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Implementation of an IoT architecture for promoting healthy air quality in 84 homes of families with children

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ABSTRACT

IoT systems incorporating low-cost air quality sensors (LCS) have emerged as valuable tools for empowering citizens to take action to improve indoor air quality (IAQ). This work aimed to assess the effectiveness of a newly developed IoT system in promoting behavioural changes and improving IAQ in 84 homes of families with children. To accomplish this aim, a modular IoT architecture using calibrated LCS was developed to collect real-time data on CO_2, temperature, relative humidity and particulate matter ($PM_{2.5}$ and PM_{10}) during a randomised cross-over trial (November 16, 2022–January 24, 2023). The intervention under study consisted of providing access to real-time IAQ data to participants and alerting them via a smartphone app when CO_2, $PM_{2.5}$, and/or PM_{10} concentrations were higher than the recommended limits. The findings showed that LCS readings were strongly correlated with those obtained from reference equipment. Nevertheless, long-term assessments revealed a signal degradation effect for the readings obtained from the LCS PM sensor. The comparison of IAQ data from control and intervention periods showed a significant alleviation of CO_2 concentrations (mean reduction of 10.3 % in 52 out of 84 participant homes). Notably, about 70 % of participants recognized that data presented through the app motivated them to take valuable actions to enhance IAQ. Overall, this study constitutes a step forward to provide valuable field evidence on the strengths and limitations of using IoT systems based on LCS to empower citizens on the factors that may influence exposure to air pollution at home.

1. Introduction

Clean air is recognized as one of the basic requirements of human health and well-being. The pollution reduction policies and measures implemented in EU member states during the past decades have decreased the hazardous emissions of pollutants to the ambient air [1]. Despite these changes, air pollution is still the largest environmental health risk factor in Europe, causing cardiovascular and respiratory diseases that lead to the loss of healthy years of life and, in the worst cases, to preventable deaths [2]. Thus, air pollution must be addressed as a ubiquitous and urgent public health problem that can be generated outside and inside buildings.

Recently, WHO has documented that the combined effects of ambient and household air pollution have been associated with 6.7 million premature deaths annually worldwide [3]. The home environment, the indoor setting in which people spend a high share of their daily time is an essential contributor to the burden of exposure to air contaminants. Poor indoor air quality (IAQ) in residential buildings has been particularly linked to an increased risk of development of health detriments, including respiratory disorders, cardiovascular diseases, and lung cancer [4]. Although household air pollution has been considered a matter of particular concern for low- and middle-income countries, mainly due to the incomplete combustion of biomass fuels widely used for cooking and heating in those nations, evidence collected for

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higher-income countries also reveals the hazardous impacts of poor home IAQ on health, in particular of children [5–10]. In this regard, studies conducted in the last few years in Portugal, showed that an important percentage of children is living in homes with unhealthy environmental conditions, namely in terms of dampness, darkness, cold and excess noise [11], and also of insufficient ventilation rates and high air pollution levels [12,13].

Children are at a higher risk of suffering from the hazardous effects of exposure to air pollution than adults due to their biological and psychosocial characteristics that can significantly potentiate air pollutant intake and toxic damage. These factors include immature respiratory and immune systems, higher inhalation rate and larger lung surface area per kilogram of body weight compared to adults, and mouth-to-hand behaviour (mainly in early years), among others [14–17]. Importantly, exposure of children to air pollution is very likely to damage their health during childhood and increase the risk of developing diseases later in life [18,19].

Recently, the growth of the Internet of Things (IoT) paradigm [20] and the incremental improvements in sensor technology for building performance evaluation and management hold great promises for providing comprehensive datasets for broadening the knowledge of indoor environment dynamics and developing innovative strategies for assisting building management [21,22]. The availability of innovative miniaturized, low-power, and low-cost sensors (LCS), often integrated into a single chip, has opened up the possibility to gather much improved spatial and temporal resolution data, which motivated their rapid dissemination over the last years [22–24]. A recent comprehensive literature review on existing evidence from the use of LCS for IAQ assessment has supported the high potential of these technologies but also disclosed that LCS have significant drawbacks that need to be considered, namely the typical worse performance in terms of accuracy than the commonly used standard techniques [24]. Further, although LCS have been recognized as an extraordinary opportunity to manage and control buildings, empowering citizens to control their environments [24], currently, there is still a lack of evidence on the potential of these IoT sensing technologies in robust citizen-science studies.

The development of environmental awareness is a basic but pivotal requisite for actively involving citizens in the risk mitigation process of promoting healthy IAQ and creating approval and adoption of the derived corrective measures. In order to unleash an effective environmental behavioural change, knowledge must be gained in an active and problem-solving manner, and it must be delivered in the local context relevant to everyday life. Families with children (parents) constitute a particularly fertile population to promote health literacy [25].

With all the above in mind, in this study, we developed, tested, and implemented a modular IoT system of LCS to continuously monitor temperature, relative humidity, CO_2, $PM_{2.5}$, and PM_{10} in a subset of 84 homes of families with children. A randomised trial was also conducted to investigate the potential of providing access to real-time data on home IAQ through a smartphone app for improving air quality and promoting behaviour changes in participants.

2. Methods

2.1. Study design

This study was developed as part of the framework designed for the Portuguese Pilot developed within a larger project, NUDGE (NUDging consumers towards enerGy Efficiency through behavioural science; https://www.nudgeproject.eu/). The NUDGE project aims at addressing multiple instances of consumer behaviour and testing a set of nudging interventions in scenarios with high potential for energy savings in residential buildings. In particular, the works conducted in Portugal intended to promote long-term energy savings in building energy use while providing healthy and comfortable homes for families with young children. The assessment plan includes collecting data on electricity consumption and indoor air quality in a sample of homes of families with children. The study was approved by the ethics committee of the University of Porto (Nr 114/CEUP/2021), and the recruitment details of participant families and respective characteristics are fully described elsewhere [26]. The intervention plan design for the pilot consisted of the implementation of 3 sequential interventions (1st/2nd/3rd intervention phases, called also of NUDGE 1, NUDGE 2, and NUDGE 3) that were independently delivered to the users using a pilot-specific interface tool (smartphone application). After each intervention phase an online questionnaire was distributed to the participants. The NUDGEs 1 and 3 focused on energy and heating-related aspects (data not included in this paper). In turn, NUDGE 2 was focused on IAQ, and the outcomes of this intervention are fully reported in this document. For this intervention study, a modular IoT architecture was developed to collect real-time IAQ data in the participant homes. This work will present: i) details of the low-cost air quality monitoring system that was developed; ii) data obtained from the validation tests by comparison of the LCS readings with calibrated reference methods before and after the implementation; iii) information on the installation of the NUDGE IAQ modules in participant homes; and iv) results from the intervention study considering as intervention the access to real-time IAQ data through a smartphone app provided to the participants. To study the effects of the intervention, the NUDGE Portuguese participants (n = 101) were randomly divided into two groups of similar size (Group 0 and Group 1). The intervention program occurred in two periods (period 1 and period 2) following a crossover trial design, ensuring that all participants were exposed to the nudging treatment. Briefly, in Period 1, Group 0 worked as the control and Group 1 as the intervention group, and in Period 2, Group 1 worked as the control and Group 0 as the intervention group. This work encompassed two visits to the participant homes.

i. 1st visits (July 2021 to April 2022) for collecting information on building and indoor space characteristics and installing smart electricity meters (relevant for NUDGE 1 and 3, data do not show);
ii. 2nd visit to install the newly developed module of IAQ sensors (necessary for NUDGE 2).

Since only 84 of the NUDGE Portuguese participants accepted to receive the 2nd visit for IAQ sensors installation, for NUDGE 2, the number of participants in Group 0 was 40, and in Group 1, 44. Each period of study lasted for four weeks during the heating season (Period 1 – from 16th November to December 14, 2022; Period 2 from December 27, 2022 to January 24, 2023), with a washout period of 13 days.

2.2. Hardware implementation

2.2.1. Sensor selection and characteristics

The sensor selection stage was conducted using relevant criteria. First, we have searched for the CO_2, particulate matter (PM), humidity, and temperature low-cost sensors available in the market. Second, we have analysed the datasheet information to assess the range, response time, and accuracy characteristics of the sensors. This information is available in Table 1. The authors have focused on calibrated sensors, and therefore, the BME680 from Bosch and SPS30 and SCD30 from Sensirion have been selected and used for the development of the IoT architectures.

2.2.2. Development of a modular system of LCS for monitoring IAQ

The modular system developed comprises a mainboard unit and a few sensing modules. The mainboard is a custom-made board that hosts the microprocessor and the power regulation and supply electronics. The microprocessor is the dual-core 32-bit Espressif ESP32 module which supports operation up to 240 MHz and features WiFi and BLE connectivity. The ESP32 is instructed to communicate with all sensing units within a specified interval, pre-process their data, and upload them to the domX cloud. Regarding the sensing modules a PM unit is

Table 1
Characteristics of the low-cost sensors selected.

Sensor	Parameter	Technical data	Reference
BME680	Gas sensor	Response time (τ 33–63 %): <1 s Sensor-to-sensor deviation:±15 %	[27]
	Humidity	Response time (τ0–63 %): 8 s Accuracy: ± 3 %	
	Temperature	Accuracy: ± 1 °C (0–65 °C)	
SPS30	PM	Mass concentration precision: ±10 % Mass concentration range: 0–1000 µg/m^3 Lifetime: >10 years Particle size range: PM$_1$, PM$_{2.5}$, PM$_4$ and PM$_{10}$	[28]
SCD30	CO$_2$	Accuracy: ±30 ppm Measurement range: 400–10000 ppm Response time: (τ63 %) 20 s	[29]
	Humidity	Typ. relative humidity accuracy: 3 %RH Operating range: 0–95 % Response time: (τ63 %) 8 s	
	Temperature	Accuracy: 0.4 °C Operating Range: 40–70 °C Response time: (τ63 %) 10 s	

employed alongside a CO$_2$ and a temperature and humidity sensor. The component employed for monitoring PM was the Sensirion SPS30, which delivers the concentration of particles of different sizes in the air based on a laser scattering principle. More specifically, the unit measures the concentration of particles that are less than 1 µm, 2.5 µm, 4 µm and 10 µm in diameter (PM$_1$, PM$_{2.5}$, PM$_4$ and PM$_{10}$, respectively), with an accuracy of ±10 %. The CO$_2$ sensor is the Sensirion SCD30, a highly accurate measurement probe based on the NDIR detection principle. Inside the same module, a temperature sensor is integrated to compensate for the external heat sources without the requirement for any additional components. Moreover, the SCD30 features a dual-channel principle for measuring CO$_2$ concentration, which automatically allows the sensor compensation for long-term drifts by design. Lastly, the device encompasses the BME680 sensor that supports temperature, humidity, barometric pressure, and VOC gas sensing capabilities. Notably, the latter sensor is placed on the side of the enclosure in a specially designed slot to monitor ambient conditions. The mainboard and sensing components were enclosed in a specially designed 3D-printed box that was developed after several iterations to improve the placement of each sensor inside the box without interfering with their measurements (Fig. 1).

