensors for specific applications requires a careful balance between cost-efficiency and measurement precision[34]. Moreover, periodic calibration using known traceable standards is essential for ensuring sensor performance, especially when it is deployed for regulatory, industrial, or scientific purposes.

Generally, calibration is performed by comparing sensor readings with those from high-accuracy reference instruments or Certified Reference Material (CRM) of gas mixtures under controlled conditions. Primary Reference Gas Mixtures are typically prepared using primary gravimetric blending methods to ensure high precision and traceability. The process involves a precise mass-based combination of pure gases, making the resultant mixture directly traceable to SI units through national mass standards[35,36]. Alternatively, dynamic dilution methods based on ISO 6145, such as orifice-based metering or mass flow-controlled blending, can produce Calibration Gas Mixtures (CGM) at target concentrations using intermediate mixtures and high-purity diluents[37]. Verification by analytical techniques, i.e. gas chromatography ensures that the final composition remains within its certified uncertainty range. These reference gases are indispensable for calibrating gas analyzers and sensors across research, industry, and environmental monitoring sectors[38].

Despite the widespread use of low-cost sensors, relatively few studies have focused on the development of portable, traceable gas calibration systems that can be deployed on-site, especially in resource-constrained settings. Existing calibration systems are often stationary, expensive, or lack interoperability with locally available instruments. Previous research on portable calibration systems has been conducted, but for specific objects like Volatile Organic Compound (VOC) using palladium catalyst[39], or gas chromatograph[40] and methane using semiconductor sensor[41], or tunable diode laser absorption spectroscopy[42]. This research addresses this critical gap by proposing a field-deployable dilution-based calibration device validated with CGM and specifically designed to comply with Indonesian National Standard SNI 9178:2023[43]. This portable dilution-based gas calibration system is targeted at low-cost sensor performance verification by Indonesian national calibration standards, offering both scientific and practical relevance for broader deployment in ambient air quality monitoring networks.

Specifically, the objectives are as follows: To design and construct a dilution-based gas mixture (DGM) system using high-purity oxygen (O_2) and nitrogen (N_2) gases mixed via two mass flow controllers for generating accurate gas concentrations in the range of 0 %mol/mol to 100 %mol/mol. To automate the gas mixing and calibration process through a LabVIEW-based interface that controls flow settings and acquires real-time sensor data. To evaluate the system calibration performance by testing a low-cost electrochemical oxygen sensor at target concentrations of 30 %mol/mol, 60 %mol/mol, and 90 %mol/mol, and to validate the outputs against certified gas mixtures.

2. Materials and Methods

This section outlines the experimental setup and procedure used to achieve the three research objectives described in the Introduction. The design of the dilution-based gas mixture (DGM) system (Objective 1), automation and control via LabVIEW (Objective 2), and calibration-validation experiments at 30, 60, and 90 %mol/mol (Objective 3) are described to ensure replicability and traceability.

This section also details the construction and operation of the portable DGM system, the calibration procedure, and the validation experiments using CGM. Each component of the methodology is directly linked to the study's goals: Objective 1 highlights the development of the hardware system, Objective 2 focuses on automating calibration using LabVIEW, and Objective 3 addresses validation with reference gases at 30, 60, and 90 %mol/mol.

The system was designed to be modular, portable, and replicable in field environments. Two identical mass flow controllers (MFCs) with a maximum capacity of 100 standard cubic centimeters per minute (sccm) were chosen for their precision and suitability in generating low to mid-range oxygen concentrations relevant to ambient air monitoring. LabVIEW was employed for real-time flow control and data acquisition due to its flexibility and compatibility with the NI USB-6008 interface hardware. A vacuum pump was used for chamber flushing to ensure rapid clearance between measurements and minimize residual gas interference. Calibration timing was standardized at 150 seconds for stabilization and 30 seconds for averaging based on preliminary trials of sensor response behavior.

The calibration of low-cost sensors in this study was conducted in accordance with the national standard SNI 9178:2023, which outlines procedures for verifying sensor accuracy using zero and span gas concentrations. As

Cite: R. Samodro et al., "Development and Evaluation of a Portable Dilution-Based Gas Mixer System for On-Site Calibration of Low-Cost Sensors in Ambient Air Monitoring". Evergreen, 13 (01) 387-395 (2026). https://doi.org/10.5109/7411073.

illustrated in Figure 1, the protocol begins by exposing the sensor to zero gas to determine its offset, followed by a series of span calibrations using at least four concentration points generated via controlled gas dilution. To implement this, a portable DGM system was developed to facilitate the precise mixing of gases for low-cost sensor calibration. The system was specifically designed for oxygen calibration and is schematically represented in Figure 2.

Zero air or zero gas is used to obtain the offset of the sensor reading[44)]. The minimum of four required span concentration points is obtained by regulating the flow rate on the calibrator[45)].

To meet the above requirements, a dilution-based gas mixture system[46)] has been developed to calibrate low-cost gas sensors, specifically an oxygen (O_2) sensor, as illustrated in Figure 2.

