Metrological characterisation of low-cost and wearable sensors for research on healthy buildings in a novel Living Laboratory

Original

Metrological characterisation of low-cost and wearable sensors for research on healthy buildings in a novel Living Laboratory / Rolle, Francesca; Favoino, Fabio; Arcamone, Giuseppina; Pellegrino, Anna; Russo, Ramona; Iacomussi, Paola; Musacchio, Chiara; Bottacin, Alberto; Pavarelli, Stefano; Prato, Andrea; Schiavi, Alessandro; Sega, Michela. - In: EPJ WEB OF CONFERENCES. - ISSN 2100-014X. - 323:(2025). (22nd International Metrology Congress, CIM 2025 Lione (Francia) 11-14 March 2025) [10.1051/epjconf/202532304001].

Publisher:
EDP Sciences

Published
DOI:10.1051/epjconf/202532304001

Metrological characterisation of low-cost and wearable sensors for research on healthy buildings in a novel Living Laboratory

Francesca Rolle [1*], *Fabio* Favoino[2], *Giuseppina* Arcamone[2], *Anna* Pellegrino[2], *Ramona* Russo[1,2], *Paola* Iacomussi[1], *Chiara* Musacchio[1], Alberto Bottacin[1], *Stefano* Pavarelli[1], *Andrea* Prato[1], *Alessandro* Schiavi[1], and *Michela* Sega[1]

[1]INRiM, Istituto Nazionale di Ricerca Metrologica, 10135 Torino, Italy
[2]Department of Energy, Politecnico di Torino, 10129 Torino, Italy

Abstract. To achieve the EU targets in terms of ecological transition, and to assure people health, wellbeing and comfort in the indoor environment, research in the building sector plays a fundamental role. In the last decades the energy efficiency and indoor environmental quality (IEQ) of buildings have increased significantly, but a gap between the actual operational performances of sensors and the expected measurement results and still exists. The Italian project "MIRABLE - Measurement Infrastructure for Research on heAlthy and zero energy Buildings in novel Living lab Ecosystems", carried out in cooperation between the Italian National Metrology Institute, INRiM, and the Polytechnic University of Torino, aims to develop a methodology to reduce this gap by creating and validating a measurement infrastructure for monitoring the multi-domain indoor environmental conditions and the occupants' interaction in a full scale Living Laboratory (denominated "H-IEQ LL"). The final goal of the research is to support the realisation of healthy and smart buildings and to reduce energy use. Among the activities of the MIRABLE project, the development of methodologies for defining a ground-truth for low-grade and wearable sensors for IEQ measurements in ongoing. After a thorough analysis of the sensors available on the market, and of the best practices to monitor the occupants' comfort and interaction with buildings, a set of sensors were selected and metrologically characterised for the four domains on interest for the H-IEQ LL: thermal conditions, lighting conditions (spectral distribution included), acoustic conditions and indoor air quality. The monitoring of the response of the occupants to these variables, by means of low-cost sensors mounted on fixed monitoring stations in the LL and of wearable sensors, will allow to evaluate their feedbacks and interaction with the building systems in a dynamic mode. An overview of the results obtained from the metrological characterisation of IEQ sensors carried out at INRiM, and the preliminary calibration for some of the measured variables (e.g. temperature, sound pressure, CO_2 level, lighting), are presented in this work. The sensors will be installed in the LL, to create a sensor network for multi-domain monitoring of the physical environment and some wearable sensors will be used to monitor the occupant related quantities in a well-controlled environment. A methodology for the sensors *in situ* use, data collection and periodic calibration is also under definition.

1 Introduction

Office workers spend an average of 8.5 h in indoor environments [1]. Indoor environment conditions have a great influence on occupants' health, feeling and work productivity [2]. The World Health Organization (WHO) has demonstrated that approximately 30 % of employees experience a level of discomfort that results in a significant decrease in productivity [3].

In this context, Indoor Environmental Quality (IEQ) is a relative measure of comfort perception by people exposed to the indoor conditions [4]. The parameters for the design and assessment of the energy performance of buildings and IEQ cover indoor air quality, thermal environment, lighting and acoustics [5]. IEQ is evaluated using two strategies: Post Occupancy Evaluation (POE) and instrumental measurements [6]. The data collected by the instrument are treated as an objective assessment of the subjective evaluation made by the POE [6]. The interaction between IEQ parameters is characterized by significant variability in both space and time, due to the complex nature of these parameters [7]. Consequently, there is an increased focus on the utilization and development of instruments for measuring these parameters, which vary in type and quantity for each domain.