2.3. *Software for data acquisition and visualization*

The researcher interface used Open Source Software (OSS) frameworks and tools. It is based on the Grafana framework, a multi-platform open source analytics and interactive visualization Web application. The Grafana platform directly communicates with the time-series database and discovers all the devices available and presents metrics associated with the IAQ devices (illustrative screenshots available Fig. S1, Supplementary Materials). Two dashboards were developed for the purposes of the researcher interface. The first dashboard illustrates all the measurements obtained by a single IAQ node, in which the researcher can move through time to view its respective data. The second dashboard lists all the IAQ devices that are online and draws the measurements in multi-line graphs, which serve the purpose of comparing IAQ devices in order to quickly detect outliers in the measurements of the on-board sensors and correct them by enabling the auto-calibration functions that are available. The latter is employed only during the verification or calibration process where the sensors are placed in the same room/chamber.

The development of the smartphone application (Android and iOS) to be implemented in the study was subcontracted to Bandora Systems (Porto, Portugal) and named “nudge.it”. The app has been made available through the two main app stores for Android and iOS smartphones. The functionalities that were activated and deactivated in the app according to the intervention and control period of NUDGE2 included (Fig. 2): i) a screen that presents the real-time levels of air parameters (CO$_2$ and particulate matter (PM$_{2.5}$ and PM$_{10}$), temperature and relative

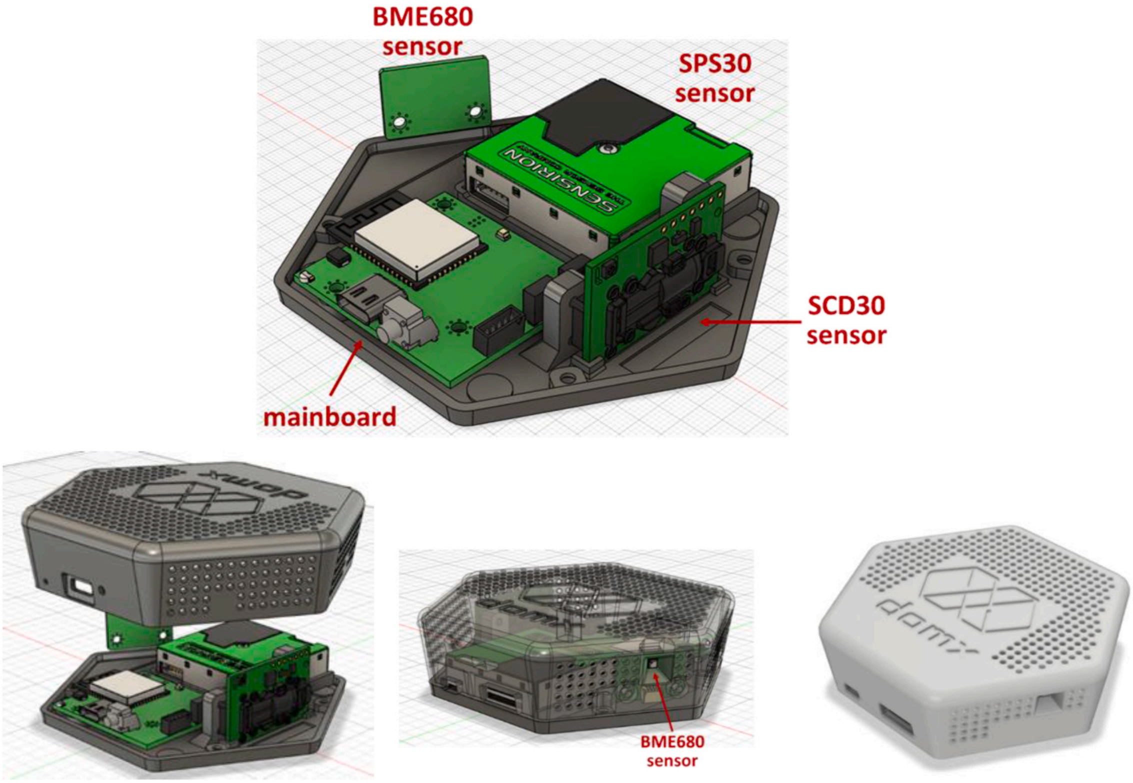
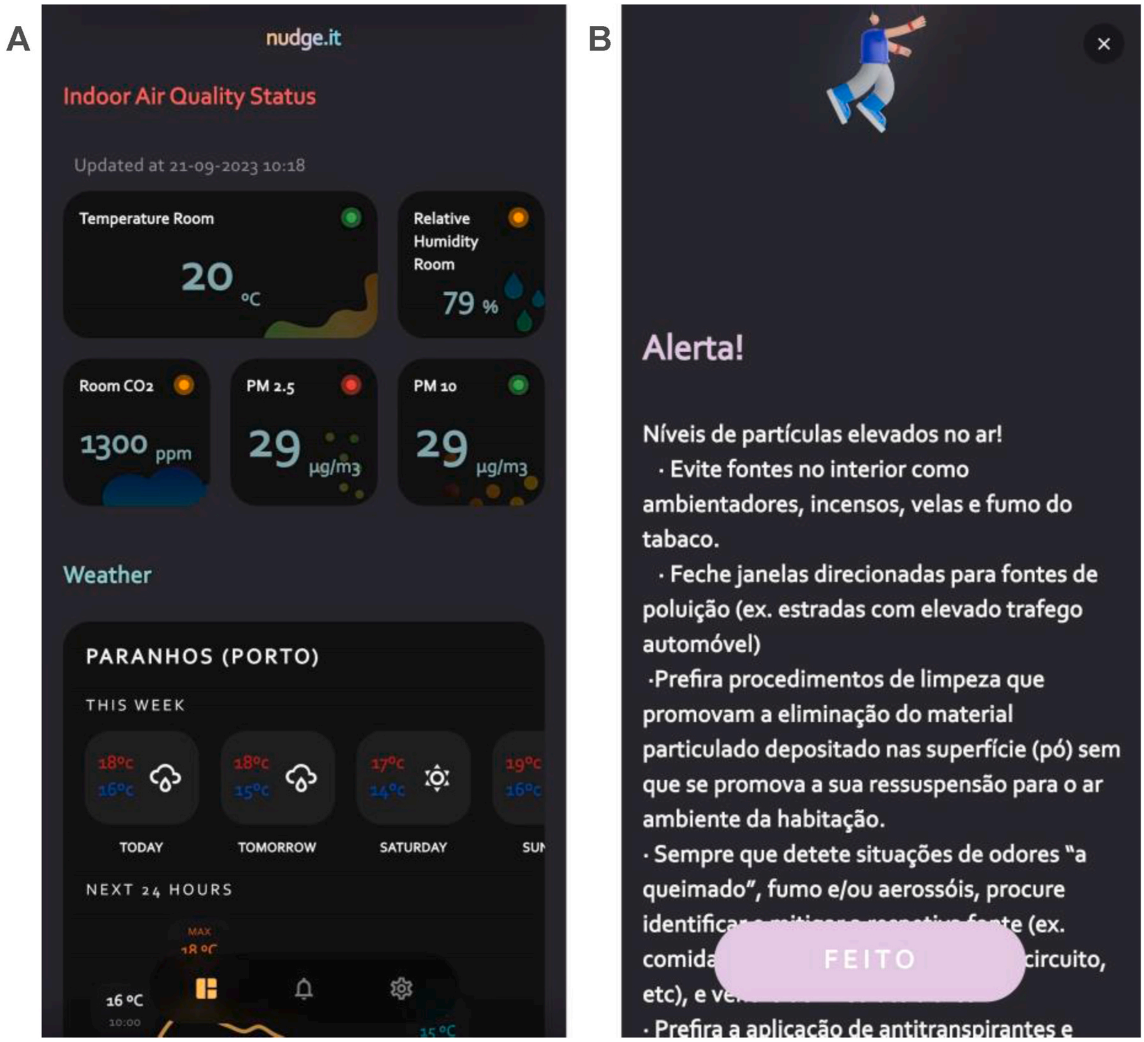


Fig. 1. 3D illustration of the developed IAQ sensor: employed sensing components and developed mainboard enclosed in the designed 3D case.



Indoor Air Quality Status

Updated at 21-09-2023 10:18

Temperature Room 20 °C

Relative Humidity Room 79 %

Room CO2 1300 ppm

PM 2.5 29 µg/m3

PM 10 29 µg/m3

Weather

PARANHOS (PORTO)

THIS WEEK

TODAY 18°C 16°C

TOMORROW 18°C 15°C

SATURDAY 17°C 14°C

SUN 19°C 16°C

NEXT 24 HOURS

MAX 18 °C

16 °C 10:00

15 °C

Alerta!

Níveis de partículas elevados no ar!

· Evite fontes no interior como ambientadores, incensos, velas e fumo do tabaco.

· Feche janelas direcionadas para fontes de poluição (ex. estradas com elevado trafego automóvel)

·Prefira procedimentos de limpeza que promovam a eliminação do material particulado depositado nas superfície (pó) sem que se promova a sua ressuspensão para o ar ambiente da habitação.

