Indoor Air Quality monitoring using low-cost sensors: Experimental set-up and characterization procedure

Original

Indoor Air Quality monitoring using low-cost sensors: Experimental set-up and characterization procedure / Russo, Ramona; Rolle, Francesca; Durbiano, Francesca; Pennecchi, Francesca Romana; Pavarelli, Stefano; Festevole, Chiara; Sega, Michela. - In: EPJ WEB OF CONFERENCES. - ISSN 2100-014X. - 352:(2026). (13th International Gas Analysis Symposium (GAS 2026) Paris (France) 27-29 January 2026) [10.1051/epjconf/202635203001].

Published

DOI:10.1051/epjconf/202635203001

Indoor Air Quality monitoring using low-cost sensors: Experimental set-up and characterization procedure

Ramona Russo[1,2*], *Francesca* Rolle[1], *Francesca* Durbiano[1], *Francesca Romana* Pennecchi[1], *Stefano* Pavarelli [1], *Chiara* Festevole[3], and *Michela* Sega[1]

[1]INRiM, Istituto Nazionale di Ricerca Metrologica, 10135 Turin, Italy
[2]DENERG, Department of Energy "Galileo Ferraris", Politecnico di Torino, 10129 Turin, Italy
[3]Department of Chemistry, Università degli Studi di Torino, 10125 Turin, Italy

Abstract. Monitoring indoor environmental quality is a key requirement for addressing challenges related to smart cities and human health, including indoor air quality. Traditionally, indoor air monitoring has relied on high-end instrumentation, limiting large-scale and widespread deployment. The increasing availability of low-cost sensors offers new opportunities for scalable monitoring systems, provided their metrological performance is properly characterised. In this context, the Italian PRIN project MIRABLE (Measurement Infrastructure for Research on Healthy and Zero Energy Buildings in Novel Living Lab Ecosystems), involving the Italian National Metrology Institute (INRiM) and the Politecnico di Torino, aims to develop a multidomain measurement infrastructure for indoor environments using low-cost sensors in a full-scale living laboratory. At INRiM, a dedicated calibration system was developed to ensure the metrological traceability of CO_2 and CO measurements obtained from low-cost sensors. Reference gas mixtures were prepared gravimetrically according to the International Standard ISO 6142-1 and dynamically diluted to reach low concentration levels. Calibration was carried out using a primary non-dispersive infrared (NDIR) reference analyser and a specially designed calibration chamber. This study presents calibration results for selected CO_2 low-cost sensors and a preliminary evaluation of measurement uncertainty. The same methodology will be extended to low-cost CO and NO_x sensors in future work.

1 Introduction

Accurate assessment of indoor air quality (IAQ) has become a key public health priority, especially considering that individuals spend approximately 80 % of their time in confined environments such as homes, schools and offices [1]. Traditionally, IAQ monitoring and the assessment of ventilation rates have relied on high-end laboratory instruments, such as photoacoustic spectroscopy (PAS) systems; although extremely accurate, these instruments present significant limitations in terms of high cost, logistical complexity, and slow response times [2].

To overcome these barriers, there has been a rapid proliferation of monitoring systems based on low-cost sensor networks [3]. These systems offer a scalable alternative for achieving high spatial and temporal resolution, enabling the identification of local emission sources and the detection of transient events related to occupant activities that may not be captured by traditional instrumentation [2].

The integration of these sensors with Internet of Things (IoT) technologies enables the transition from sparse measurement points to truly distributed monitoring networks [3].

However, the use of low-cost sensors (LCSs) introduces significant metrological challenges. Low-cost sensors are often subject to drift, cross-sensitivity to gases other than those intended to be measured and dependence on thermo-hygrometric conditions (temperature and humidity) [4]. To ensure the robustness and reliability of the collected data, it is essential to implement rigorous procedures ranging from laboratory calibration to in-field validation.

In this context, metrological traceability represents the fundamental link between the deployment of low-cost sensors and the ability to support reliable decision-making for health protection and smart building management. It ensures that the measurements obtained are linked to international primary standards, such as reference gas mixtures prepared in accordance with the International Standard ISO 6145-1 [5], thereby guaranteeing that the reported concentrations are accurate and not affected by systematic errors. Only through traceable measurement results is it possible to correctly quantify personal exposure to pollutants, enabling both authorities and citizens to take informed actions to mitigate health risks [3]. In modern buildings, defined as “cognitive”, the metrological characterisation of sensor performance is not merely an observational tool but a critical prerequisite for automation, control strategies, and the large-scale deployment of measurement infrastructures in complex urban environments [3].