A number of recent studies have demonstrated the potential of low-cost instruments [8, 9, 10] and wearable devices [11, 12, 13] for monitoring IEQ, with the notable advantage of costing up to three orders of magnitude less than standard reference instruments [14]. Low-cost sensors used for measurements often have lower and more questionable data quality than the official monitoring stations conducted by EU Member States in accordance with European legislation and international standards methods at this stage of development [15]. However, low cost sensors are poorly characterized and the lack of standardized validation

---

[*] Corresponding author: f.rolle@inrim.it

methods for this systems is a significant obstacle to the market's orderly expansion [16]. Some of the most innovative research involves multi-sensors [17, 18], which attempt to integrate as many sensors as possible into a single instrument to capture environmental parameters that affect user comfort. It is clear that the variety and amount of these data make the development of such instruments a complex and necessarily multidisciplinary research process.

2 MIRABLE Project

Among the Research Projects of Relevant National Interest (PRIN) 2022 is the MIRABLE project - Measurement Infrastructure for Research on heAlthy and zero energy Buildings in novel Living lab Ecosystems", carried out in cooperation between the Italian National Metrology Institute, INRiM, and the Polytechnic University of Torino. 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 indoor air quality (IAQ) to understand their interactions and effects on occupants. This holistic approach contrasts with existing studies that often focus on single domains. The future monitor Living Lab (LL) will involve people in both monitoring and innovation, creating a real-life environment for research into IEQ and occupant behaviour, as well as advanced building technologies.

MIRABLE also emphasises the inclusion of the occupants as sensors. This involves the use of wearable sensors to both the environmental parameters that influence the occupant's comfort and some "human" parameters that provide immediate feedback on the human perception of the environment. 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 addresses the challenge of using low-cost sensors and wearable devices by developing a framework to define, calibrate and test them.

3 Low-Cost and Wearable Sensors for each domain

The European standard EN 15251:2007 [5] specifies indoor environmental parameters that have an impact on the energy performance of buildings, without directly considering occupant comfort and calibration method of instruments. The standard deals in detail with the thermal environment, acoustics, lighting and indoor air quality. The research therefore followed the same division of study areas, each of which is discussed in more detail in the following paragraphs.

3.1 Thermal domain

Air temperature is one of the environmental parameters contributing to the evaluation of the IEQ. However, sensors of different type, shown in Fig. 1, are included in the characterization protocol because an effective estimation of thermal comfort not only requires the knowledge of the environmental temperature, but also the study of correlations with the skin temperature of the occupant. Therefore, board mount thermometers will be characterized for the measurement of air temperature, whereas a wearable sensor and different infrared cameras will be test for the measurement of the occupant skin temperature.

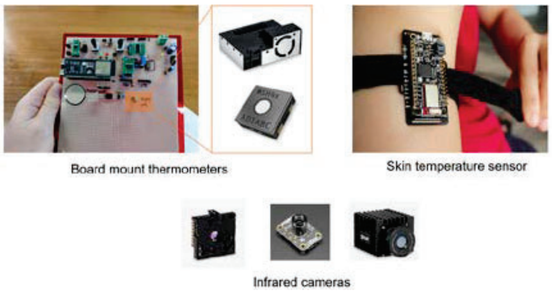

Fig. 1. Low-cost sensors under characterization for the thermal domain.

3.1.1 Board mount thermometers

Low-cost board mount thermometers can come in different design and working principles depending on the manufacturer. However, the accuracy of these sensors not only depends on the production quality or manufacturer calibration, but it can be mainly dependent on the position on the board, which should be optimized to reduce the influence of unwanted heat sources. Moreover, the coupling between the sensor and the medium of interest (air) should also be enhanced, as for example in Fig. 1 where a low-cost sensor is exposed to air by mounting it vertically.

Having in mind such design considerations, a batch of board mount thermometers will be characterized in a climatic chamber using reference Pt100 traceable to the ITS-90 (Fig. 2) to test their accuracy and production variability. During the characterization some sensors will be moved in different positions on the board prototype to check the influence of heat sources from other electronic components. After a year of full operation, it is planned to re-characterized the sensors to verify their stability and reliability over time.