· Sempre que detete situações de odores "a queimado", fumo e/ou aerossóis, procure identifica te (ex. comida circuito, etc), e ve

· Prefira a aplicação de antitranspirantes e

Fig. 2. App screens representing the functionalities that were visible to the participants during the intervention period. **A.** Screen for the visualization of real-time levels with coloured qualitative indicators (varied from green to red in accordance to the comparison of the readings with threshold levels); **B.** example of a push-notification with recommendation in the native language delivered to the participants when the 1 h mean indoor levels exceeded the recommended limit values (as described in section 2.3 of the manuscript). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

humidity. It included qualitative indicators using a coloured grade, allowing the participant to identify when the levels are within the recommended limit values (green), when the levels are reaching the limit values (yellow), and when the levels are out of the limit values (red); and ii) push notifications when average concentrations for the last hour exceed healthy thresholds. In order to avoid disturbing the participants during the typical sleeping hours, this push notification system was only active from 8 a.m. to 10 p.m. For CO_2 (If mean 1h $[CO_2] > 1500$ ppm), the message was "High CO_2 levels! Please open the window(s) to introduce fresh air into the room for at least 10 min" For PM (If mean 1h $[PM_{2.5}] > 25\ \mu g/m^3$ OR If mean 1h $[PM_{10}] > 50\ \mu g/m^3$) the notification shown to the participants stated:

"High particle levels in the air! Please.

- Avoid indoor sources such as air fresheners, incense, candles and tobacco smoke.
- Close windows facing sources of pollution (e.g., roads with heavy car traffic).
- Prefer cleaning procedures that promote the elimination of particles deposited on surfaces (dust) without promoting its resuspension into the room's ambient air.
- Whenever you detect "burning" odours, smoke, and/or aerosols, try to identify and mitigate the respective source (e.g., burnt food) and immediately ventilate the area.
- Prefer to apply antiperspirants and other personal and cosmetic products in spaces with mechanical/forced ventilation (bathroom) and check the correct functioning and hygiene of these systems."

Some indicators of the app usage, including date of login, number of openings of the app and new data requests, were continuously monitored during the study.

2.4. Prototype validation experiments: comparison with reference instruments

In the first stage, 3 similar units of the prototypes (named fa8, abc, and 2e4) were developed for the first series of validation assays with manipulated conditions to test reproducibility within sensors and ascertain the need for implementing off-set adjustments. These assays consisted of a series of tests to compare the developed prototype readings with concurrent measurements acquired by calibrated reference instruments (Fig. 3). The instrument of reference for temperature, relative humidity, and CO_2 was IAQ-CALC (model 7545, TSI, Inc., MN,

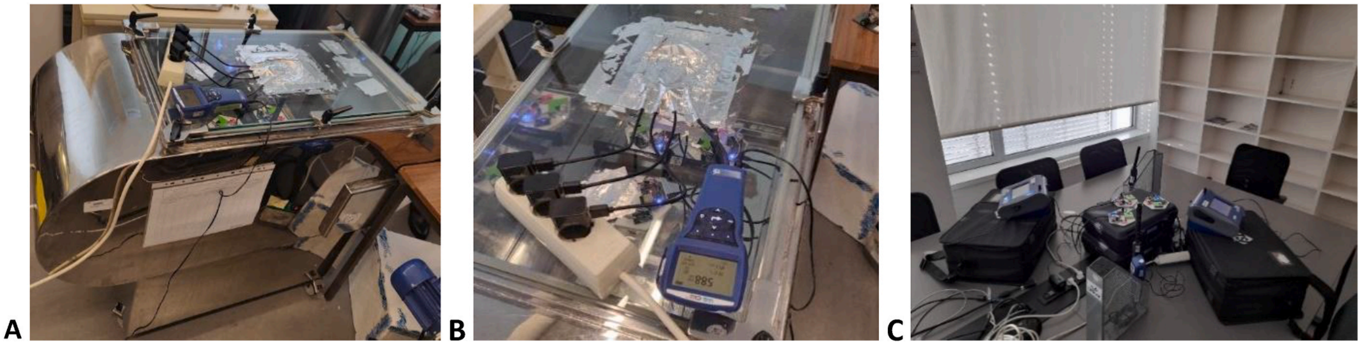


Fig. 3. Location of the equipment during the tests for comparing IAQ modular prototypes readings with reference methods. A and B, photos of the chamber tests with manipulated CO_2 performed at the Air quality laboratory of INEGI (LQAI). C, tests performed in a meeting room.

USA), which presents a working range from 0 to 5000 ppm and an accuracy of ±3 % of reading or ± 50 ppm. DustTrak DRX Aerosol Monitors (model 8533, TSI, Inc., MN, USA) having a working range from 0.001 a 150 mg/m^3 and an accuracy of ±0.1 % of reading able to measure particles from 0.1 a 10 μm was used as the reference for particle size fractions ($PM_{2.5}$ and PM_{10}). To minimize the impact of instrument drift on the measurement, DustTrak monitors were auto-zeroed immediately before the monitoring work conducted in each test. All reference equipment employed were recently calibrated (<12 months) by external accredited laboratories.

2.4.1. *Chamber test at different manipulated CO_2 concentrations*

The first study was performed in a test chamber with a volume of 0.255 m^3, having a controlled environment for temperature, relative humidity, air velocity, and air exchange rate, and being fed by purified air. Briefly, the prototypes were placed along with the reference equipment in the test chamber, which was properly closed. Then, the purified air was progressively replaced by a bottle of synthetic air with CO_2 (5126 ppm, provided by Linde, Dublin, Ireland). After about 2 h (when the CO_2 concentration inside the chamber reached values > 3000 ppm, based on IAQ-CALC readings), the bottle was replaced by purified air until the next day. The study was repeated at similar conditions the next day to test repeatability.

2.4.2. *Tests in a small room with cycles of windows closed and opened*

This study was conducted in an unoccupied meeting room on the 3rd floor of INEGI's eighth-floor office building, which is located in an urban area of the Porto, near a highway and other busy roads. The meeting room has a volume of 64 m^3 and a glassed façade with openable windows is oriented to the south. Throughout the test, the windows were opened and closed in cycles to observe the effect of the fluctuation of the levels of particles $PM_{2.5}$ and PM_{10} from outdoor origin in the reading of prototypes and of two DustTrak equipment. The location of the devices in the meeting room during the test is shown in Fig. 3. The test was conducted on the afternoon of January 14, 2022, from 12:00 to 18:00.

2.4.3. *Testing of the IAQ modules to install in the participant homes*

Since the results obtained from testing of the 3 initial prototypes were very promising, an additional batch of 84 IAQ modules were produced. Before installation in participants' homes, all the sensors were tested for comparison with reference methods (temperature, relative humidity, CO_2 levels, $PM_{2.5}$ and PM_{10}) to ensure they are ready for use. The chosen location for the first batch of tests was an unoccupied meeting room on the 8th floor of INEGI's building, and the duration of the tests was in all cases ≥12 h. Due to the limitation of the number of plugs available, the validation tests were conducted on different days and with different IAQ sensors. Some of the modules ($n = 10$) were randomly collected after a period of more than 5 months of monitoring in the participant homes in order to be subjected to an extra test to determine whether the results of the comparison between the LCS and reference equipment readings remain consistent after the period of usage in the intervention study. This test was conducted from continuous monitoring from 15th May to May 22, 2023 in an occupied open-space office (25 people, on average) with an area of 160 m^2.

2.5. *Intervention study: implementation of a IoT-based IAQ monitoring system in homes of families with children*

All the 101 Portuguese families recruited for the PT pilot of the NUDGE project were contacted and invited to participate. From this contact, 84 agreed to receive a visit to install IEQ sensors (works conducted from September to December 2022). The sensors were installed in a common area where families spend most of their time at home, usually in the living room (with some rare exceptions, in which the location of installation was the dining room ($n = 7$) or the kitchen ($n = 2$)). For defining the exact location of the sensors, whenever possible, the following criteria were considered: i) height from the ground between 1 and 1.5 m; and ii) avoid locations nearby (>1 m) sources of heat, windows/doors, and declared sources of pollution (e.g., air fresheners); and iii) locations nearby a standard power plug but that do not affect the everyday routine life of the family. Not all homes had a suitable location fulfilling all the referred requisites, and commonly, the criteria i) was the one that was more neglected, as is evidenced by the average height of the effective installation of the sensors (0.96 m). All the participant families were also invited to install the app Nudge.it and they were notified once they had the functionalities of the app that allowed the visualization of IAQ levels to be active by an automatic push notification in the app and an informative email.

2.6. *Questionnaires to participants*

As part of the project, we launched a series of online surveys to gather insights into participant behaviour in multiple waves, each with slightly varying thematic focuses. These questionnaires were programmed in Qualtrics. Participants were asked to complete the survey through a request (enclosing the survey link) that was sent by email. For this study, we will primarily focus on the third survey wave (released immediately after NUDGE 2), which emphasised IAQ while also allowed participants to reflect on their app usage over an extended period. Within this context, we assessed the user experience of the application using a modified version of the User Experience Questionnaire (UEQ) scale [30]. We presented participants with thirteen item pairs, where they were asked to express their level of agreement with statements ranging from confusing to clear or frustrating to inspiring. The scoring ranged from 1 (lowest) to 5 (highest). Additionally, we employed a three-item scale to gauge whether participants actively sought to enhance indoor air quality, adapting a scale proposed by Ajzen [31]. Following this, we posed a series of questions about the information provided by the application, the presentation of data within the app and energy-saving behaviours in relation to IAQ. Five-point Likert scales were used, anchored by 'not at all true' (1) and 'very true' (5). Moreover, we asked about participants' reasons for opening windows and the types of notifications they received.

2.7. Data management and statistical analysis

Hourly data from all IAQ sensors were exported from the Grafana platform and structured in an Excel file for treatment and analysis. Data from validation tests were compared with the data downloaded from the reference data loggers. From the comparison, an average offset value was calculated for each parameter based on the difference between the two assessments (IAQ LCS vs reference methods), except the CO_2 levels, as will be reported later in this document. The offset correction was defined by analysing the results obtained from all comparison tests of the modules with the reference instruments. Precisely, an average difference between the two sets of values was calculated to facilitate this adjustment process.

IBM SPSS Statistics (version 27) was used for the statistical analysis, considering a significance level of $p < 0.05$. The normality of the data was tested by the Kolmogorov-Smirnov test. Wilcoxon tests were applied to compare parameter levels between intervention and control periods (comparing the groups with themselves or together). Spearman methods were used to assess significant associations between the levels of each parameter measured by the "Reference" equipment and the prototypes/modules. Indoor-to-outdoor (I/O) ratios were calculated for PM_{10} using air quality data from each home's nearest local monitoring station (https://qualar.apambiente.pt/). Statistical association between continuously monitored IAQ parameters and the characteristics of the households was tested using t-tests, Mann-Whitney *U* tests, and Spearman methods.

