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Metrological traceability for measuring Indoor Air Quality using low-cost sensors

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***Abstract* – Indoor air quality (IAQ) monitoring has gained significant attention due to its impact on human health. Low-cost sensors allow widespread data collection but often lack proper characterisation and standard validation, affecting reliability. The Italian PRIN project "MIRABLE" - Measurement Infrastructure for Research on heAlthy and zero energy Buildings in novel Living lab Ecosystems - led by Italian National Metrology Institute, INRiM, and Politecnico di Torino, aims to develop a measurement infrastructure for monitoring multi-domain indoor environmental conditions using low-cost sensors. In this framework INRiM started activities on the metrological characterization of low-cost sensors for CO_2, CO, NO_X. For CO_2 sensors, a calibration system using reference gas mixtures ensures metrological traceability, employing a primary reference analyser based on non-dispersive infrared spectroscopy. Exploratory findings and preliminary results with CO_2 sensors are detailed in this work and a similar approach is planned for CO and NO_X sensors.**

I. INTRODUCTION

Considering the time spent at home and in the office, it is estimated that people spend 90 % of their time in enclosed buildings [1]. Over the past two decades, there has been a growing concern among the scientific community regarding the impact of indoor air quality on health [2]. According to the World Health Organization (WHO), exposure to poor air quality is the first environmental threat to global public health, and 90 % of the world's population suffers from exposure to air quality that is below the WHO guidelines' prescriptions [3].

Modern energy-efficient buildings, often constructed with synthetic materials and increased airtightness, can contribute to non-industrial indoor air pollution, which is associated with a range of symptoms and health issues [4]. Indoor Air Pollutants (IAPs) include particulate matter (PM), biological organisms (fungal spores, bacteria and viruses), allergens, volatile organic compounds (VOCs), inorganic compounds (ICs) such as carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxides (NO_x) and ozone (O_3) [5].

The primary sources of indoor CO_2 are combustion reactions during household activities and from human metabolism [6]. CO_2 concentration is often used as an indicator of Indoor Air Quality (IAQ) due to the direct relationship between human occupancy and CO_2 levels in indoor environments [7].

IAQ problems can occur when CO_2 levels exceed 1000 ppm, for this reason real-time monitoring of CO_2 levels is essential to identify problems and take prompt action within the building [7].

Traditional approaches to air pollution monitoring are based on the use of expensive stationary equipment, which makes it very difficult to carry out detailed observations in indoor environments [8].

In the last two decades, there have been substantial advancements in low-cost sensor technologies, which has enhanced the monitoring of air pollution but also caused a rapid modification of the prevailing circumstances [7].

In this context, the term "low-cost" is typically associated with the expense of the fundamental sensing analytical component (the sensor) required for measurement, as opposed to the overall operational costs associated with sensor systems [9]. The utilisation of low-cost sensors for measurement purposes has been demonstrated to frequently yield data of inferior quality and affected by larger uncertainty in comparison to the data produced by official monitoring stations operated by EU Member States [10]. These stations adhere to European legislation and international standard methodologies at this stage of development [10]. Nonetheless, the current characterisation of low-cost sensors is inadequate [11]. The absence of standardised validation methods for these systems presents a considerable barrier to the orderly growth of the market, as indicated by manufacturers of sensors and systems [11].

The present work investigates the characteristics of a typical low-cost sensor for IAQ monitoring by comparison with high-quality instruments, using a climate chamber that isolates the sensor from external environmental influences. This study distinguishes itself from previous works by placing particular attention on metrological traceability in all the characterization process and not only for the gaseous mixtures used like in [7]. This study is part of a multidisciplinary Italian project for the monitoring of internal environmental quality (IEQ), the MIRABLE Project.

II. MIRABLE PROJECT

The MIRABLE project - Measurement Infrastructure for Research on heAlthy and zero energy Buildings in novel Living lab Ecosystems - is among the Research Projects of Relevant National Interest (PRIN) 2022. It is carried out in cooperation between the Italian National Metrology Institute, INRiM, and the Politecnico di Torino, PoliTo. The project aims to develop a measurement infrastructure for research on healthy and zero-energy buildings, focusing on the characterization of low-cost and wearable sensors within a Living Lab (LL) ecosystem. This project seeks to bridge the gap between expected and actual building performance by incorporating multi-domain studies of indoor environmental quality (IEQ) and occupant interaction.