---

* Corresponding author: r.russo@inrim.it

2 MIRABLE Project

The "Measurement Infrastructure for Research on heAlthy and zero energy Buildings in novel Living lab Ecosystems" (MIRABLE) project, already presented in [6], aims to develop an integrated system for measuring environmental parameters within a living lab. The system development is divided into two phases. The first phase, currently at a more advanced stage, involves the creation of a desktop multisensor for measuring parameters such as temperature, relative humidity and other environmental indicators. The system also includes a component integrated into the chair, designed to measure temperature and relative humidity at two points: on the backrest, at neck height, and on the lower support of the chair, near the feet. The second phase involves the development of an instrumented living lab, in which the entire structure integrates fixed sensors distributed in different positions to monitor the main environmental parameters. In order to obtain more accurate control of the factors that influence the occupants' comfort, the functioning of some wearable sensors already available on the market, capable of measuring parameters such as temperature, physiological variables and lighting, was also analysed. Finally, this article presents the carbon dioxide (CO_2) concentration measurements acquired by using low-cost sensors, which are used to define the generic calibration procedure for low-cost sensors to be applied throughout the project.

3 Analysis of CO_2 amount fraction with low-cost sensors

The analyses conducted at INRiM involved three low-cost sensors and two high-quality sensors for CO_2 measurement.

3.1 Materials and Method

To ensure metrological traceability, in accordance with ISO 17025 and ISO 17043 International Standards [7], [8], the tests conducted at INRiM were performed using a high-quality CO_2 analyser as a reference instrument, previously calibrated according to the Institute's procedures using certified gas mixtures.

Specifically, the instrument used is a LI-cor 850, manufactured by LI-cor, based on NDIR (Non-Dispersive Infrared Technology), with a measurement range between 0 ppm and 20000 ppm and a declared accuracy of ± 1,5% of the reading [9].

In this article, this instrument is referred to as the primary instrument and identified as LI-cor 1.

A second high-quality instrument was also used, also a LI-cor 850 with identical nominal characteristics to the first, referred to as the secondary instrument (LI-cor 2). This instrument was not previously calibrated, but it was used to evaluate the typical behaviour of a high-quality uncalibrated sensor in comparison with the low-cost ones.

Three low-cost sensors were used, identified as LCS 1, LCS 2 and LCS 3. These are based on NDIR technology for CO_2 detection.

According to the manufacturer's datasheet, the declared accuracy varies depending on the measurement range:

- (0-1250) ppm: ± 1 % FS (± 50 ppm)
- (1250-2500) ppm: ± 2 % FS (±1 00 ppm)
- (2500-5000) ppm: ± 5 % FS (± 250 ppm)

The data was acquired at a sampling rate of one data point every 5 s.

To test the low-cost CO_2 sensors, which were not designed for use with a dedicated gas mixture inlet, an insulator measuring 80x80x80 cm, previously characterised, was designed at INRiM (Fig.1). The isolator was used for the simultaneous positioning of all the sensors used in the study, namely the two LI-cor 850 and the three low-cost sensors and was used as a mixing chamber. To ensure the homogeneous distribution of gases inside the isolator, a 15 V fan was used.