3. Results and discussion

3.1. Comparison of IAQ LCS modules with reference equipment

The data monitored using the first prototypes were evaluated against the concurrent measurements from reference equipment to investigate the robustness of the readings of the developed IAQ LCS modules and, to provide confidence on their use for IAQ monitoring work in the participant's homes. The validation tests designed for this work included chamber tests under manipulated environment and assessments in a small room with cycles of windows opened and closed that successfully promoted a significant variation of concentrations of CO_2 and particles, respectively (Fig. 4). This allowed the performance of the prototype to be assessed at different concentration ranges. The results of these validation tests are fully reported in the Supplementary Material and summarized in this section. The controlled environment created in the laboratory through chamber tests allowed the promotion of a variation

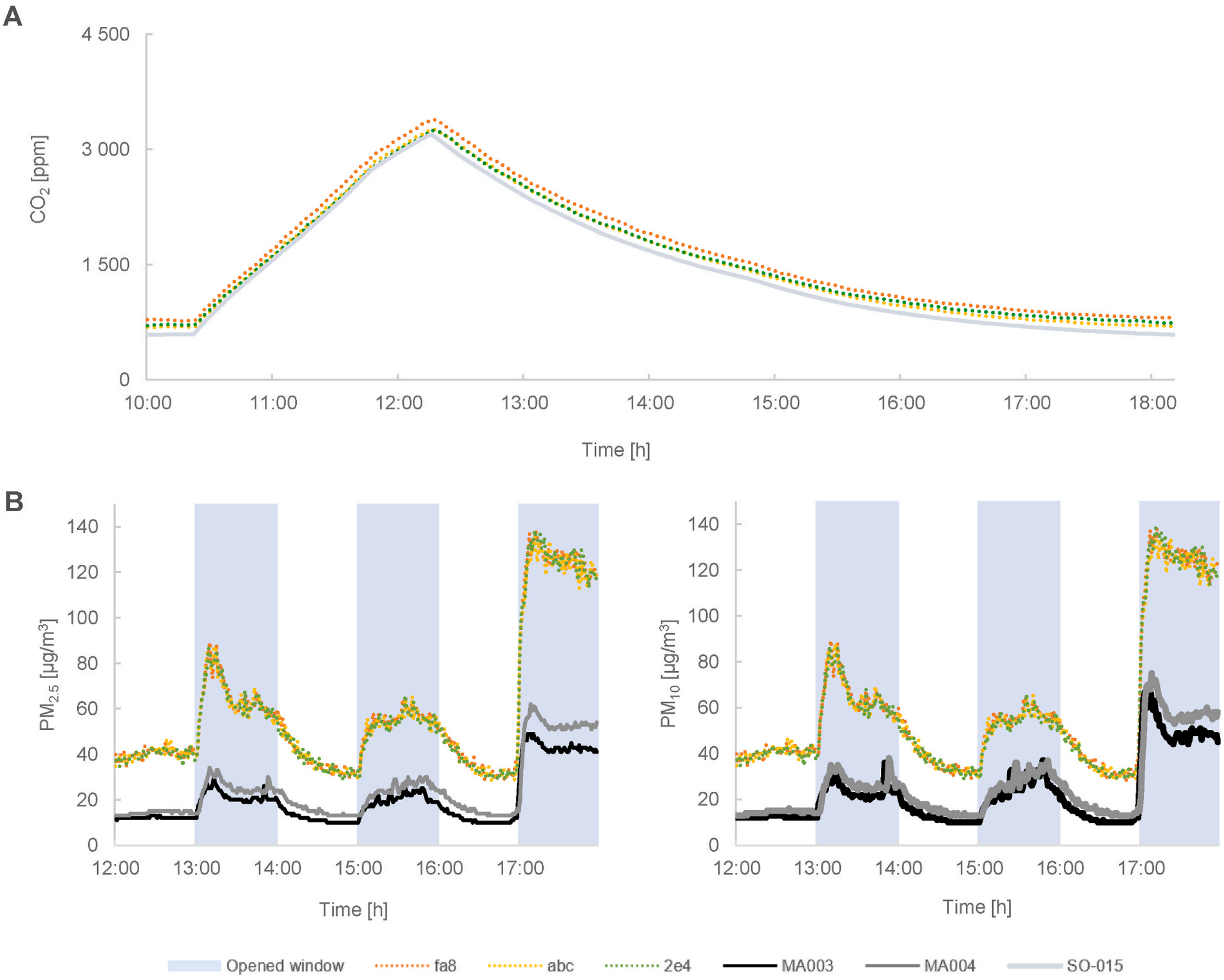


Fig. 4. Results from the test for comparing the 3 initial prototype units with the reference equipment showing the obtained variation of **A.** carbon dioxide (CO_2) during the chamber test with manipulated CO_2 concentrations, and **B.** $PM_{2.5}$ and PM_{10} during the assay conducted in a room with cycles of opened (grey areas) and closed windows (white areas), to manipulate airborne particle levels.

of CO_2 levels from 586 to 3195 ppm (in accordance with reference measurements, Fig. 4A). It was observed that the prototype readings exhibited a similar trend under this controlled environment, as observed in the measurements obtained with the reference equipment. It was found that CO_2 concentrations (fa8: $r_s = 0.999$, $p < 0.001$; abc: $r_s = 1.000$, $p < 0.001$; 2e4: $r_s = 0.999$, $p < 0.001$), relative humidity (fa8: $r_s = 0.999$, $p < 0.001$; abc: $r_s = 0.999$, $p < 0.001$; 2e4: $r_s = 0.999$, $p < 0.001$) and temperature (fa8: $r_s = 0.913$, $p < 0.001$; abc: $r_s = 0.890$, $p < 0.001$; 2e4: $r_s = 0.937$, $p < 0.001$) measured by the prototypes were well and positively correlated with those assessed by the reference equipment.

Similarly, the results from the test conducted in a small room with windows facing important traffic-related sources demonstrated the instantaneous impact of the outdoor particles that penetrate the room in

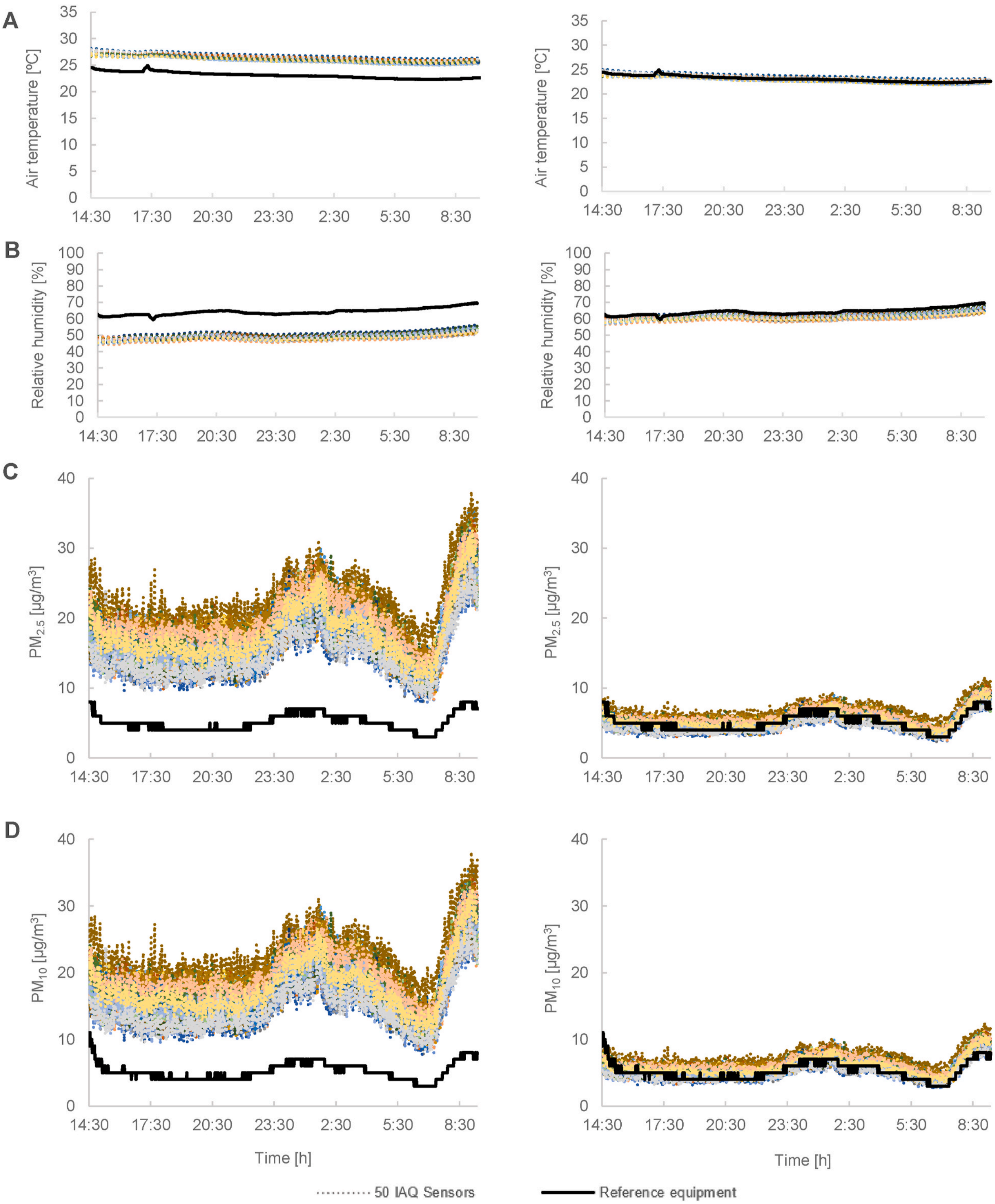


Fig. 5. Example of the variation of levels assessed by the different equipment throughout the consecutive assays conducted, before and after the implementation of offset corrections for **A.** temperature, **B.** relative humidity, **C.** $PM_{2.5}$, and **D.** PM_{10}.