This system uses certified gas of O_2 99.999 %mol/mol and N_2 99.999 %mol/mol as the zero gas or the dilution gas. Two identical ranges of MFCs with a maximum capacity of 100 sccm are employed to mix these gases to obtain the required concentration of the gas mixture[47,48)]. A 14-bit NI USB-6008 device controls the MFCs by sending setpoints and simultaneously reading the flow rates. A LabVIEW-based graphical user interface for controlling the system. Additionally, this software also functions as a data acquisition (DAQ) system for the ADC/DAC devices and low-cost sensors.

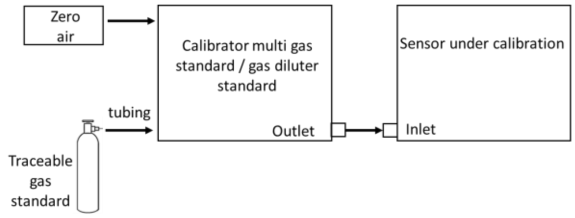

Fig. 1: Schematic calibration of a low-cost sensor according to SNI 9178:2023 using traceable gas standard diluted with zero air at different concentration values[43)]

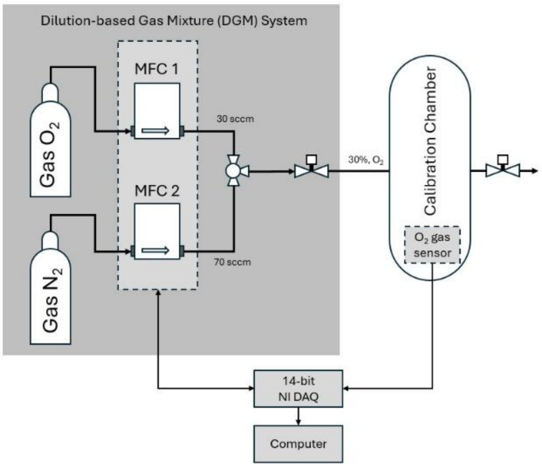

Fig. 2: Schematic of the dilution-based gas mixture system consists of oxygen, nitrogen, and MFCs to obtain the required concentration of the gas mixture

The following simplified Equation 1 is used to obtain a concentration of the gas mixture with a certain value.

$$x = (Q_{O2} / (Q_{O2} + Q_{N2})) \times 100\% \qquad (1)$$

where x is the concentration of O_2 gas mixture generated by the DGM system in % mol/mol, and Q_{O2} and Q_{N2} are the mass flow of the gas from O2 and N2 in sccm. For instance, the above Figure 2 illustrates a configuration of DGM System to produce an O_2 gas mixture with a concentration of 30% by adjusting the MFC flow rates from the O_2 and N_2 cylinders to 30 sccm and 70 sccm, respectively, in accordance with Equation 1.

This mixing model assumes ideal gas behavior, where volumetric flow rates of component gases (O_2 and N_2) are directly proportional to their molar concentrations under steady-state and isothermal conditions. This simplification is widely used in dynamic gas dilution systems due to its practicality and traceability to gravimetric preparation principles. In this system, the flow rates of oxygen (Q_{O2}) and nitrogen (Q_{N2}) are independently controlled via two mass flow controllers, and the resulting concentration (x) defines the oxygen content in the gas mixture in %mol/mol. This numerical model serves a dual role: (1) it defines the system's setpoints to generate target calibration concentrations (e.g., 30%, 60%, 90%), and (2) it forms the theoretical basis for validating the system's performance against CGM. This model allows reliable prediction of oxygen concentrations within acceptable error margins for field-grade calibration systems. The dilution-based gas mixture system developed in this study relies on a simple but robust numerical model to determine the target gas concentration[49,50)]. As shown in Equation 1, the final concentration of the oxygen gas mixture is calculated based on the ratio of flow rates of oxygen and nitrogen, where oxygen acts as the analyte gas and nitrogen serves as the diluent[51)]. This proportional mixing model assumes ideal gas behavior and steady flow conditions within the calibrated range of the mass flow controllers.

The calibration chamber used in this research is equipped with mounting ports at various positions to accommodate low-cost sensors that either cannot be inserted into the chamber or require a specific orientation. Instead of using zero gas to flush out the previous gas, the chamber is connected to a vacuum pump that removes the prior gas efficiently, allowing for the next measurement of different gas concentrations easier[52)].

An electrochemical oxygen sensor, VT650, is employed to evaluate the performance of the DGM System. This sensor has a capacity of 0% to 100% with an accuracy and resolution of 1% and 0.1%, respectively.

In addition, CGMs of O_2 with 3 different concentrations of 30 %mol/mol, 60 %mol/mol, and 90 %mol/mol are also provided for validation[53]. These CGMs are provided by PT. Askara Ardhana Nusantara, traceable to the National Institute of Standards and Technology (NIST).

3. Result and discussion

Calibration was carried out using the developed system following the outline guidelines of SNI 9178:2023. The gas concentration produced by the dilution-based gas mixture (DGM) system was measured continuously. The calibration points are evenly distributed from 0 %mol/mol to 100 %mol/mol with a 10 %mol/mol increment, covering the full dynamic range of the oxygen gas sensor reading. The measurement results of the oxygen concentration readings are shown in Figure 3.