The range of air temperature for the tests will be from 15 to 35 °C

Fig. 2. INRiM laboratory setup: on the right the Kambic climatic chamber, whereas on the left the reference Pt100 and the Fluke DAQ temperature scanner.

3.1.2 Wearable skin thermometer and infrared cameras

The thermodynamic state of a wearable skin thermometer changes for two main causes: the heat conduction between the sensor and the skin and the convective heat transfer with the air. To characterize the behaviour of a wearable skin thermometer is therefore necessary the use of a controlled surface temperature source. The setup should be placed in a climatic chamber to increase the representativeness of the procedure and verify the influence of the environment on the sensor.

Based on the equipment available at INRiM laboratory, a surface temperature source will be obtained by circulating demineralized water of a thermostatic bath inside an aluminium box (Fig. 3). The developed system will be characterized by estimating the surface temperature using calibrated mini Pt100, and evaluating stability and uniformity of the surface. The wearable sensor will be placed on the surface for the characterization by comparison with the surface temperature estimated by the mini Pt100. This setup satisfies the accuracy required for the intended use, being also compatible with the use in a climatic chamber and allows to analyse the behaviour under different combinations of surface/skin and environmental temperatures.

Sensors will be tested in a range of temperature between 25 and 37 °C for ambient condition between 15 and 35 °C.

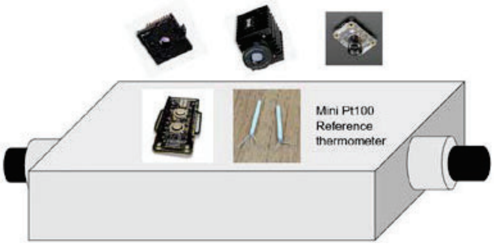

Fig. 3. Controlled surface temperature source for characterization of skin thermometers and tests of infrared cameras.

Exploiting the developed system, it is also possible to test low-cost infrared cameras. In principle, the characterization of these sensors requires high-grade equipment such as blackbody calibrators. However, having a stable surface temperature with an estimated homogeneity, it is possible to test the measurement repeatability of the cameras, the pixel-homogeneity, but also check their stability in the short and medium term.

3.2 Acoustic domain

The application of MEMS technology to acoustic sensors has led to the development of small and low-cost microphones with very high performance. MEMS microphones are fabricated on semiconductor production lines using silicon wafers and highly automated processes. Nevertheless, at present day, current standards do not provide adequate procedures for calibrating this kind of sensors, due to geometric limitations and other incompatibilities. The consequence is that reliability of data provided by MEMS microphone is not supported by uncertainty budget and traceability statement, being a relevant obstacle for safe and accurate implementations.

The characterization of the MEMS microphone (STM Model MP34DT05-DS) was carried out starting from the IEC 61094-5 standard [19], which provides a calibration method for comparison with standard laboratory microphones. This method consists of placing two microphones, the reference one and the one under test, at close distance (≤ 1 mm), facing the membranes of the two microphones in a sound pressure field. The detailed description can be found in [20]. By measuring the MEMS output voltage, the various acoustic parameters were obtained. Sensitivity, frequency response, stability, signal-to-noise ratio and distortion were measured in a semi-anechoic chamber. To measure the variation of sensitivity with temperature, the two microphones were placed in a small climate chamber, using a horn speaker as a source.

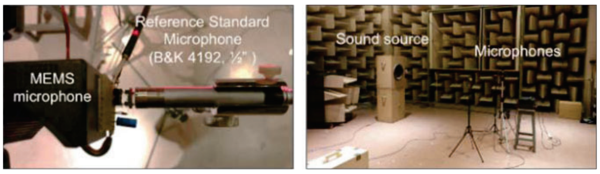

Fig. 4. The MEMS microphone and the reference microphone in a semi-anechoic chamber.

To evaluate the sensitivity and frequency response, pure tones from 20 Hz to 5 kHz with 1/3 octave step were generated for about 30 seconds, as shown in Fig 5.