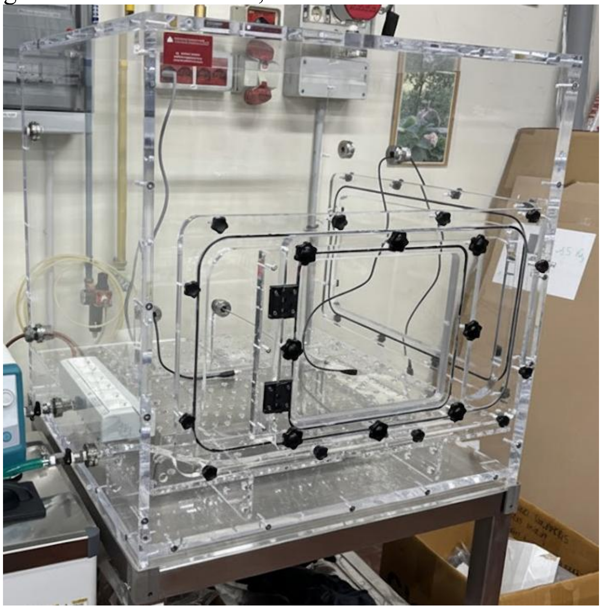

Fig. 1. Picture of the insulator used at INRiM

Two gas mixtures of CO_2 were employed: the first is CO_2 in synthetic air (SA) with a nominal concentration of 500.3 ppm (SAPIO s/n 5113566) and the second CO_2 in nitrogen (N_2) with a concentration of 80325 ppm (INRiM s/n D580464). A cylinder of pure N_2, (grade 6.0) supplied by Air Liquide (Italy) was also used as zero gas. The 500.3 ppm CO_2 mixture was used to define the initial and final span of the two LI-cor 850 instruments, while the 80325 ppm mixture was used for dynamic mixing inside the isolator.

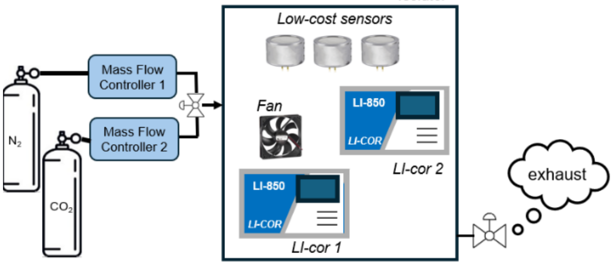

Fig. 2. Experimental set-up diagram

Knowing the volume of the isolator, the opening time of the CO_2 cylinder at 80325 ppm required to reach a target concentration inside the chamber was estimated. The gas flow was controlled by two calibrated Mass Flow Controllers (MFC) (MKS Instruments, USA), with full scales of 1000 standard cubic centimetres per minute (SCCM) and 2000 SCCM, respectively.

The experimental approach involved a series of measurements at different CO_2 concentrations, aimed at evaluating the response time of the sensors, their short-term stability and evaluating the uncertainty associated with the readings of the low-cost sensors. These analyses were carried out by normalising the measurements, using the measurements provided by the high-quality calibrated LI-cor 1 instrument as a reference.

For each test, the average measured value (avg. v.) was considered, calculated by excluding the extreme values of the measurement, which could potentially be affected by temporary instability. The average difference avg(Δ) value was also calculated, defined as the difference between the average value measured by the sensor in question and the average reference value (avg. ref. v.).

$$\text{avg}(\Delta) = \text{avg. v.} - \text{avg. ref. v.} \tag{1}$$

The standard deviation of the measurement differences $s(\Delta)$ was analysed, and the expanded repeatability uncertainty $U(\Delta)$ and the relative expanded uncertainty $U_r(\Delta)$, evaluated as explained below in equations (2) and (3), were considered relevant. A coverage factor k of 2 was adopted.

$$U(\Delta) = k \cdot s(\Delta) \tag{2}$$

$$U_r(\Delta) = U(\Delta)/\text{avg}(\Delta) \tag{3}$$

3.2 Experiment and results

The experiment began once the isolator had been closed. The initial phase involved continuously flushing N_2 into the chamber for 4 h. During this process, the exit valve was used to manage gas outflow and prevent overpressure conditions that could have compromised the sensors or the chamber's structural integrity. Internal overpressure was monitored throughout this phase to ensure it never exceeded 40 mbar, enabling the system to reach the minimum CO_2 concentration level of 5 ppm, detected by the calibrated reference instrument. At this concentration, the LI-cor 2 provided measurements that were closely comparable to the reference instrument, recording an average value of 2 ppm; in contrast, the low-cost CO_2 sensors exhibited significant deviations, with respective mean biases of 250 ppm, 188 ppm and 210 ppm (Fig. 3), respectively. These results highlight a pronounced systematic offset even at the lower detection limits.

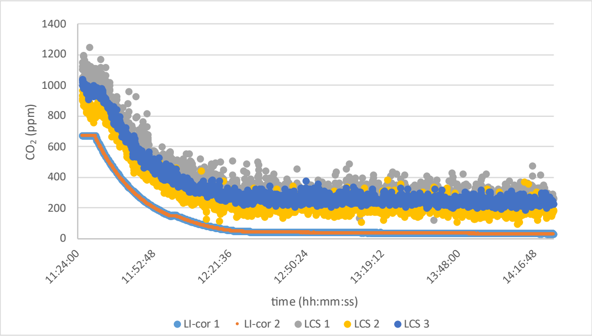

Fig. 3. Measurement of CO_2 from ambient concentration to nearly zero concentration.