As shown in Figure 3, the real-time response of the sensor displays a sharp rise in concentration during the first 150 seconds at each calibration point. This is due to an initial mixing imbalance between standard and diluent gases. After stabilization, the signal becomes consistent, allowing for reliable averaging over the last 30 seconds of each step. This behavior of sudden rise or drop in concentration readings was mainly caused by the imperfect mixing process between the standard gas and the diluent gas entering the calibration chamber. The standard gas reaches the calibration chamber before the diluent gas, as there is no mixing tube used before the chamber. Consequently, a waiting time of 150 seconds is implemented before collecting data for an additional 30 seconds in subsequent measurements and analyses.

Figure 4 presents the average O_2 sensor response across ten calibration points. The data reveal excellent linearity ($R^2 = 0.9987$) with low standard deviation (<0.2 %mol/mol), indicating strong repeatability. However, slight measurement drift from true values suggests the need for error correction via certified reference gases.

To correct the measurement result, validation using a calibration gas mixture (CGM) is needed to verify the origin of the error, whether it was from the gas mixture or the characteristics of the oxygen sensor used in this research.

These results demonstrate that the system can reliably produce accurate oxygen gas concentrations for calibration purposes, especially within the typical operational range of most ambient air monitoring applications (0–60 %mol/mol). Furthermore, they validate the use of a dilution-based approach as a cost-effective and scalable alternative to using multiple fixed-concentration certified gas cylinders, which are often expensive and logistically challenging to deploy.

The concentration of O_2 gas mixtures from the DGMS was validated against CGM gases. Three separate cylinders with different CGM concentration levels of 30% mol/mol, 60% mol/mol, and 90% mol/mol were used by opening corresponding shut-off valves, as illustrated by Figure 5.

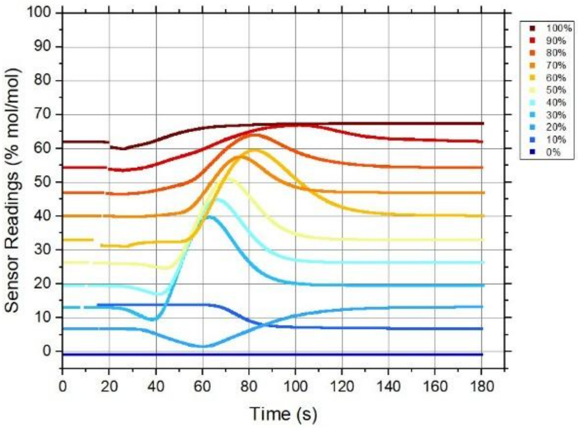

Fig. 3: Continues sensor readings on the concentration of gas mixture generated by the dilution-based gas mixture system

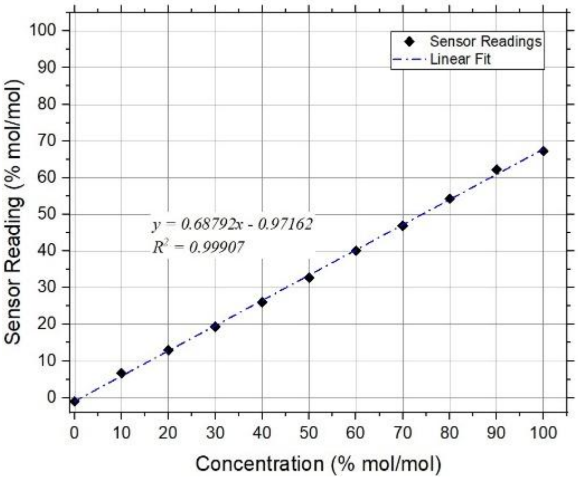

Fig. 4: The average of sensor readings at 10 concentration calibration points

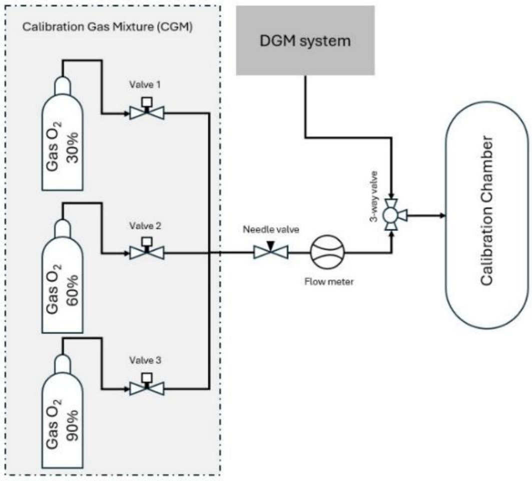

Fig. 5: Schematic configuration of gas mixture validation

The DGMS is set to a certain nominal concentration that corresponds to the selected CGM gas concentration value. A three-way valve is used to alternately direct the gas from the DGM system and the CGM cylinder to a sensor for

Cite: R. Samodro et al., "Development and Evaluation of a Portable Dilution-Based Gas Mixer System for On-Site Calibration of Low-Cost Sensors in Ambient Air Monitoring". Evergreen, 13 (01) 387-395 (2026). https://doi.org/10.5109/7411073.