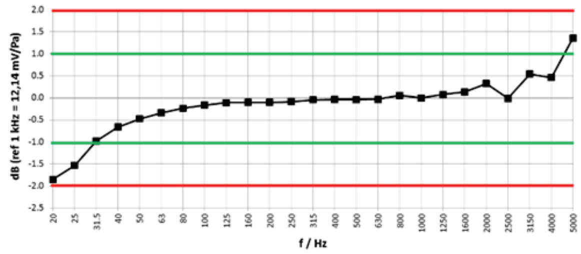

Fig. 5. Frequency response of the MEMS microphone

The measured sensitivity of the MEMS microphone is 12.14 mV/Pa (-38.32 dB, ref 1 V/Pa), at 1000 Hz. In

Fig. 5, the graph shows the frequency response of the MEMS microphone, normalized with respect to 1000 Hz and compared with the Sound Level Meter limits for Class 1 (green) and Class 2 (red).

The stability was measured using a pure tone at 1000 Hz for a period of 140 minutes. In particular, there is an increase of 0.1 dB in 813 seconds, an increase of 0.2 dB in 2030 seconds and an increase of 0.3 dB in 5095 seconds.

The measured internal noise of the reference microphone and the measurement chain was 17.5 dBA, while for the MEMS microphone 32.9 dBA were measured. In this case, A-weighting was used to eliminate the contribution of ambient noise due to low frequencies. This resulted in a S/N ratio of 61.1 dB (reference set to 94 dB).

For the measurement of distortion (THD), a 1000 Hz sinusoid was generated at 1 dB intervals starting from 110 dB up to 125 dB. Compared to the signal measured with the reference microphone whose distortion, below 140 dB, is completely negligible, a THD of 0.8% at 121 dB, 3.8% at 122 dB and 9.7% at 124 dB was obtained.

3.3 Lighting domain

The knowledge of individual light exposure plays a crucial role on studies on human health and wellbeing, especially since the discovery of photosensitive retinal ganglion cells (ipRGCs) having nonvisual effects on human release of various neurotransmitters and hormones (e.g. sleep / wake pattern) [21]. In addition, even the level and spectral distributions of light seem having effects on brain health [22] and eyesight defects (e.g. myopia) [23]. Low-cost, portable spectrometers capable of measuring the spectral power distributions of light sources and ad hoc wearable sensors are available on the market. They can capture spectral power density data in the visible and nearer ranges (near IR, blue light) and by using the tabulated ipRGCs spectral sensitivity functions stated in CIE S026:2018 report [24], calculate the relevant α-opic irradiances.

3.3.1 Preliminary tests

The first tests have been carried out on 14 LYS wearable sensor and one nano-Lambda miniaturized portable spectrometer. The tested quantities were illuminance, melanopic irradiance and Correlated Colour Temperature (CCT). Melanopic irradiance is crucial for understanding key impact of light on human well-being, monitoring IEQ and designing circadian friendly lighting. The sensors have been tested at different irradiance levels (from 3 lx up to 14 klx), CCT (3000 K, 4000 K, 6000 K) by exposing the sensors for short and long time to light (1 minute up to 3 hours). Further test will include PWM sensitivity and stress tests by cycling exposure to dark and light set-up. Preliminary results showed large discrepancies among the different LYS sensors and reference instruments (variable from 4% up to 30%, depending on the quantity of interest) and investigations are on the way because influences of LED flicker is supposed to explain discrepancies. Further tests will include PWM sensitivity and stress tests by cycling exposure to dark and light set-up.

3.4 Indoor Air Quality domain

Indoor Air Pollutant (IAP) is a generic acronym, including several categories of pollutants, including inorganic compounds (ICs) such as carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxides (NO_x) and ozone (O_3), among others [25].

The primary sources of CO, SO_2 and NO_2 in residential environments are the combustion process in gas stoves and woodstoves [25].

The main source of indoor CO_2 are combustion reactions during household activities and from human metabolism [25]. Metabolic CO_2 released by respiration has a major impact on the overall CO_2 concentration in office environments and transportation vehicles [25].

Various regulations and standards define acceptable CO_2 concentration levels for the design of ventilation systems in buildings. The European Standard EN 13779:2008 [26] sets the minimum indoor air guideline value (IAGV) for CO_2 at 800 ppm_v. In the United States, the Occupational Safety and Health Administration (OSHA) has established a Permissible Exposure Limit (PEL) for CO_2 at 5000 ppm_v averaged over an 8-hour workday [27].