Various concentrations of CO_2 were analysed, namely: 5, 400, 840, 1360, 3000, 4000 and 5000 ppm. Not all levels were analysed in detail, as some fell outside the calibration range of the reference instrument. However, the overall trend of the measurements taken by the low-cost sensors is consistent with that of the reference instruments (Fig. 4).

The response time of the low-cost sensors was approximately 2 min, which is comparable to that of the high-quality instruments used in the test (Fig. 4).

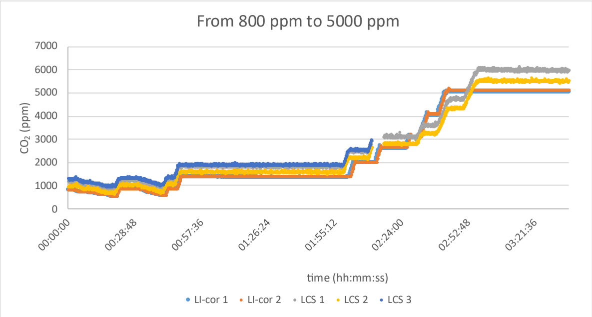

Fig. 4. Measurements taken from concentrations of 800 ppm to 5000 ppm of CO_2.

Figure 4 shows that, at a concentration of 3000 ppm, the LCS 3 low-cost sensor stopped collecting data. The analyses had been ongoing for three consecutive days after the LCS 3 sensor failed; its data collection was suspended to prevent further data loss. In the range between 3000 ppm and 4000 ppm, the low-cost sensors consistently underestimated CO_2 levels, probably due to their recent reactivation.

Table 1 shows the analysed data relating to concentrations of 5, 400, 840 and 1360 ppm. The high-quality sensors (LI-cor 2) show low extended repeatability uncertainties $U(\Delta)$ (< 4 ppm), while the low-cost sensors show much higher values (up to ~ 80–90 ppm), exceeding the accuracy declared by the manufacturer (± 50 ppm, 1 % FS). The relative expanded uncertainty, which for low-cost sensors reaches values of around 20–60 %, makes measurements unreliable without an adequate metrological procedure, especially at low concentrations.

Table 1. Comparative analysis of data collected by sensors for different levels of CO_2 mole fraction (5, 400, 840, 1360 ppm).

LI-cor 1 measurement: 5 ppm				
	LI-cor 2	LCS 1	LCS 2	LCS 3
avg. v.	2 ppm	250 ppm	188 ppm	210 ppm
avg(Δ)	-3	245	183	205
$s(\Delta)$	0.243	44.367	40.046	21.847
$U(\Delta)$	0.486	88.734	80.092	43.695
$U_\mathrm{r}(\Delta)$	16 %	36 %	44 %	21 %
LI-cor 1 measurement: 400 ppm				
avg. v.	398 ppm	695 ppm	537 ppm	635 ppm
avg(Δ)	-2	295	137	235
$s(\Delta)$	0.417	43.461	40.752	24.604
$U(\Delta)$	0.835	86.923	81.504	49.207
$U_\mathrm{r}(\Delta)$	35 %	29 %	60 %	21 %
LI-cor 1 measurement: 840 ppm				
avg. v.	840 ppm	1219 ppm	1008 ppm	120 ppm
avg(Δ)	0	379	169	280
$s(\Delta)$	0.673	36.876	32.245	26.396
$U(\Delta)$	1.345	73.751	64.489	52.792
$U_\mathrm{r}(\Delta)$	*	19 %	38 %	19 %
LI-cor 1 measurement: 1360 ppm				
avg. v.	1364 ppm	1816 ppm	1579 ppm	1888 ppm
avg(Δ)	4	456	220	529
$s(\Delta)$	0.758	38.036	32.364	24.298
$U(\Delta)$	1.515	76.072	64.728	48.596
$U_\mathrm{r}(\Delta)$	37 %	17 %	29 %	9 %

*Undetermined value because the average difference is zero

Figures 5 and 6 below shows, as an example, the analysis of the mole fraction of CO_2 measured with low-cost sensors, normalised to a reference value of 400 ppm. Figure 5 shows the absolute values measured over time. Even under steady-state conditions, low-cost sensors show significant systematic offsets from the reference, with average values between + 137 ppm and + 295 ppm, indicating poor absolute accuracy. Figure 6 shows the effect of correction to the reference value (400 ppm). Normalization reduces the average offset, but does not eliminate data dispersion, which remains high for low-cost sensors, indicating that the error is not only systematic but also related to repeatability.