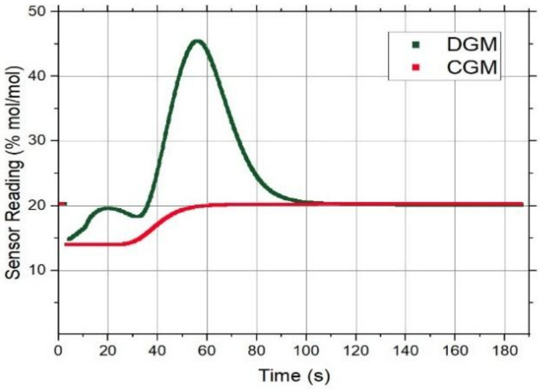

Fig. 6: The difference of typical sensor readings on gas mixture generated by the dilution-based gas mixture system against those of CGM at 30%mol/mol

measurement. To ensure comparability, the flow rate of gas from the CGM cylinder is adjusted to be similar to the flow rate from the DGM system, using a flow control valve and a digital flow meter. The typical sensor readings of this validation step are shown in Figure 6.

Figure 6 shows the characteristics of the sensor response to the gas mixture from DGM and CGM with the same nominal concentration at 30 %mol/mol. When exposed to a gas mixture of CGM, the gas concentration reading increases slowly until it stabilizes, around 60 seconds, unlike the DGMS, which shows a sudden increase at the beginning and starts to stabilize after 100 seconds, with a similar value, indicating that the mixing process of DGM takes more time because it combines two outlets before reaching the chamber, unlike CGM with its single outlet.

The $A(BA)_n$ comparison method was carried out in order to evaluate the concentration difference between both sources while avoiding the drift effect of the sensor[54,55)]. This approach is conceptually related to the AB(BA) comparison method reported in metrological studies[56-57)], where alternating measurement sequences are used to suppress linear drift and temporal instability of the measuring system. Starting by measuring the gas concentration from the DGM system (A), then simultaneously changing to measuring the gas concentration from the CGM (B), for $n = 2$ repetitions. The measurements were taken with the same stabilization and measuring time (t) of 150 s and 30 s, respectively. The method is illustrated in Table 1, while the results are shown in Table 2.

Table 2 compares the sensor's response to gas mixtures produced by the DGM system and CGMs. The concentration differences at 30% and 60% were negligible (0.046 %mol/mol and –0.002 %mol/mol, respectively), whereas a slightly larger deviation (–1.952 %mol/mol) occurred at 90%, likely due to delayed stabilization and sensor saturation effects at high O_2 levels.

This deviation can be attributed to the increased sensitivity of the electrochemical sensor in upper concentration ranges, where nonlinear effects and sensor saturation may begin to affect performance. It may also reflect minor limitations in the dynamic range or response time of the MFCs and flow stabilization at high oxygen dominance. Nevertheless, the overall error remains within acceptable limits for field-grade calibration and well below the inherent accuracy threshold of the sensor.

Table 1: The *A(BA)n* method is used to calculate the concentration difference between the gas mixture generated by the DGM system and the CGM

Stabil. Time	**Meas. Time**	**Operation**	**Average Conc.**	**Concentration Diff. Δ(*AB*)**	**Final Conc. Diff. Δ(*AB*)*n***
(t)	(t)	-	-	(% mol/mol)	(% mol/mol)
150	30	DGM	A_1	-	-
150	30	CGM	B_1	$\Delta(AB)_1 = B_1 - (A_1+A_2)/2$	-
150	30	DGM	A_2	-	$\Delta(AB)n = (\Delta(AB)_1 + \Delta(AB)_2)/2$
150	30	CGM	B_2	$\Delta(AB)_2 = B_2 - (A_2+A_3)/2$	-
150	30	DGM	A_3	-	-

Table 2: Comparison of the O_2 concentration generated by the system against that of CGM

Meas.	**O_2 concentration read by the sensor**					
	30%		**60%**		**90%**	
	DGM	**CGM**	**DGM**	**CGM**	**DGM**	**CGM**
	A	**B**	**A**	**B**	**A**	**B**
1	21.621	21.434	41.703	41.698	67.353	62.896
2	21.067	20.985	41.700	41.700	64.622	63.700
3	20.900	-	41.700	-	64.381	-
Δ	0.046		-0.002		-1.952	

Cite: R. Samodro et al., "Development and Evaluation of a Portable Dilution-Based Gas Mixer System for On-Site Calibration of Low-Cost Sensors in Ambient Air Monitoring". Evergreen, 13 (01) 387-395 (2026). https://doi.org/10.5109/7411073.

In order to verify the degradation in sensor performance, Figure 7 illustrates the calibration responses of the same electrochemical O_2 sensor VT650 in 2023 and 2024. Both datasets display excellent linearity ($R^2 \approx 0.9999$), confirming that the output of the sensor varies linearly with oxygen concentration. However, the slope of the calibration line declines from 0.9267 to 0.6950 (%mol/mol reading per %mol/mol CGM), while the intercept shifts modestly from –0.10 to –0.23. The practical effect is concentration-dependent: at the 30 % CGM point, the 2024 reading is only ~3 % lower than that in 2023, but at 60 % and 90 % CGM, the shortfall widens to ~11 % and ~18 %, respectively. Approximately 0.2% decline in differences relative to CGM concentration was observed over the year. Because the sensor readings remain strictly linear, random noise or sporadic malfunctions can be dismissed. This evidence points to a systematic drift in the electrochemical gain of the sensor.

Such behavior is a typical characteristic of irreversible electrochemical cells, whose active materials gradually deplete, dry out, or become fouled by contaminants during sustained exposure. The observed ~0.2 % relative decline in readings per year provides a useful diagnostic benchmark. On the positive side, the intact linearity means that the sensor can still be utilized as a valid comparator between the DGM concentrations produced by the DGM system and the CGM concentrations in this study.