3.4.1 Preliminary tests

The first activities carried out at INRiM in the IAQ framework within the MIRABLE project were focused on CO and CO_2, due to their importance as indoor air pollutants and their adverse health effects attributable to accumulation in indoor spaces. The first tests were carried out on a pair of low-cost CO sensor (model MQ-7, HANWEI ELECTRONICS CO., LTD., China).

The MQ-7 gas sensor is composed of a sensitive material, SnO_2, which exhibits reduced conductivity in clean air. The sensor detects CO in the presence of low temperatures (heated by 1.5 V), utilising method of cycle of high and low temperatures [28]. The sensor's conductivity increases in proportion to the gas concentration. It is necessary to utilise a simple electrocircuit to transform the change of conductivity into a corresponding output signal of gas concentration. In this instance, an Arduino board was employed, with specific programming.

In this study, two sensors of the same type were utilised. According to the technical datasheet [28], the initial stabilisation time required a minimum of 48 hours. The MQ-7_02 sensor had been activated in the days prior to the experimental trials for the purpose of conducting preventative analyses.

Figure 6 shows the short-term stability of the two sensors, MQ-7_01 and MQ-7_02, from the moment they were activated. It is evident that the MQ-7_01 sensor demonstrates greater stability than the MQ-7_02 sensor, which was previously warmed up before use. In addition, the MQ-7_02 sensor attained stability in a shorter time compared to the MQ-7_01 sensor. This occurrence can be attributed to the fact that the MQ-

7_02 sensor had previously been activated. The two data were then normalized, following the indications in the technical data sheet.

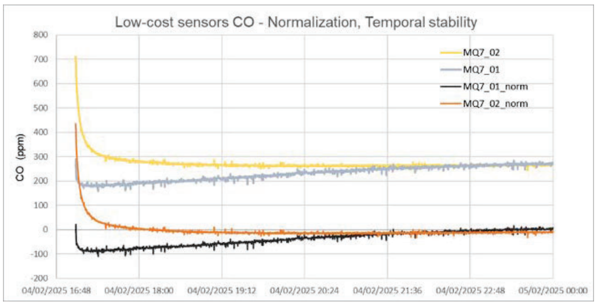

Fig. 6. Test on temporal stability of two CO low-cost sensors, namely MQ-7_01 and MQ-7_02.

Subsequently, the sensors were tested for their response time. The sensors were exposed to a source of smoke, containing CO, using a sheet of paper that was incinerated near the sensors. The response time of the sensors was investigated by repeatedly switching on and off the paper fire, and the results suggest that the sensors respond immediately, with a response time of few seconds.

3.4.2 Procedure for calibration of CO_2 and CO low-cost sensors

At INRiM, a procedure for the calibration of low-cost sensors (CO_2 and CO, but adaptable also to other analytes, e.g. nitrogen oxides) was developed. The system for the calibration of the sensors comprises an *ad hoc* climatic chamber (realised by Montepaone S.r.l., Italy), in which the sensors can be housed, with their corresponding Arduino microcontroller. The chamber can be evacuated and then filled with gas mixtures of CO_2 or CO at known composition, by using a system of mass-flow controllers (MFC) and a small dilution chamber. Certified reference gas mixtures are connected to one of the gas lines and diluted with a proper pure gas (either nitrogen 6.0 grade or synthetic air) to the final target concentration). The climatic chamber is then connected to a non-dispersive infrared analyser (NDIR, ABB model URAS 14, Switzerland), equipped with different measurement channels selective for CO_2 and CO, to allow the verification of the concentration of the mixtures filling the climatic chamber, and to compare the response of the low-cost sensors with a high-quality laboratory instrument.

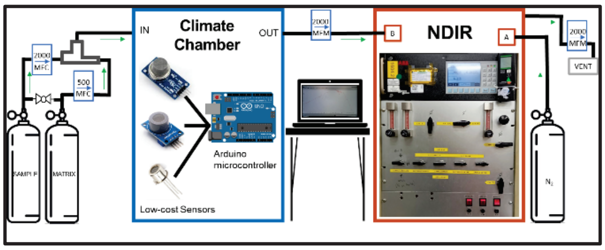

Fig. 7. Schematic representation of the INRiM set-up for the calibration of CO_2 and CO low-cost sensors.

In figure 7, the schematic representation of the system realised at INRiM for the characterisation and calibration of CO_2 and CO low-cost sensors is represented.