The project will establish a methodology for monitoring various aspects of IEQ, including thermal comfort, acoustics, lighting and IAQ to understand their interactions and effects on occupants. This holistic approach contrasts with existing studies that often focus on single domains.

A core objective is to define, calibrate, and test both static and wearable sensors to ensure reliable data. This includes developing metrological characterization protocols and ensuring traceability to national standards. This also addresses the challenge of using low-cost sensors and wearable devices by developing a framework to define, calibrate and test them.

III. MATERIALS AND METHOD

To ensure the reliability and metrological traceability of the measurement results, an experimental approach was adopted, based on the use of certified gas mixtures for the calibration of the used instrumentation.

The exploitation of certified reference materials ensures the comparability and traceability of results obtained by different laboratories. This, in turn, fosters traceability across diverse societal domains and maintains a global and uniform system of measurement [7]. Traceability chains have a tree form during calibrations, adhering to ISO 17025 and ISO 17043 [12], [13].

The tests carried out at INRiM involved the use of a reference instrument, a LI-850 gas analyzer (Fig. 1) produced by LI-COR (USA) that uses non-dispersive infrared spectroscopy (NDIR) as measurement principle to detect gases in air [14]. NDIR is proposed by the World Meteorological Organisation (WMO) as a method of detection because it is a robust and selective technique that can be easily adapted to portable instruments [15]. The measurement range of CO_2 for this instrument is (0-20,000) ppm and for H_2O is (0-60) mmol/mol from datasheet [14]. The instrument was previously characterised and calibrated in the range (0-1000) ppm, according to an internal procedure established by INRiM. The procedure was carried out in accordance with a seven-point calibration, employing certified gas mixtures of CO_2 in N_2.

Fig. 1. LI-850 gas Analyser

The used low-cost CO_2 sensor was a CozIR-LP (Fig. 2) produced by Gas Sensing Solution Ltd [16]. The CozIR-LP is a low power NDIR CO_2 sensor using state-of-the-art solid-state LED optical technology. The CO_2 measurement range from the datasheet is (0-5000) ppm and the performance characteristics declared an accuracy of ± 30 ppm +3 %, and a response time of 30 s [16].

Fig. 2. Low-cost CO_2 sensor CozIR-LP, front and back

Seven certified gas mixtures were used as references of known CO_2 concentration in N_2 plus one as span gas. These were prepared by other National Metrology Institutes (NMI) and Italian Accredited Calibration Laboratory (LAT), namely the National Metrology Institute of Netherlands (VSL), the National Physical Laboratory of UK (NPL) and Società Italiana Acetilene e Derivati (SIAD, Italy). The span gas was produced by LAT SAPIO (Italy). Concentrations ranging from 200 ppm to 900 ppm were selected to cover the environmental range (Table 1). Furthermore, a cylinder of pure N_2 (6.0 grade) from Air Liquide (Italy) was utilised as zero gas.

Table 1. Gas Mixtures used for the characterisation tests

Producer	Mixture	CO_2 in N_2	U (CO_2)

	Code	Concentration (ppm)	$k = 2$ (ppm)
VSL	D245855	200.13	0.40
SIAD	189824	300.0	1.0
VSL	D563026	400.7	0.8
VSL	D245865	500.11	0.75
SIAD	189835	700.7	1.8
NPL	D109159	751.8	1.5
VSL	D245748	900.3	1.4
SAPIO	5113561	801.0	13

In the present work, two calibrated Mass Flow Controllers (MFCs) (MKS Instruments, USA), with full-scale range of 1000 standard cubic centimetres (SCCM) and 2000 SCCM, respectively, were used.

The chamber into which the low-cost sensor was inserted is a linear AISI 304L stainless steel tube with a narrower end to allow the sensor cables to exit without too much ambient air entering (Fig. 3). Consequently, a known concentration environment was established, isolated from external influences.