The accuracy and reliability of the low-cost oxygen sensor (model: VT650) were critically assessed throughout the calibration process using the DGM system. The VT650 sensor is an electrochemical type with a specified measurement range of 0 %mol/mol to 100 %mol/mol, an accuracy of ±1%, and a resolution of 0.1%. To evaluate the system's calibration performance, the sensor was exposed to both the generated gas mixtures and CGMs at three distinct concentration points: 30 %mol/mol, 60 %mol/mol, and 90 %mol/mol.

Each calibration point was tested in triplicate. The output of the sensor was recorded after reaching a stable voltage plateau, typically within 90–120 seconds of exposure. The relative standard deviation (RSD) across the three replicates at each point was consistently below 0.5%, indicating excellent repeatability under controlled conditions. Additionally, the absolute errors observed between the sensor output and the CGM reference were 0.046 %mol/mol, –0.002 %mol/mol, and –1.952 %mol/mol for the 30 %mol/mol, 60 %mol/mol, and 90 %mol/mol points, respectively. These errors fall within acceptable limits based on both the factory-specified uncertainty of the sensor and the national uncertainty and national metrological tolerance for field-grade calibration. The short-term linearity of the sensor response across the measured range was assessed by plotting the analog output voltage (V) against the target oxygen concentration (%mol/mol). A linear regression yielded an R^2 value of 0.9987, confirming high linearity within the 30 %mol/mol to 90 %mol/mol range. No significant signal drift, lag, or overshoot was observed during the transition between concentrations, further reinforcing reliability of the system for sequential calibrations.

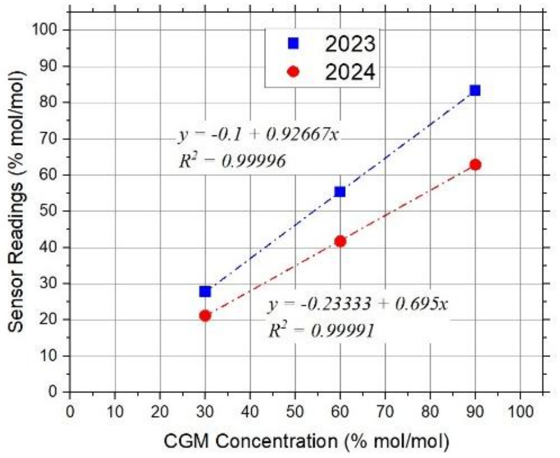

Fig. 7: Decreased sensor performance over time

Furthermore, the stability of the system was tested under continuous operation. Over a 2-hour continuous calibration run with periodic cycling between concentrations, the sensor response remained stable without deviation beyond ±0.15 %mol/mol, demonstrating the robust stability of both the DGM system and the sensor under prolonged use.

Compared with previously reported portable Volatile Organic Compound (VOC) and methane calibration systems, the DGM system developed in this study offers superior flexibility for oxygen calibration in ambient air applications. Although previous works have demonstrated field-deployable gas generation, they often lack validation against CGM or do not comply with national standards such as SNI 9178:2023. Our system fills this gap by integrating traceable calibration with low-cost, modular components and real-time data acquisition.

These findings have important implications for environmental monitoring, particularly in developing regions where access to laboratory infrastructure is limited. The system enables on-site calibration of low-cost sensors, supporting the deployment of affordable and scalable air quality monitoring networks. Its compatibility with national standards enhances its potential for regulatory and research applications.

Nonetheless, this study has some limitations. The system was validated only under controlled laboratory conditions and solely focused on oxygen sensors. The sensor response at high O_2 concentrations showed greater variability, potentially due to nonlinearity or saturation effects. In addition, long-term field durability, multi-gas capability, and integration with wireless telemetry remain subject to future development. Addressing these aspects is essential to broaden the system's real-world applicability and robustness.

4. Conclusions

This portable dilution-based gas mixture (DGM) system for calibrating low-cost oxygen sensors is developed for accessible and traceable calibration tools in ambient air monitoring, using dual mass flow controllers and a LabVIEW interface to generate target gas concentrations on-site. Calibration results at 30 %mol/mol, 60 %mol/mol, and 90 %mol/mol oxygen levels demonstrated high accuracy, with deviations ranging from –1.952 %mol/mol to +0.046 %mol/mol when validated against calibration gas mixtures (CRM). These findings confirm that the DGM system offers a cost-effective, portable, and nationally compliant with the Indonesian National Standard SNI 9178:2023 as solution for improving the reliability of low-cost sensors in both laboratory and field applications, which supports regulatory and environmental monitoring initiatives. Future work should explore extending the system to support multi-gas calibration (e.g., CO_2, NOx) and utilizing AI-assisted control to validate long-term field performance under variable environmental conditions.

Acknowledgment

We thank Mu'afa A. S., Izzah K. K., and Tiffany A. C. students from FTEIC-ITS, for their efforts in collecting research data during their internship at PRTPS. The author would also like to thank the PRTPS and OREM management for providing the necessary research facilities.