the periods in which the windows are opened (Fig. 4B). As expected, the referred effect was evident for both readings obtained from prototypes and reference methods. For $PM_{2.5}$ and PM_{10} concentrations, IAQ reference instruments and the prototypes reacted very similarly to the fluctuations of indoor particulate matter levels. Indeed, the readings obtained from the 3 initial prototypes were significantly correlated with the levels assessed with the two reference DustTrak (for MA-003: $PM_{2.5}$ – fa8: $r_s = 0.967$, $p < 0.001$; abc: $r_s = 0.965$, $p < 0.001$; 2e4: $r_s = 0.967$, $p < 0.001$; PM_{10} – fa8: $r_s = 0.950$, $p < 0.001$; abc: $r_s = 0.950$, $p < 0.001$; 2e4: $r_s = 0.952$, $p < 0.001$; and for MA-004: $PM_{2.5}$ – fa8: $r_s = 0.932$, $p < 0.001$; abc: $r_s = 0.932$, $p < 0.001$; 2e4: $r_s = 0.936$, $p < 0.001$: PM_{10} – fa8: $r_s = 0.917$, $p < 0.001$; abc: $r_s = 0.918$, $p < 0.001$; 2e4: $r_s = 0.922$, $p < 0.001$). These results suggest that the prototypes respond well to the fluctuations in the airborne levels of particles, showing that they could constitute a valuable tool to identify the periods of high emission of particles in higher-scale applications. This is entirely in agreement with

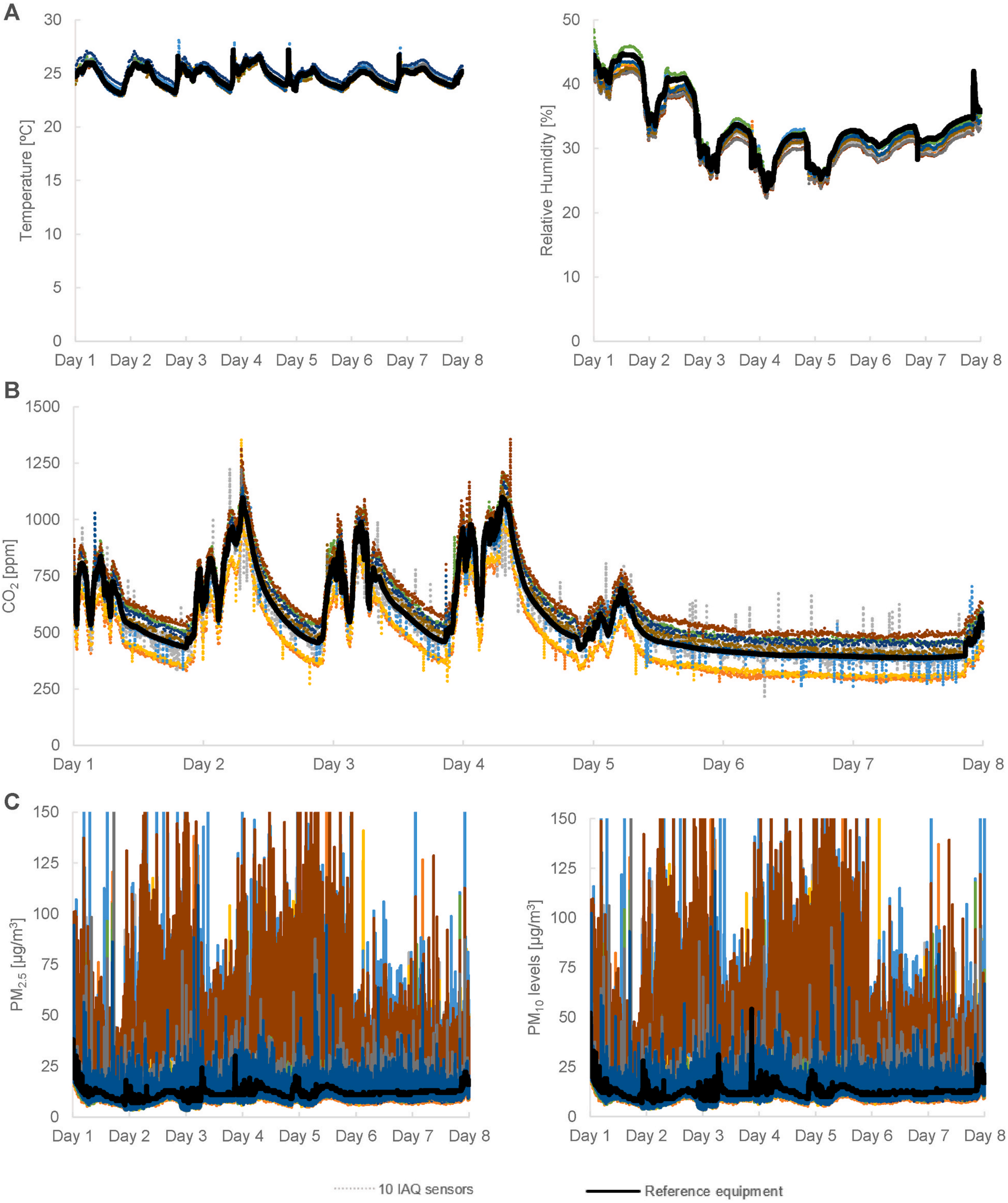


Fig. 6. Representation of time series of the IAQ data collected during the testing of 10 IAQ modules after more than 5 months of continuous monitoring work in the participant homes for **A.** temperature and relative humidity, **B.** CO_2, and **C.** $PM_{2.5}$ and PM_{10}.

the aim of the present study which intends to make available information with the potential to assist the participants in identifying sources and events that may potentiate exposure to particles in their homes, and, hopefully, in promoting behaviours to reduce the risk of hazardous exposure.

Given the promissory results, 84 units of IAQ LCS modular systems with the entire case were produced for deployment in the participant homes. Before deployment, all modules were tested to evaluate the sensors' performance against reference monitoring equipment. The overall results obtained from testing the prototypes showed good reproducibility within units, with opportunities for offset correction, in particular for temperature, relative humidity, $PM_{2.5}$, and PM_{10}. In particular, for airborne particles, the LCS readings were about 3-fold the levels obtained for the reference methods. Although this difference is very high, the overestimation of the particle measurement by LCS is an observation that has been reported previously by other authors [32,33]. Based on the overall data obtained from the tests of the final IAQ LCS modules, offset corrections were implemented. Fig. 5 shows an example of the readings of a test without and with adjustments considering the average difference values obtained from the set of tests of the 84 modules. A simple and easy-to-reproduce approach, in which the same correction was applied to all sensors, was considered to be acceptable for the adjustments because.

i) the modules developed presented very well-correlated readings across the different units;
ii) the levels assessed were very in line with those obtained from previous projects employing short-term assessments employing reference methods (fully addressed in section 3.2), and
iii) the planned statistical analysis was mainly focused on investigating differences between dependent samples.

The correction conducted allowed approximating the readings of the LCS with those obtained by the reference methods (e.g., average values obtained by LCS vs. reference for the test presented in Fig. 5: temperature – 23.09 vs. 23.10 °C; relative humidity – 61.28 vs. 64.29 %; $PM_{2.5}$: 5.37 vs. 5.20 μg/m^3; PM_{10}: 5.80 vs. 5.36 μg/m^3).

After these performance tests, the IAQ LCS modules were installed in participant homes to implement the intervention study. In order to study the status of the modules after the monitoring work, new tests were conducted using the time series of data from 10 units of IAQ LCS (randomly selected out of the total sample of 84 modules). According to results presented in Fig. 6, the more problematic behaviour was noticed for airborne particles, with the deviation of the readings based on the reference varying, on average, from −2.8 % (11.5 μg/m^3) to 250.5 % (41.5 μg/m^3) for $PM_{2.5}$ and from −0.3 % (12.4 μg/m^3) to 260.3 % (44.9 μg/m^3) for PM_{10}. Nevertheless, the readings of all modules tested were significantly correlated with those obtained from the respective reference method (Table 2). In fact, it was found that CO_2 concentrations (r_s ranging from 0.962 to 0.995 and $p < 0.001$), relative humidity (r_s ranging from 0.979 to 0.995 and $p < 0.001$), and temperature (r_s ranging from 0.936 to 0.974 and $p < 0.001$) measured by the LCS were significantly and positively correlated with those assessed by the reference equipment. In turn, a weak (based on the low correlations coefficients obtained) but significant association was obtained for $PM_{2.5}$ (r_s ranging from 0.025 to 0.421 and p ranging from <0.001 to 0.012) and PM_{10} (r_s ranging from 0.088 to 0.354 and $p < 0.001$). These results suggest that the data obtained in the homes can be analysed with an acceptable degree of confidence for CO_2, temperature, and relative humidity. In contrast, the results obtained for particles should be interpreted with caution since a relevant sensor degradation effect cannot be excluded. For instance, the findings obtained are in line with some evidence existing in literature, with some authors recognizing that the main limitation of LCS is that they are generally characterized by worse performance in terms of accuracy compared to the commonly used standard techniques, and aging of LCS produces drift, which affects their long-term stability and their performance, eventually leading to shortening their lifetime [24]. In particular, it has been reported by other authors that the operation time of sensors of particles could also affect their performance due to the degradation of components or malfunction [34]. Interestingly, other studies using the same SPS30 sensors, found that they had a good performance over time in a high-concentration environment, suggesting that their sheath air flow and automatic cleaning features might protect them from contamination during extended use in a high-concentration environment [35]. However, the referred research considered the analysis based on the execution of short-duration assays (18h). A more recent study conducting tests for a period similar to our work also found that there is the possibility that SPS30 sensors experience sudden changes in their measurements during the experiment [36].

3.2. IAQ levels assessed in 84 participant homes

The IAQ data collected through LCS modules during the monitoring period, which took place between November 16, 2022 and January 24, 2023, is presented in Fig. 7. In general, the levels of the parameters assessed in this work showed a considerable fluctuation across the 84 households surveyed. The average values recorded in participant ranged from 14.8 to 22.4 °C for temperature and from 52.4 to 79.9 % for relative humidity. For CO_2, measured as an indicator of occupancy and of the quality of ventilation conditions of homes, the mean concentrations varied from 442 to 1690 ppm. Interestingly, this range of values aligns with the concentrations reported from a previous study conducted in homes of 30 families with infants living in the same geographical region using reference methods (22-hr monitoring; range of mean concentrations: 509–1603 ppm) [12]. Comparing the assessed concentrations with the limit value that has been widely recognized as representative of good or excellent IAQ/ventilation conditions for indoor environments of 1000 ppm [37], it was found that 21 (25 %) out of 84 homes presented mean CO_2 concentrations that exceeded this limit. Also, 7 homes (8 %) presented mean CO_2 concentrations exceeding the limit imposed by the national recommendation of 1250 ppm [38].