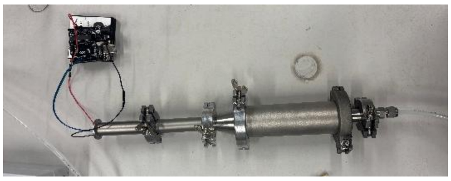

Fig. 3. Linear AISI 304L stainless steel tube with a narrower end into which the low-cost sensor is inserted

The experimental setup involves the sequential passage of the gas mixtures through the MFCs, to regulate the flow rate to 775 SCCM. The gas is introduced into the LI-COR 850 reference instrument, where the initial measurement is conducted. The LI-COR 850 output is connected to the stainless-steel tube into which the low-cost sensor is inserted, where it takes the measurements.

Fig. 4 presents a schematic representation of the complete measuring system.

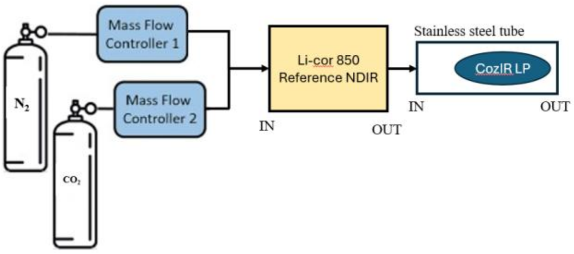

Fig. 4. Schematic representation of the measuring system

The utilisation of this system permitted the acquisition of a calibration curve for the low-cost sensor.

IV. EXPERIMENTS AND RESULTS

The first activities carried out at INRiM in the IAQ framework within the MIRABLE project were focused on CO_2, due to its importance as indoor air pollutant and the adverse health effects attributable to its accumulation in indoor spaces.

Initially, the span gas was measured, which is subsequently analysed in this study as a preliminary test of the short-term stability of the low-cost sensor CozIR-LP (Fig. 5). The test was conducted from the zero point, at which N_2 was fluxed, to the point at which the sensor reached its own stability. The gas mixture utilised was the SAPIO 5113561 at a concentration of CO_2 of 801.0 ppm. The sensor achieved its stability after 60 s, while the return to the initial state occurred within 50 s. The median value of CO_2 obtained from the acquisitions of the low-cost sensor is 660 ppm. The high-quality instrument does not exhibit systematic deviations, due to the greater stability and superior accuracy of the primary instrument, whereas the low-cost instrument shows an average systematic deviation of 140 ppm.

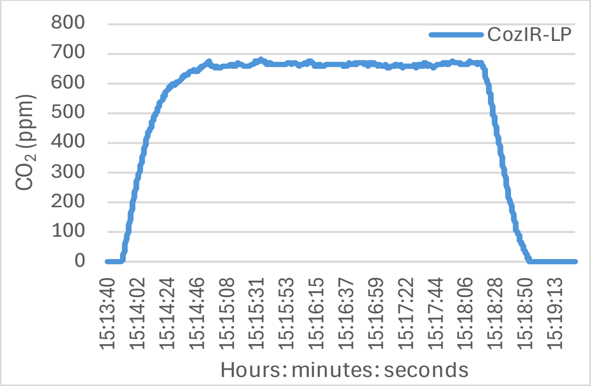

Fig. 5. Short-term stability of the low-cost sensor CozIR-LP, with a gas mixture of known concentration of CO_2 in N_2 of 801.0 ppm

The measurements were obtained on two consecutive days, employing the seven mixtures reported in Table 1. On the first day of the experiment, the mixtures were analysed following an increasing concentration of CO_2 in N_2. On the second day, the analyses were carried out in decreasing order.

The experimental process involved the repetition of the measurement of each sample for five times for each mixture. Each measurement was interspersed with the passage of N_2 to obtain a sensor perturbation. The contribution of the measurement repeatability was considered by calculating the standard deviation of the repeated analyses.

Fig. 6 illustrates, as an example, five measurements made with the two devices for the gaseous mixture of CO_2 in N_2

with a known concentration of 500.11 ppm, on two consecutive days. Evidently, the LI-COR 850 demonstrates superior accuracy and repeatability in comparison with the low-cost sensor. The standard deviation of the LI-COR 850 is only 0.11 ppm the first day and 0.2 ppm on the second day. For the CozIR-LP the standard deviation is 6.37 ppm and 6.06 ppm, respectively.