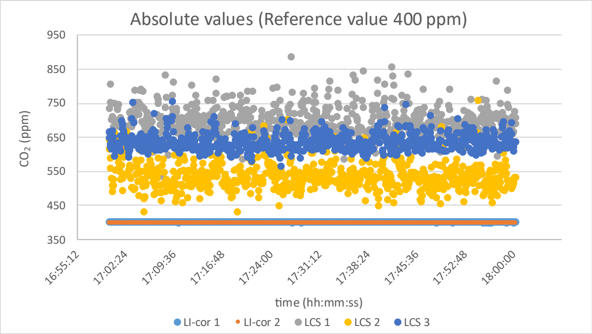

Fig. 5. Absolute CO_2 values measured by all sensors

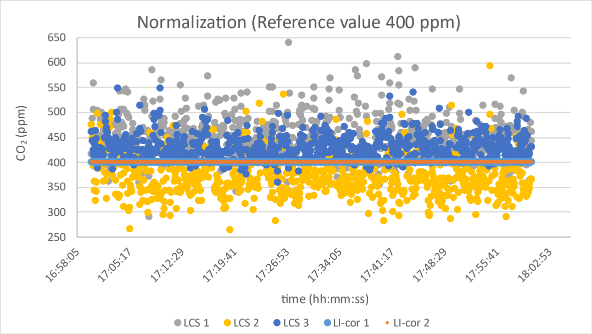

Fig. 6. Data normalised to the reference value of 400 ppm of CO_2

This demonstrates that normalisation to a single reference point is not sufficient to guarantee reliable measurements with low-cost sensors, and that multi-point calibration procedures and structured metrological analyses are necessary.

It is interesting to note that the deviation between the measured value and the reference value (avg(Δ)) increases as the concentration increases (Fig. 7); on the contrary, the standard deviation of the difference, and consequently the standard uncertainty of the correction, tends to decrease as the concentration increases (Fig. 8).

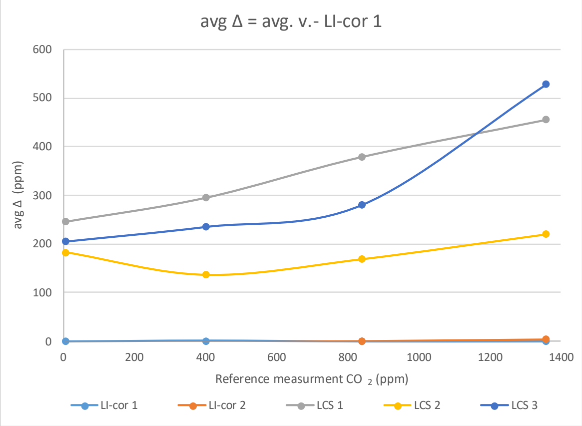

Fig. 7. Difference between measured value and reference value

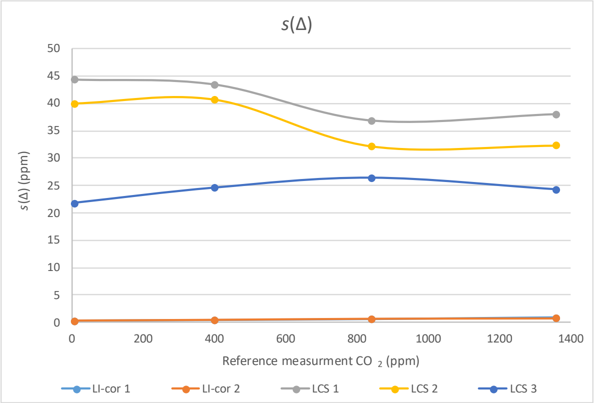

Fig. 8. Typical uncertainty of correction

Fig. 9 shows the absolute values measured by the different sensors as a function of the reference CO_2 concentration, highlighting increasing systematic deviations and dispersion that increases with concentration, particularly for low-cost sensors (LCS 1–3).