4 Conclusion

In summary, the aim of the project is to define, realise and demonstrate the effectiveness of a methodology for multi-domain research to be implemented in Living Labs, including the measurement of physical variables related to IAQ, thermal, lighting and acoustic environments, and the collection of non-physical data related to the occupant, their responses and interactions. The main outcome of the project will be the design and implementation of a working model for Living Labs dedicated to research on healthy and energy efficient buildings. In particular, a metrologically calibrated measurement infrastructure with high and/or low-grade sensors for monitoring the whole physical environment through static and dynamic measurements (wearable sensors for occupant related measurements) will be set-up. A very important part is the definition of measurement procedures and protocols for both environmental sensors and personal (wearable) sensors to ensure appropriate data sampling for each domain without compromising the realistic aspect of the environment.

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. V. Surawattanasakul, W. Sirikul, R. Sapbamrer, K. Wangsan, J. Panumasvivat, P. Assavanopakun, S. Muangkaew, Respiratory Symptoms and Skin Sick Building Syndrome among Office Workers at University Hospital, Chiang Mai, Thailand: Associations with Indoor Air Quality, AIRMED Project, Int. J. Environ. Res. Public Health **19**, 17, 10850, (2022). https://doi.org/10.3390/ijerph191710850
2. J. Wu, J. Weng, B. Xia, Y. Zhao, Q. Song, he Synergistic Effect of PM2.5 and CO2 Concentrations on Occupant Satisfaction and Work Productivity in a Meeting Room, Int. J. Environ. Res. Public. Health. **18**, 4109 (2021). https://doi.org/10.3390/ijerph18084109
3. World Health Organization, World Health Organization eds: Indoor air quality: biological contaminants: report on a WHO meeting, Rautavaara, 29 August-2 September 1988. World Health Organization, Regional Office for Europe, Copenhagen, 67, (1990).