Regarding airborne particles for the study period, assessed concentrations varied on average from 13 to 187 μg/m^3 for $PM_{2.5}$ and 14–202 μg/m^3 for PM_{10}. These concentrations are also quite in agreement with the range of particle levels achieved in a previous study conducted in 30 homes in the area of Porto (range of 22-hr mean values: $PM_{2.5}$,

Table 2
Spearman correlation coefficients per parameter between the 10 modules and respective reference method.

	c4c	@908	68c	@158	@230	@044	@918	@680	67c	@250
CO_2	0.991[b]	0.962[b]	0.991[b]	0.992[b]	0.993[b]	0.986[b]	0.989[b]	0.995[b]	0.987[b]	0.994[b]
RH	0.990[b]	0.991[b]	0.989[b]	0.979[b]	0.985[b]	0.993[b]	0.995[b]	0.994***	0.994[b]	0.994[b]
T	0.955[b]	0.962[b]	0.957[b]	0.936[b]	0.956[b]	0.958[b]	0.974[b]	0.964[b]	0.969[b]	0.957[b]
$PM_{2.5}$	0.222[b]	0.314[b]	0.308[b]	0.075[b]	0.366[b]	0.314[b]	0.025[a]	[b]	0.421[b]	0.386[b]
PM_{10}	0.223[b]	0.248[b]	0.238[b]	0.132[b]	0.297[b]	0.279[b]	0.088[b]	0.328[b]	0.354[b]	0.330[b]

CO_2, carbon dioxide; PM, particulate matter; RH, relative humidity; T, temperature.

** Correlation is significant at 0.01 level (2-tailed).

[a] Correlation is significant at 0.05 level (2-tailed).

[b] Correlation is significant at 0.001 level (2-tailed).

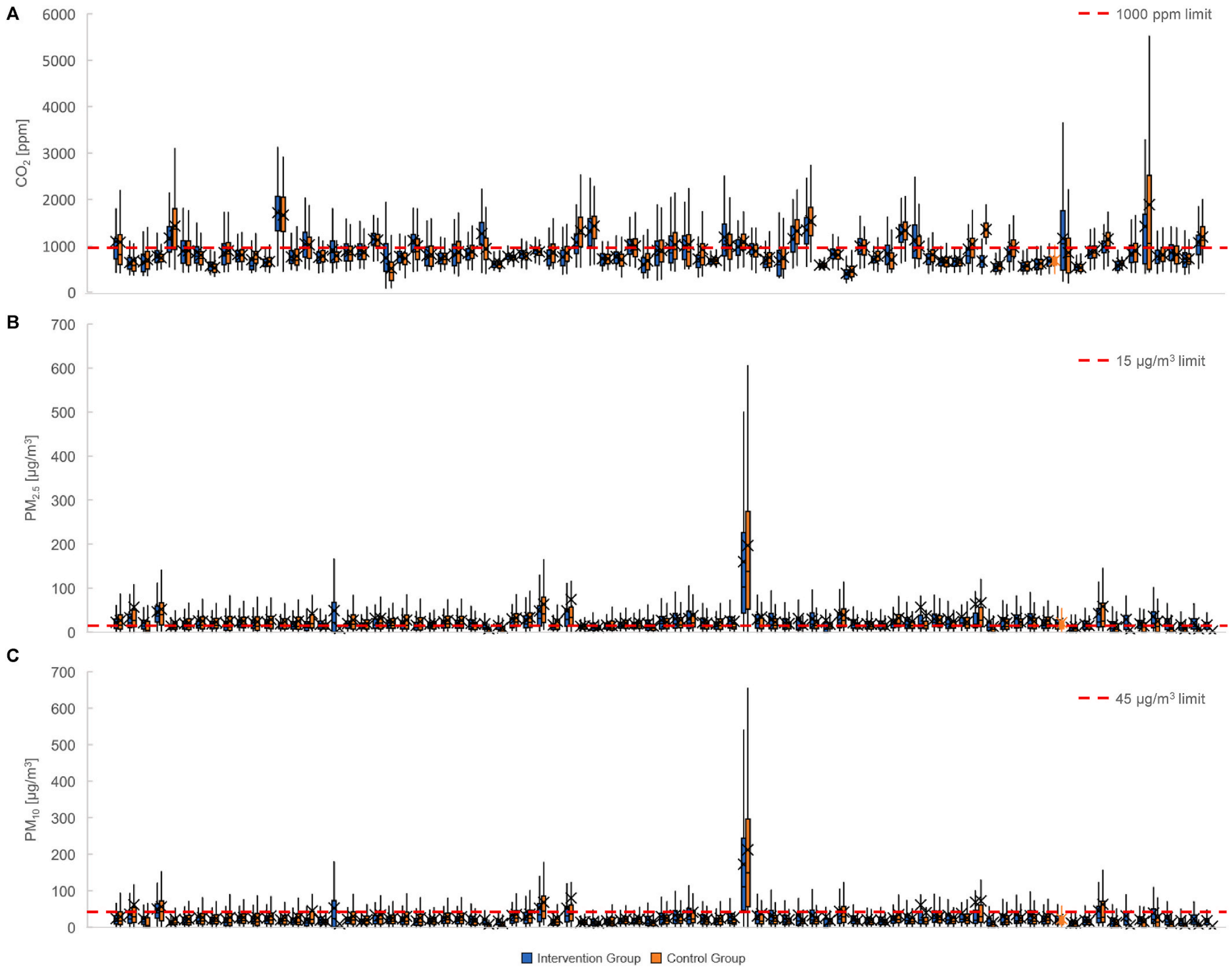


Fig. 7. Box-plot representing the concentrations of **A.** CO_2, **B.** $PM_{2.5}$ and **C.** PM_{10} levels obtained in the 84 participant homes during the respective control and intervention periods. The bottom and the top of the boxes represent the 25th and 75th percentiles. The band near the middle of the box and the X represent the median and the mean values, respectively. The ends of the whiskers indicate the 10th and 90th percentiles.

11.2–126.2 $\mu g/m^3$; PM_{10}, 13.2–135.1 $\mu g/m^3$. Comparing the $PM_{2.5}$ and PM_{10} average concentrations with the most updated WHO short-term 24-h guidelines of 15 and 45 $\mu g/m^3$, respectively [39], it was found that, on average, most of the homes (n = 82, 98 %) exceeded the $PM_{2.5}$ limit, while only 11 participant homes (13 %) surpassed the PM_{10} limit. This achievement is also in line with the previous investigations employing short-term monitoring work using reference equipment, which reported that a great percentage of homes of Portuguese families with children present high concentrations of $PM_{2.5}$ [10,12]. Because the current study conducted a long-term assessment plan, comparing the obtained concentration with the WHO annual air quality guidelines would be the most suitable and protective approach to characterize study participants' exposure in their homes. It can be observed that all participant homes registered average $PM_{2.5}$ concentration above the annual limit (5 $\mu g/m^3$), with 95 % of the study homes also presenting PM_{10} levels exceeding the respective annual exposure limit value (15 $\mu g/m^3$) [39] These findings support the need to establish corrective actions for decreasing exposure levels to particulate air pollution and protecting health.

The investigation of a statistical association between continuously monitored data for the period of study and the characteristics of the households (building survey checklist data) showed important significant associations. In particular, homes built before 1980 (16 out of 101) presented higher relative humidity levels ($t(82) = 2.999$, $p = 0.004$) along with lower indoor temperature ($t(82) = -2.068$, $p = 0.042$) than those reported for more recent dwellings. While the age of the building is identified as an important factor that can significantly impact hygrothermal comfort, indoor temperature, and relative humidity may strongly influence each other. The data collected showed that lower indoor temperatures were significantly associated with increased relative humidity levels ($r_s = -0.719$, $p < 0.001$). In addition, signs of water damage or pathologies related to dampness and mould, observed in about 39 % of the participant homes, were significantly linked to higher air relative humidity levels ($t(82) = 2.077$, $p = 0.041$). Noteworthy, the percentage of the existence of pathologies was about 1.6-fold higher than the percentage obtained in previous studies conducted in homes of families with newborns and infants [12].

Concerning CO_2, the mean concentrations obtained were significantly increased in homes with lower areas (m^2) ($r_s = -0.268$, $p = 0.014$) and higher density of occupancy (persons/m^2) ($r_s = 0.311$, $p = 0.004$). Interestingly, significantly higher CO_2 concentrations were found in homes using bottled gas (propane or butane) for indoor environment and/or water heating ($U = 310.0$, $z = -2.160$, $p = 0.031$). In turn, concentrations of airborne particulate matter were significantly linked to both the use of bottled gas ($PM_{2.5}$: $U = 289.0$, $z = -2.413$, $p = 0.016$; PM_{10}: $U = 288.0$, $z = -2.425$, $p = 0.015$) but also of wood or pellets for heating purposes ($PM_{2.5}$: $U = 538.5$, $z = -2.839$, $p = 0.005$; PM_{10}: $U = 539.5$, $z = -2.830$, $p = 0.005$). Further, according to the results obtained from the statistical analysis, the practice of smoking indoors and the existence of evident signs of physical pathologies (e.g., noticeable cracks, fissures, altered staining or peeling in the dwelling's surfaces) can constitute factors that may contribute to the risk of being exposed to higher $PM_{2.5}$ (smoking indoors: $U = 64.0$, $z = -2.524$, $p = 0.009$; physical pathologies: $U = 462.5$, $z = -2.056$, $p = 0.040$) and PM_{10} (smoking indoors: $U = 64.0$, $z = -2.524$, $p = 0.009$; physical pathologies: $U = 463.0$, $z = -2.051$, $p = 0.040$) concentrations at home.

3.3. *Results from intervention study*

The intervention study allowed the users to visualize IAQ levels monitored in their homes for a defined study period (intervention period) through an interface tool specifically developed for this project (app). In addition, real-time notifications informing when CO_2 and/or PM concentrations were too high were sent to residents. Participants might exploit the provided data to identify the periods or situations in which the home air quality can be compromised and assist them in conducting actions to enhance IAQ. It was expected that the data presented through the app could encourage behavioural changes and alert the user to act as soon as possible in a situation of poor IAQ.