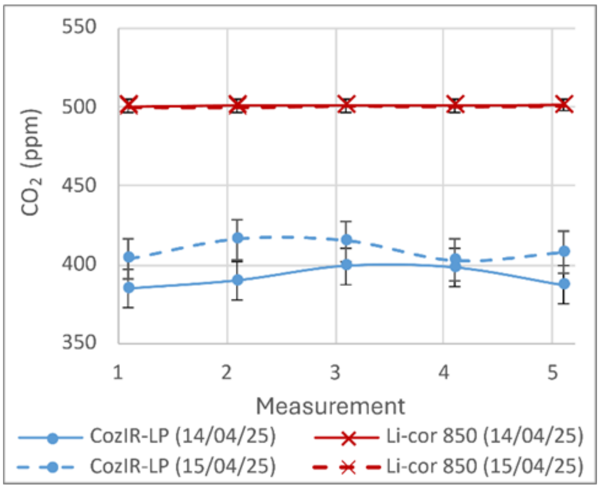

Fig. 6. Measurements made with a mixture CO_2 in N_2 of known concentration (500.11 ppm) using the reference instrument LI-COR 850 and the low-cost sensor CozIR-LP, on two consecutive days

The data were processed using the CCC software [17] developed at INRiM. The software applies the Weighted Total Least Squares algorithm (WTLS) and calculates the estimates of the fitting curve parameters and associated covariance matrix, the normalised chi-squared value of the fit, the fitted y values and associated covariance matrix, and the plot of the fitting curve with uncertainty bars on the y-axis.

The calibration curve is usually fit to the data (concentration/response pairs) using a least squares approach [18]. Fig. 7. Calibration curve of the low-cost sensor CozIR-LP obtained using CCC softwareFig. 7 presents the calibration curve of the low-cost sensor, obtained with the use of WTLS, where the uncertainties in both the dependent and the independent variables are kept into account. The x-axis denotes the certified concentration values, whilst the y-axis indicates the instrument readings. The errors bars in the graph represent the standard deviation of y-values. It is immediately evident that the low-cost CO_2 sensor demonstrates linear behaviour over the entire measurement range.

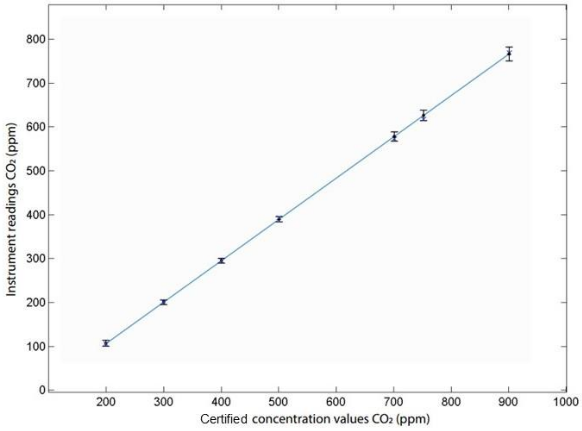

Fig. 7. Calibration curve of the low-cost sensor CozIR-LP obtained using CCC software

The chi-square value, when normalized (or reduced), provides a measure of how well a statistical model fits a set of observations, considering the expected variations in the data. A reduced chi-square value close to or smaller than 1 is generally an indication of good fit. The chi-square value result obtained via the CCC software was, in this case, 0.12.

V. CONCLUSION

This work presents the activity carried out at INRiM for ensuring metrological traceability of the measurement results of CO_2 obtained with a typical low-cost sensor, as part of the activities carried out in the MIRABLE Project.

The study utilised certified gas mixtures and calibrated instrumentation for this purpose. A comparison was conducted between the low-cost sensor CozIR-LP, with a CO_2 detection range of (0-5000) ppm, and the LI-COR 850 NDIR analyser. The LI-COR reference instrument demonstrated superior precision and accuracy in measurement when compared with the CozIR-LP. The short-term stability of the low-cost sensor was analysed, which proved to stabilise in 60 s instead of 30 s, as stated in the datasheet. The CozIR-LP exhibited optimal linear performance across the entire study range, as evidenced by its remarkably low chi-squared value. Future tests will involve the analysis of unknown gas mixtures with the characterised low-cost sensor to further evaluate the sensor's performance and measurement reliability.

Low-cost IAQ sensor characterization studies and calibration procedures will enable future expansion of more accessible, integrable monitoring systems for indoor environmental quality studies.

VI. ACKNOWLEDGMENT

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