4. M. Piasecki, K. Kostyrko, S. Pykacz, Indoor environmental quality assessment: Part 1: Choice of the indoor environmental quality sub-component models, J. Build. Phys. **41**, 264 (2017). https://doi.org/10.1177/1744259117702882
5. EN 15251:2007 - UNI Ente Italiano di Normazione, (2017).
6. I. Mujan, A. S. Anđelković, V. Munćan, M. Kljajić, D. Ružić, Influence of indoor environmental quality on human health and productivity - A review, J. Clean. Prod. **217**, 646 (2019). https://doi.org/10.1016/j.jclepro.2019.01.307
7. T. Parkinson, A. Parkinson, R. de Dear, Continuous IEQ monitoring system: Context and development, Build. Environ. **149**, 15 (2019). https://doi.org/10.1016/j.buildenv.2018.12.010
8. G. Coulby, A. K. Clear, O. Jones, A. Godfrey, Low-cost, multimodal environmental monitoring based on the Internet of Things, Build. Environ. **203**, (2021). https://doi.org/10.1016/j.buildenv.2021.108014
9. M. Kim, H. Zhang, A. Tzempelikos, A. Gasparella, F. Cappelletti, New Low-Cost Sensing Network for Indoor Environmental Monitoring and Control in Buildings., 41st AIVC/ASHRAE IAQ- 9th TightVent - 7th venticool Conference - Athens, Greece - 4-6 May 2022, (2023).
10. M. Gola, A. Laghezza,Y. Yu, G. Settimo, S. Capolongo, How to promote health in indoor living and working spaces: quali-quantitative analysis to evaluate the indoor air quality through users' perception and low-cost sensors. Eur. J. Public Health. **34**, ckae144.491 (2024). https://doi.org/10.1093/eurpub/ckae144.491
11. B. Abboushi, S. Safranek, E. Rodriguez-Feo Bermudez, S. Pratoomratana, Y. Chen, M. Poplawski, R. Davis, A Review of the Use of Wearables in Indoor Environmental Quality Studies and an Evaluation of Data Accessibility from a Wearable Device., Front. Built Environ. **8**, (2022). https://doi.org/10.3389/fbuil.2022.787289
12. F. Salamone, S. Sibilio, M. Masullo, Integrated Approach for Human Wellbeing and Environmental Assessment Based on a Wearable IoT System: A Pilot Case Study in Singapore., Sensors. **24**, 6126 (2024). https://doi.org/10.3390/s24186126
13. M. Kong, J. An, D. Jung, T. Hong, Occupant-centered indoor environmental quality management: Physiological response measuring methods., Build. Environ. **243**, 110661 (2023). https://doi.org/10.1016/j.buildenv.2023.110661
14. L. Morawska, P. K. Thai, X. Liu, A. Asumadu-Sakyi, G. Ayoko, A. Bartonova, A. Bedini, F. Chai, B. Christensen, M. Dunbabin, J. Gao, G. S. W. Hagler, R. Jayaratne, P. Kumar, A. K. H. Lau, P. K. K. Louie, M. Mazaheri, Z. Ning, N. Motta, B. Mullins, M. M. Rahman, Z. Ristovski, M. Shafiei, D. Tjondronegoro, D. Westerdahl, R. Williams, Applications of low-cost sensing technologies for air quality monitoring and exposure assessment: How far have they gone? Environ. Int. **116**, 286 (2018). https://doi.org/10.1016/j.envint.2018.04.018
15. Measuring air pollution with low-cost sensors Thoughts on the quality of data measured by sensors, European Commission, JRC, (2017).
16. Pioneering next-generation air quality monitoring by metrological validationof low-cost particulate matter sensor, Euramet, Call 2023.
17. T. Parkinson, A. Parkinson, R. de Dear, Introducing the SAMBA indoor environmental quality monitoring system., 49th International Conference of the Architectural Science Association (2015).
18. A. Barbaro, P. Chiavassa, V. I. Fissore, A. Servetti, E. Raviola, G. Ramírez-Espinosa,E. Giusto, B. Montrucchio, A. Astolfi, F. Fiori, Data Acquisition, Processing, and Aggregation in a Low-Cost IoT System for Indoor Environmental Quality Monitoring. Appl. Sci. **14**, 4021 (2024). https://doi.org/10.3390/app14104021
19. IEC 61094-5:2001, Measurement microphones - Part 5: Methods for pressure calibration of working standard microphones by comparison. Available: https://webstore.iec.ch/en/publication/4489 (Accessed 20 Feb. 2025)
20. A. Prato, N. Montali, C. Guglielmone, A. Schiavi., Pressure calibration of a digital microelectromechanical system microphone by comparison, J. Acoust. Soc. Am. **144(4)**:EL297-EL303 (2018)
21. D. M. Dacey, H.W. Liao, B.B. Peterson, F.R. Robinson, V.C. Smith, J. Pokorny, K.W. Yau, P.D. Gamlin., Melanopsin-expressing ganglion cells in primate retina signal colour and irradiance and project to the LGN. Nature. **433**,749–754 (2025). doi: 10.1038/nature03387
22. K. A. Mazurek, L. Li, R.J. Klein, S. Rong, A. F. Mullan, D. T. Jones, E. K. St. Louis, G. A. Worrell, C. Y. Chen., Investigating the effects of indoor lighting on measures of brain health in older adults: protocol for a cross-over randomized controlled trial. BMC Geriatr 24, 816 (2024). https://doi.org/10.1186/s12877-023-04594-7
23. A. N. French, R.S. Ashby, I.G. Morgan, K.A. Rose, Time outdoors and the prevention of myopia. Exp. Eye Res. **114**, 58–68 (2013). doi: 10.1016/j.exer.2013.04.018
24. Commission International de l'Éclairage. CIE S 026/E:2018 System for Metrology of Optical Radiation for ipRGC-Influenced Responses to Light. Vienna: CIE, (2018).
25. L. R. López, P. Dessì, A. Cabrera-Codony, L. Rocha-Melongo, B. Kraakman, V. Naddeo, M. D. Balaguer, S. Puig, CO2 in indoor environments: From environmental and health risk to potential renewable carbon source, Sci. Total environ. **859** (2023). http://dx.doi.org/10.1016/j.scitotenv.2022.159088
26. UNI EN 13779:2008, Ventilation for non-residential buildings - Performance requirements for ventilation and room-conditioning systems. https://webstore.uni.com/en/uni-en-13779-2008
27. OSHA, Carbon Dioxide in Workplace atmospheres. Available: https://www.osha.gov/sites/default/files/methods/osha-id172.pdf (Accessed 24 Feb. 2025).
28. MQ-7 Semiconductor Sensor for Carbon Monoxide, Datasheet. Available: https://www.pololu.com/file/0j313/mq7.pdf (Accessed 24 Feb. 2025).