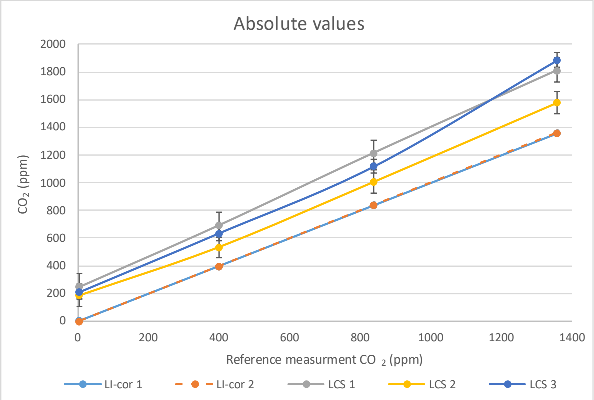

Fig. 9. Absolute CO_2 values measured in the range 5-1360 ppm, reported with repeatability expanded

4 Conclusion

This paper presents the experimental set-up and characterization procedure for a preliminary analysis of the measurement uncertainty of the mole fraction of CO_2 obtained with low-cost sensors, compared with reference instruments (LI-cor) in a range between 5 ppm and 1360 ppm. While the reference instrumentation guarantees low uncertainties (< 4 ppm), the low-cost sensors show dispersions of up to 80–90 ppm, exceeding the specifications declared by the manufacturer. The analysis highlights the need for calibration, as the direct use of these sensors, without corrections, leads to high and uncontrolled errors. Metrological traceability is therefore essential to ensure data reliability. Although low-cost sensors are an affordable solution for indoor air quality monitoring, the validity of their measurements depends heavily on the adoption of standardised calibration protocols. This study mainly analysed repeatability uncertainty; however, in view of future developments, other components of the uncertainty budget will also need to be considered. The obtained results provide the basis for defining a rigorous calibration procedure specific to low-cost CO_2 sensors.

Acknowledgment

The MIRABLE Project was funded by the Italian PIANO NAZIONALE DI RIPRESA E RESILIENZA (PNRR) - Missione 4 “Istruzione e Ricerca” - Componente C2 Investimento 1.1, “Fondo per il Programma Nazionale di Ricerca e Progetti di Rilevante Interesse Nazionale (PRIN)” Decreto Direttoriale n. 104 del 2 febbraio 2022. Progetto PRIN 2022 «MIRABLE – Measurement Infrastructure for Research on heAlthy and zero energy Buildings in novel Living lab Ecosystems» Codice di progetto: 2022ZNJHHY.

References

[1] J. Wu, J. Weng, B. Xia, Y. Zhao, and Q. Song, ‘The Synergistic Effect of PM2.5 and CO2 Concentrations on Occupant Satisfaction and Work Productivity in a Meeting Room’, *IJERPH*, vol. 18, no. 8, Art. no. 8 (2021). doi: 10.3390/ijerph18084109.

[2] V. Gentile and M. Perino, ‘Low-Cost Tracer Gas Sensor for Building Ventilation’, *Journal of Physics: Conference Series*, vol. 3140, p. 092001 (2025). doi: 10.1088/1742-6596/3140/9/092001.

[3] S. Lopes *et al.*, ‘Low-Cost Sensor Systems and IoT Technologies for Indoor Air Quality Monitoring: Instrumentation, Models, Implementation, and Perspectives for Validation’, *Sensors*, vol. 25, p. 7567 (2025). doi: 10.3390/s25247567.

[4] E. Bagkis, T. Kassandros, and K. Karatzas, ‘Learning Calibration Functions on the Fly: Hybrid Batch Online Stacking Ensembles for the Calibration of Low-Cost Air Quality Sensor Networks in the Presence of Concept Drift’, *Atmosphere*, vol. 13, no. 3, p. 416 (2022). doi: 10.3390/atmos13030416.

[5] ‘ISO 6142-1:2015’, ISO. Accessed: Jan. 12, 2026. [Online]. Available: https://www.iso.org/standard/59631.html

[6] F. Rolle *et al.*, ‘Metrological characterisation of low-cost and wearable sensors for research on healthy buildings in a novel Living Laboratory’, *EPJ Web of Conferences*, vol. 323 (2025). doi: 10.1051/epjconf/202532304001.

[7] ‘ISO - ISO/IEC 17025 — Testing and calibration laboratories’, ISO. Accessed: Apr. 17, 2025. [Online]. Available: https://www.iso.org/ISO-IEC-17025-testing-and-calibration-laboratories.html

[8] ‘ISO/IEC 17043:2023’, ISO. Accessed: Jan. 08, 2026. [Online]. Available: https://www.iso.org/standard/80864.html

[9] ‘LI-COR Environmental’, LI-COR Environmental. Accessed: Jan. 08, 2026. [Online]. Available: https://www.licor.com/products/gas-analysis/LI-830-LI-850