References

1) F. Concas et al., "Low-cost outdoor air quality monitoring and sensor calibration," *ACM Transactions on Sensor Networks*, **17** (2) 1–44 (2021). doi: 10.1145/3446005.
2) D. Singh, and A. Singh, "Role of building automation technology in creating a smart and sustainable built environment," *Evergreen*, **10** (1) 412–420 (2023). doi: 10.5109/6781101.
3) M. Ayundyahrini, N. D. A. Susanto, H. Febriansyah, N. F. M. Rizanulhaq, and N. G. H. Aditya, "Smart farming: Integrated solar water pumping irrigation system in Thailand," *Evergreen* **10** (1) 553–563 (2023). doi: 10.5109/6782161.
4) S. Morau, L. Macedo, E. Morais, R. Menegardo, J. Nedoma, R. Martinek, and A. Leal-Junior, "Low-cost AI-enabled optoelectronic wearable for GAIT and breathing monitoring: design, validation, and applications," *Biosensors*, **15** (9) 612 (2025). doi: 10.3390/bios15090612.
5) S. I. Lopes et al., "Low-cost sensor systems and IoT technologies for indoor air quality monitoring: instrumentation, models, implementation, and perspectives for validation," *Sensors*, **25** (24) 7567 (2025). doi: 10.3390/s25247567.
6) D. A. H. Fakra, D. A. S. Andriatoavina, N. A. M. N. Razafindralambo, K. A. Amarillis, and J. M. M. Andriamampianina, "A simple and low-cost integrative sensor system for methane and hydrogen measurement," *Sensors International*, **1** 100032 (2020). doi: 10.1016/j.sintl.2020.100032.
7) L. Liang, and J. Daniels, "What influences low-cost sensor data calibration? - A systematic assessment of algorithms, duration, and predictor selection," *Aerosol and Air Quality Research* **22** (9) 220076 (2022). doi: 10.4209/aaqr.220076.
8) S. M. Abbas, J. A. Mohammed, and W. E. Abdul-Lateef, "Modeling and implementation of an open-loop single-axis solar tracking system driven by an SMA spring actuator," *Evergreen*, **11** (4) 3109–3118 (2024). doi: 10.5109/7326949.
9) T. Sulistyo, K. Achmad, and N. I. B. I. Purnama, "Empowering low-cost survey instrument for the stake-out measurements using android application," *Evergreen*, **8** (3) 610–617 (2021). doi: 10.5109/4491653.
10) Y. G. Wijaya et al., "A cost-effective solution for measuring vibration and impact on small twin engine electric fixed wing UAV," *Evergreen*, **11** (3) 2367–2385 (2024). doi: 10.5109/7236880.
11) L. Spinelle, M. Gerboles, G. Kok, S. Persijn, and T. Sauerwald, "Review of portable and low-cost sensors for the ambient air monitoring of benzene and other volatile organic compounds," *Sensors*, **17** (7) 1520 (2017). doi: 10.3390/s17071520.
12) N. H. Nguyen, H. X. Nguyen, T. T. B. Le, and C. D. Vu, "Evaluating low-cost commercially available sensors for air quality monitoring and application of sensor calibration methods for improving accuracy," *Open Journal of Air Pollution*, **10** (1) 1–17 (2021). doi: 10.4236/ojap.2021.101001.
13) B. Maag, Z. Zhou, and L. Thiele, "A survey on sensor calibration in air pollution monitoring deployments," *IEEE Internet of Things Journal*, **5** (6) 4857–4870 (2018). doi: 10.1109/jiot.2018.2853660.
14) V. D. Juyal and S. Kakran, "CNN-LSTM based weather forecasting and its application in a residential home energy management system," *Evergreen*, **11** (4) 3243–3253 (2024). doi: 10.5109/7326959.
15) H. Kim, M. Müller, S. Henne, and C. Hüglin, "Long-term behavior and stability of calibration models for NO and NO2 low-cost sensors," *Atmospheric Measurement Techniques*, **15** (9) 2979–2992 (2022). doi: 10.5194/amt-15-2979-2022.
16) A. Dewan, S. U. Ay, M. N. Karim, and H. Beyenal, "Alternative power sources for remote sensors: a

review," *Journal of Power Sources*, **245** 129–143 (2013). doi: 10.1016/j.jpowsour.2013.06.081.

17) M. R. García et al., "Review of low-cost sensors for indoor air quality: features and applications," *Applied Spectroscopy Reviews*, **57** (9–10) 747–779 (2022). doi: 10.1080/05704928.2022.2085734.

18) O. Bamodu, F. Osebor, L. Xia, A. Cheshmehzangi, and L. Tang, "Indoor environment monitoring based on humidity conditions using a low-cost sensor network," *Energy Procedia*, **145** 464–471 (2018). doi: 10.1016/j.egypro.2018.04.093.

19) A. Bender, F.G.A. Francisco, and J. Sundberg, "A Review of Methods and Models for Environmental Monitoring of Marine Renewable Energy," *Proceedings of the 12th European Wave and Tidal Energy Conference*, 1092-1-10 (2017). https://uu.diva-portal.org/smash/get/diva2:1144892/FULLTEXT01.pdf.

20) Shahnawaj and S. Chanana, "Cascaded Fractional Control approach for frequency regulation of multi-source power system integrating renewable energy resources," *Evergreen*, **11** (2) 949–963 (2024). doi: 10.5109/7183377.