3.3.1. *User-interface interactions and questionnaire data*

Although all participants were invited to install the app, we found that only 78 out of the 84 engaged participants (93 %) had successfully installed the app and used it at least once during the study period. Based on the data related to the usage frequency of the app (Fig. 8), the active participants used the app during the intervention period on average 21 times. When using the app, participants requested the latest data (refreshed the screen to visualize the latest IAQ data) several times (average number of requests: 56). About the questionnaires that were distributed to the participants immediately after the period of study, in total 72 people completed the survey, with two people indicating that they did not use the app. We thus report the results of the 70 participants who noted that they use the application (Table S1, Supplementary Materials). Recall that application usability was measured using a semantic differential scale with 13 questions. Scale reliability was satisfactory with Cronbach's α 0.911. The overall satisfaction with the application's usability scored 3.56 out of 5, indicating moderate satisfaction. Participants scored the difficult-easy question especially high, with a score of 4.1, also reflected in the hard to use - easy to use question, with a score of 3.986. The lowest-scoring question, anchored with unadaptable to my needs - adaptable to my needs, received a rating of 2.457. This was also reflected in the score for the question 'force me to relinquish control - enable control', which received a rating of 2.814.

Based on data collected from the online questionnaires distributed after the intervention period regarding efforts to improve IAQ, 86 % agreed or strongly agreed with the statement ’I tried to improve the indoor air quality at home in the last two months'. However, fewer

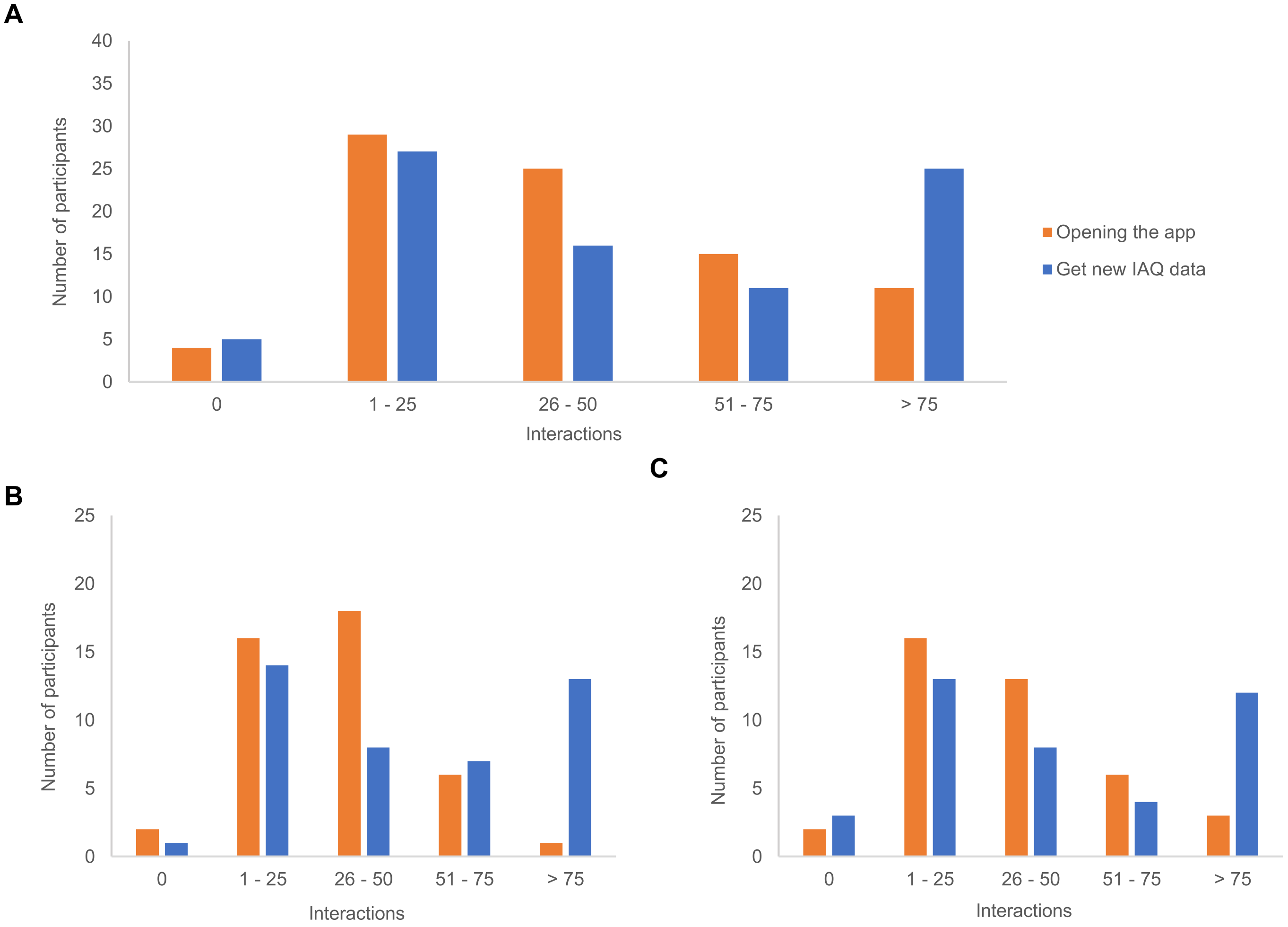


Fig. 8. Number of interactions of the participants with the app during the intervention periods for **A.** the whole sample, and per participant Group for **B.** Group 1 and **C.** Group 0.

persons agreed or strongly agreed with the statement ’I think I have improved the indoor air quality in the last two months’ at 56 %. Finally, 91 % stated that they will try to improve the indoor air quality in the next two months, again selecting ’agree’ or ’strongly agree’.

Looking more in-depth at the information provided by the application, we found that 71 % of participants indicated ’somewhat true’, ’mostly true’ or ’very true’ on the question ’I found it useful and the recommendations provided were easy to implement.’ This aligns with 76 % of participants agreeing with the statement ’I did not find it useful at all’ was ’not at all true’ or ’a little bit true’.

Additionally, most participants expressed interest in learning more about recommendations and best practices for improving air quality, with 93 % indicating responses of ’somewhat true,’ ’mostly true,’ or ’very true’ to the question, ’I would like to know more about recommendations and best practices to improve air quality.’ When examining the data presented within the application, a notable 67 % of respondents agreed with the statements ’somewhat true,’ ’mostly true,’ or ’very true’ when asked if the data helped them to better understand the factors influencing indoor air quality. Furthermore, a significant majority (73 %), reported that the information provided by the application had shifted their perception of home air quality, with responses falling into the categories of ’somewhat true,’ ’mostly true,’ or ’very true.’ Lastly, participants overwhelmingly felt that the data presented in the application motivated them to take useful actions to enhance indoor environmental quality, with a substantial 77 % indicating responses such as ’somewhat true,’ ’mostly true,’ or ’very true’. We also asked participants about energy consumption, and a significant 74 % of respondents expressed their agreement with the statement: ’I would be more motivated to conserve energy if considerations related to indoor environmental quality, encompassing thermal comfort and air quality, were integrated into the process.’ These respondents indicated responses such as ’somewhat true,’ ’mostly true,’ or ’very true.’ However, it’s worth noting that a comparatively smaller percentage of participants agreed with the statement: ’I would be willing to sacrifice some degree of thermal comfort to ensure healthier air quality,’ as reflected by their responses of ’somewhat true,’ ’mostly true,’ or ’very true.’"

Respondents were also asked about their primary reason for opening windows in their homes in the last two months. It was found that 6 % of participants did so to adapt the indoor temperature. A significant majority, 49 % of respondents, cited the removal of air stuffiness, including issues like stuffy odours and increased CO_2 levels, as their main motivation for opening windows. Furthermore, 37 % of those surveyed indicated that they opened windows to dilute indoor air pollutants, emphasising the importance of ventilation for addressing air quality concerns, with 9 % giving ’other’ as the reason.

When asked about the types of warning notifications they received regarding indoor air quality parameters in the past two months, 13 % stated that they did not receive any alerts at all. The majority, constituting 47 % of participants, reported receiving alerts for multiple indoor air quality parameters. Another significant portion, accounting for 36 %, reported receiving notifications, but these were exclusively related to particles. In contrast, only 4 % mentioned receiving alerts solely for CO_2 levels.

3.3.2. Effectiveness of the intervention in promoting healthy IAQ levels

The descriptive statistics of the IAQ parameters levels assessed in the participant groups for the control and intervention period are presented in Table 3. For the investigation of the impact of the intervention (access to real-time IAQ data in the app) on the participants’ behaviours towards promoting better air quality in their homes, the statistical analysis conducted was mainly based on pairwise comparisons employing Wilcoxon tests for comparing the participants with themselves (considering data obtained in the periods in which they worked as: control vs. intervention). This approach is expected to reduce the effect of external sources of variability, including home characteristics, occupants’ behaviours and surrounding outdoor conditions. Interestingly, significantly lower mean CO_2 concentrations ($z = -2.644$, $p = 0.008$) were detected in the homes for the nudging periods (when app functionalities for presenting IAQ data were active). If we analyse homes individually, considering the indoor CO_2 concentrations assessed with IAQ LCS modules, it was observed that 52 (62 %) homes (22 of Group 1 and 30 of Group 0) presented lower average CO_2 concentrations in the period in which they were able to visualize IAQ data in the app than those found in the control period (in which no IAQ data was available). Considering these 52 households, the achieved reduction of indoor CO_2 concentration from the control to the intervention period was, on average, 10.3 % (varying from 0.2 % to 45.3 %). Although a limited number of similar studies existing in the current literature, Basien et al. [40]implemented a CO_2 meter with a display to effectively inform students’ behaviour, prompting them to take action to improve IAQ in their dwellings. The referred study achieved a reduced median CO_2 level in 74 % of living rooms. Considering the median CO_2 concentration obtained in this work, we found reduced median CO_2 levels in 68 % of the participant homes, which is a percentage slightly similar to those reported by Basien et al.

The investigation of differences between nudging and non-nudging periods, taking into consideration the isolation of data for the period of the day in which participants typically occupy living room and that

Table 3
Descriptive statistics for the parameters measured in 84 homes for the relevant periods of study.