21) J. Thorson, A. Collier-Oxandale, and M. Hannigan, "Using a low-cost sensor array and machine learning techniques to detect complex pollutant mixtures and identify likely sources," *Sensors*, **19** (17) 3723 (2019). doi: 10.3390/s19173723.

22) G. Tancev and F. G. Toro, "Variational bayesian calibration of low-cost gas sensor systems in air quality monitoring," *Measurement Sensors*, **19** 100365 (2021). doi: 10.1016/j.measen.2021.100365.

23) T. Pisanu, S. Garau, P. Ortu, L. Schirru, and C. Macciò, "Prototype of a low-cost electronic platform for real time greenhouse environment monitoring: an agriculture 4.0 perspective," *Electronics*, **9** (5) 726 (2020). doi: 10.3390/electronics9050726.

24) D. D. Uyeh et al., "An online machine learning-based sensors clustering system for efficient and cost-effective environmental monitoring in controlled environment agriculture," *Computers and Electronics in Agriculture*, **199** 107139 (2022). doi: 10.1016/j.compag.2022.107139.

25) M. Si, Y. Xiong, S. Du, and K. Du, "Evaluation and calibration of a low-cost particle sensor in ambient conditions using machine-learning methods," *Atmospheric Measurement Techniques*, **13** (4) 1693–1707 (2020). doi: 10.5194/amt-13-1693-2020.

26) A. Bigi, M. Mueller, S. K. Grange, G. Ghermandi, and C. Hueglin, "Performance of NO, NO2 low-cost sensors and three calibration approaches within a real world application," *Atmospheric Measurement Techniques*, **11** (6) 3717–3735 (2018). doi: 10.5194/amt-11-3717-2018.

27) D. Shlenkevitch, S. Stolyarova, T. Blank, I. Brouk, and Y. Nemirovsky, "Novel miniature and selective combustion-type CMOS gas sensor for gas-mixture analysis—Part 1: emphasis on chemical aspects," *Micromachines*, **11** (4) 345 (2020). doi: 10.3390/mi11040345.

28) K. Aula, E. Lagerspetz, P. Nurmi, and S. Tarkoma, "Evaluation of low-cost air quality sensor calibration models," *ACM Transactions on Sensor Networks*, **18** (4) 1–32 (2022). doi: 10.1145/3512889.

29) H. Cui et al., "A new calibration system for low-cost sensor network in air pollution monitoring," *Atmospheric Pollution Research*, **12** (5) 101049 (2021). doi: 10.1016/j.apr.2021.03.012.

30) L. Liang, "Calibrating low-cost sensors for ambient air monitoring: techniques, trends, and challenges," *Environmental Research*, **197** 111163 (2021). doi: 10.1016/j.envres.2021.111163.

31) A. Wang et al., "Leveraging machine learning algorithms to advance low-cost air sensor calibration in stationary and mobile settings," *Atmospheric Environment*, **301** 119692 (2023). doi: 10.1016/j.atmosenv.2023.119692.

32) H. S. Russell et al., "Enhanced ambient sensing environment—a new method for calibrating low-cost gas sensors," *Sensors*, **22** (19) 7238 (2022). doi: 10.3390/s22197238.

33) V. S. Gamboa, É. J. Kinast, and M. Pires, "System for performance evaluation and calibration of low-cost gas sensors applied to air quality monitoring," *Atmospheric Pollution Research*, **14** (2) 101645 (2023). doi: 10.1016/j.apr.2022.101645.

34) "Low-cost sensors for the measurement of atmospheric composition: overview of topic and future applications," World Meteorological Organization. https://www.ccacoalition.org/resources/low-cost-sensors-measurement-atmospheric-composition-overview-topic-and-future-applications (accessed February 19, 2025).

35) "Gas analysis — Preparation of calibration gas mixtures," ISO 6142-1:2015. https://www.iso.org/standard/59631.html (accessed March 1, 2025)

36) H. Budiman, M. R. Mulyana, and O. Zuas, "Gravimetric dilution of calibration gas mixtures (CO2, CO, and CH4 in He balance): Toward their uncertainty estimation," *AIP Conference Proceedings*, **1803** 020056 (2017). doi: 10.1063/1.4973183.

37) H. Budiman, M. R. Mulyana, and O. Zuas, "Preparation of calibration standard gas mixtures by primary gravimetric method: a case study on 960 µmol/mol of carbon dioxide in a nitrogen matrix," *Engineering and Applied Science Research*, **45** (3)

173-176 (2018). doi: 10.14456/easr.2018.29.

38) A. Hindayani, M. R. Mulyana, H. Budiman, N. T. E. Darmayanti, and O. Zuas, "Development of calibration gas mixtures (carbon dioxide and oxygen in nitrogen matrix) at a typical concentration range of modified atmosphere packaging," *Periódico Tchê Química*, **17** (36) 674–687 (2020). doi: 10.52571/ptq.v17.n36.2020.689_periodico36_pgs_674_687.pdf.

39) P. Veres et al., "Development and validation of a portable gas phase standard generation and calibration system for volatile organic compounds," *Atmospheric Measurement Techniques*, **3** (3) 683–691 (2010). doi: 10.5194/amt-3-683-2010.