Period[a]	Group[b]	n	Temperature [°C]		Relative Humidity [%]		CO_2 [ppm]		$PM_{2.5}$ [μg/m^3]		PM_{10} [μg/m^3]	
			Mean ± SD	Min – Max[c]	Mean ± SD	Min – Max[c]	Mean ± SD	Min – Max[c]	Mean ± SD	Min – Max[c]	Mean ± SD	Min – Max[c]
Period 1	Control	40	18.7 ± 1.2	14.4–22.1	64.9 ± 5.8	52.9–76.7	927 ± 312	473–1885	29.2 ± 43.5	10.7–216.2	31.5 ± 47.0	11.6–233.6
	Intervention	44	18.9 ± 1.1	16.0–22.2	63.0 ± 5.8	54.3–79.0	849 ± 258	570–1717	25.6 ± 37.3	12.5–74.9	27.7 ± 40.4	13.5–81.0
Period 2	Control	44	18.4 ± 1.1	15.3–22.7	63.2 ± 5.8	50.5–80.9	869 ± 279	510–1664	37.9 ± 63.3	14.3–310.5	40.9 ± 68.6	15.4–335.1
	Intervention	40	18.3 ± 1.1	15.1–20.9	63.8 ± 6.3	50.5–77.1	851 ± 271	510–1421	31.9 ± 48.9	15.7–159.5	34.4 ± 52.8	16.9–172.4
Period 1 + 2	Control	84	18.5 ± 1.2	14.4–22.7	64.1 ± 5.8	50.5–80.9	897 ± 295	473–1885	34.1 ± 54.6	10.7–310.5	36.8 ± 59.1	11.6–335.1
	Intervention	84	18.6 ± 1.1	15.1–22.2	63.4 ± 6.0	53.1–79.0	857 ± 279	410–1717	28.4 ± 43.1	12.5–159.5	30.6 ± 46.6	13.5–172.4

n refers to the total number of families (homes).

Max, maximum; Min, minimum; SD, standard deviation.

[a] Period 1 – corresponds to levels monitored from 16/11/22 to 14/12/22; Period 2 – from 27/12/22 to 24/01/23; Period 1 + 2 – from 16/11/22 to 24/01/23.

[b] Control group: No IAQ data in the app; Intervention Group: group having access to the real-time IAQ data and alerts in the app.

[c] Corresponds to the range of values for the mean obtained in the sample of homes.

are able to implement actions to improve IAQ (diurnal period from 8 a.m. to 10 p.m.) was also conducted. The outcomes obtained also supported that significantly higher CO_2 levels were found in the control periods than in the intervention period ($z = -2.199$, $p = 0.028$). In contrast, for particles no statistically significant changes were observed for both timeframes.

Conducting individual analysis for Group 1 and Group 0 participants, the desirable statistically significant result was only detected for Group 0 ($z = -3.426$, $p < 0.001$). This can be justified by the specific peculiarities of the crossover study design implemented in this trial. Participants from Group worked first as the control in Period 1 and as the intervention group in the subsequent Period 2; in turn, individuals from Group 1 started the study as the intervention group that had the IAQ app functionalities active and then as the control in the second term. Although a wash out period was considered in between the switching of the groups, the possibility that Group 1 experienced a long-lasting learning effect should not be excluded, and this is likely to justify why no significant differences were observed for CO_2 levels found in homes of Group 1 for control and interventions periods ($z = -0.054$, $p = 0.959$).

For airborne particles, no significant differences were obtained between levels assessed in control and intervention periods for both participant groups. However, compared to the control period, a reduction of the average both $PM_{2.5}$ and PM_{10} levels in the intervention period was observed in 46 homes (37 of Group 1 and 9 of Group 0). Unlike CO_2, which has a well-defined predominant source (the occupants), indoor particles can be multifactorial in their origin. There is plenty of putative sources from indoor (e.g., combustion sources, consumer products, biologicals, and occupants' behaviours, including smoking, cleaning, and cooking) and outdoor origins (e.g., traffic-related sources and specific events, including wildfire, and construction works) that can have a relevant contribution to the dynamics of particulate pollution load found in indoor environments. Thus, it would be necessary to have a comprehensive control of these emission sources/events for the different study phases in order to properly investigate the nature of variation in the particle concentrations in the participants' homes. Although the sources occurring indoors were not controlled, for considering the outdoor contribution, PM_{10} concentrations in ambient air were obtained from a public database to estimate the respective I/O concentration ratios. Results showed that although the I/O for PM_{10} concentrations were found to be higher in the control period than in the intervention period (1.67 vs 1.40), the difference was not statistically significant. As expected, the I/O concentrations for PM_{10} were generally equal or near 1, meaning that the indoor levels have their putative nature attributed to both outdoor and indoor sources. Also, it was found that 44 homes (26 from Group 1 and 18 from Group 0) presented higher I/O in the control period compared to those obtained in the intervention period, at an average of 56 %. However this difference was not statistically significant for none of the groups.

4. Study strengths and limitations

This study constitutes a step forward in providing innovative evidence of the usability of the IoT systems using LCS for citizen-oriented science aiming to promote healthy environments. Nevertheless, a considerable number of limitations are identified in the study design and procedures employed, as described below.

The testing of LCS, in comparison with standard equipment, was solely based on short-term tests, long-term tests would be helpful to establish more robust corrections and characterize sensor aging changes. Additionally, there is a high degree of uncertainty regarding the results obtained from the tests conducted five months after the monitoring start for 10 units of IAQ LCS modules, which could not be fully representative of the status of all 84 modules employed in the study. For instance, although a degree of sensor deterioration was noticed mainly for particle sensors, sensor degradation effects were not considered in the analysis. However, to the best of our knowledge, no study has assessed the reliability of multiple sensor readings after 5 months of applicability. The sensor degradation can be related to the environmental conditions and lack of maintenance of the used IoT systems. Further investigations are necessary to describe reliable maintenance procedures for this kind of system. Furthermore, a relevant effect of the localization of the systems in complex environments such as living rooms with open kitchens, high levels of particle emission and heat sources that possibly relate to the degradation of PM sensors should not be excluded.

It would be valuable to include a comparison with reference equipment in some of the homes surveyed to properly control the effects of sensor aging/signal degradation. Further, the crossover design implemented in this pilot study made that Group 1 did not work as a real control group in Period 2 due to putative learning effects that were very likely to occur (supported by the questionnaire data). This likely represented a limitation in finding significant differences between control and intervention groups for the whole sample. For assessing the impacts of the nudging treatment in enhancing IAQ, the analyses did not consider the effect of potential relevant confounding factors (e.g., changes in occupancy, in the frequency of occurrence relevant events or pollution sources, in meteorological conditions from control to intervention periods).

5. Conclusion

The comprehensive approach developed in this work allowed to provide new evidence on the strengths and limitations of using a low-cost IoT system in providing much improved spatial and temporal resolution IAQ data in indoor environments compared to the traditional reference equipment and in empowering citizens to control their living environments. In particular, it was found that the developed IoT architecture was very effective in identifying peaks of CO_2, $PM_{2.5}$, and PM_{10} concentrations, with the readings being significantly correlated with those obtained by standard equipment. Nevertheless, although a good long-term accuracy was noticed for CO_2, temperature, and relative humidity, for SPS30, the sensor used for monitoring PM, a substantial decay in the correlation coefficient was observed. This result shows that sensor aging or degradation stands out as an important factor that needs to be accounted for when conducting further studies aiming at long-term measurements using the LCS, particularly for monitoring airborne particles.

Further, the implementation of the developed IoT system in 84 homes of families with children resulted in an apparent beneficial impact on the CO_2 levels of an important number of homes for the period in which participants were allowed to visualize real-time information on IAQ levels and recommendations on corrective actions. Some evidence of the existence of long-lasting behaviour effects in participants, who appear to learn to identify the periods in which ventilation rates can be compromised and in implementing actions for improvement (opening windows to reduce CO_2 concentrations, etc.) was also observed. For instance, a very positive finding of this work was that about 70 % of participants stated that the data provided helped them gain a better understanding of the factors influencing indoor air quality and referred to being very motivated to contribute to improving IAQ in the future. Additionally, outcomes of this study showed that participants would like to have more detailed and personalized information on IAQ, suggesting that further studies need to be conducted to develop an optimized framework that incorporates the household characteristics in the models to derive tailored recommendations. Overall, the use of IoT systems based on LCS in empowering citizens while promoting awareness and increasing their literacy level on the factors that may influence exposure to air pollution at home is a fertile topic for further research. Nevertheless, due to the limitations inherent to the use of LCS, it is of utmost importance to consider, in parallel with the implementation, the execution of a robust sensor performance testing plan to ensure the data quality.

Effective actions for mitigating IAQ-related health risks will require regulatory measures, behavioural changes through awareness-raising actions, and simple and readily deployable tools to promote environmental justice and capture peak exposures to inform emission source control policies. The findings from this work revealed that the promotion of the use of LCS-based IoT systems could be a key element in the designing of further risk communication policies to improve the public engagement with air pollution mitigation actions. Indeed, such approaches constitute a valuable contribution to the strategic framework under the Zero Pollution Action Plan of the Green Deal by reducing citizens' exposure and the incidence of adverse health outcomes in Europe caused by residential indoor pollution.

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CRediT authorship contribution statement

Marta Fonseca Gabriel: Writing – original draft, Validation, Supervision, Project administration, Methodology, Investigation, Conceptualization. **Gonçalo Marques:** Writing – review & editing, Software, Methodology, Conceptualization. **David Filipe:** Writing – original draft, Software, Investigation, Data curation. **Fátima Felgueiras:** Writing – original draft, Investigation, Formal analysis, Data curation. **João Pedro Cardoso:** Writing – review & editing, Investigation. **Joana Azeredo:** Writing – original draft, Investigation, Data curation. **Giannis Kazdaridis:** Writing – original draft, Software, Methodology, Investigation. **Polychronis Symeonidis:** Writing – original draft, Software, Methodology, Investigation. **Stratos Keranidis:** Writing – review & editing, Methodology, Investigation, Funding acquisition, Conceptualization. **Peter Conradie:** Writing – original draft, Methodology, Formal analysis. **Isabel Azevedo:** Writing – review & editing, Supervision, Project administration, Funding acquisition. **Filippos Anagnostopoulos:** Writing – review & editing, Validation, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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