40) D.-W. You, Y.-S. Seon, Y. Jang, J. Bang, J.-S. Oh, and K.-W. Jung, "A portable gas chromatograph for real-time monitoring of aromatic volatile organic compounds in air samples," *Journal of Chromatography A*, **1625** 461267 (2020). doi: 10.1016/j.chroma.2020.461267.

41) L. Furst, M. Feliciano, L. Frare, and G. Igrejas, "A portable device for methane measurement using a low-cost semiconductor sensor: development, calibration and environmental applications," *Sensors*, **21** (22) 7456 (2021). doi: 10.3390/s21227456.

42) G. Wang et al., "Portable methane sensor system using miniature multi-pass cell for mobile monitoring of natural gas leaks," *Sensors and Actuators B: Chemical,* **431** 137457 (2025). doi: 10.1016/j.snb.2025.137457.

43) "Ambient air – Performance test of an air quality monitoring device using a low-cost sensor," Indonesian National Standard SNI 9178:2023. https://pesta.bsn.go.id/produk/detail/14487-sni91782023 (accessed Mar 10, 2025).

44) T. Sauerwald et al., "Highly sensitive benzene detection with metal oxide semiconductor gas sensors – an inter-laboratory comparison," *Journal of Sensors and Sensor Systems*, **7** (1) 235–243 (2018). doi: 10.5194/jsss-7-235-2018.

45) T. Baur, M. Bastuck, C. Schultealbert, T. Sauerwald, and A. Schütze, "Random gas mixtures for efficient gas sensor calibration," *Journal of Sensors and Sensor Systems*, **9** (2) 411–424 (2020). doi: 10.5194/jsss-9-411-2020.

46) Z. Zhou, Y. Zhou, C. He, and Z. Bi, "Development of calibration device for on-line atmospheric gas analyzers," *Measurement*, **151** 107265 (2019). doi: 10.1016/j.measurement.2019.107265.

47) V. Loianno and G. Mensitieri, "A novel dynamic method for the storage of calibration gas mixtures based on thermal mass flow controllers," *Measurement Science and Technology*, **33** (6) 065017 (2022). doi: 10.1088/1361-6501/ac5a2f.

48) F. Rolle, M. Sega, F. R. Pennecchi, P. G. Spazzini, S. Pavarelli, and M. Santiano, "Realisation and preliminary validation of a dilution device for the generation of CO2 gas mixtures," *Measurement Sensors*, **18** 100242 (2021). doi: 10.1016/j.measen.2021.100242.

49) H. Nara, T. Saito, T. Umezawa, and Y. Tohjima, "A high-accuracy dynamic dilution method for generating reference gas mixtures of carbonyl sulfide at sub-nanomole-per-mole levels for long-term atmospheric observation," *Atmospheric Measurement Techniques*, **17** (17) 5187–5200 (2024). doi: 10.5194/amt-17-5187-2024.

50) Y. Liu, Q. Xue, H. Zuo, X. She, and J. Wang, "Effects of CO2 and N2 dilution on the characteristics and NOX emission of H2/CH4/CO/air partially premixed flame," *International Journal of Hydrogen Energy*, **47** (35) 15909–15921 (2022). doi: 10.1016/j.ijhydene.2022.03.060.

51) S. Zhang and Z. Lin, "Dilution-based evaluation of airborne infection risk - thorough expansion of Wells-Riley model," *Building and Environment*, **194** 107674 (2021). doi: 10.1016/j.buildenv.2021.107674.

52) J. D. Raal and W. M. Nelson, "Gas chromatograph calibration of gas mixtures using a versatile precision volumetric apparatus," *Review of Scientific Instruments*, **93** (5) 054108 (2022). doi: 10.1063/5.0083028.

53) F. Rolle et al., "Generation of CO2 gas mixtures by dynamic dilution for the development of gaseous certified reference materials," *Measurement Sensors*, **24** 100415 (2022). doi: 10.1016/j.measen.2022.100415.

54) A. V. Ega, G. Ginanjar, E. Firmansyah, and D. R. Utomo, "Study on the implementation of single pressure balance with iterative A-B-A-B-A method in the differential pressure calibration of ventilator tester," *MAPAN - Journal of Metrology Society of India*, **36** (3) 629–638 (2021). doi: 10.1007/s12647-021-00499-1.

55) M. Kojima, T. Kobata, K. Saitou, and M. Hirata, "Development of small differential pressure standard using double pressure balances," *Metrologia*, **42** (6) S227–S230 (2005). doi: 10.1088/0026-1394/42/6/s18.

56) T. Kobata and D. A. Olson, "Accurate determination of equilibrium state between two pressure balances using a pressure transducer," *Metrologia*, **42** (6) S231–S234 (2005). doi: 10.1088/0026-1394/42/6/s19.

57) S.-Y. Woo, I.-M. Choi, and H.-W. Song, "A low differential pressure standard in the range of 1 Pa to 31 kPa at KRISS," *Metrologia*, **46** (1) 125–128 (2009). doi: 10.1088/0026-1394/46/1/016.

Cite: R. Samodro et al., "Development and Evaluation of a Portable Dilution-Based Gas Mixer System for On-Site Calibration of Low-Cost Sensors in Ambient Air Monitoring". Evergreen, 13 (01) 387-395 (2026). https://doi.org/10.5109/7411073.