

Healthy Indoor Congress

Valladolid, Spain

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Table of contents

11 Welcome to the Healthy Indoor Congress

17 Healthy Indoors Conference Organisers

19 Collaborators

Session 1 – Indoor Pollutants and Microbiome Dynamics

20 Microbes and PAHs in indoor air of polish schools
Adam Muszyński, Artur Badyda, Katarzyna Affek, Nina Doskocz, Piotr Kępa, Mariusz Rogulski, Dominika Mucha, Anna Piórkowska, Monika Załęska-Radziwiłł

26 Assessment of volatile organic compounds in urban transitional environments: Seasonal monitoring in a metro station and public market in Barcelona
Alberto Rodríguez-López, Ángela Lao-Zea, Andrea Medina-Fuentes, Raúl Matesanz-Sanz, Gloria Simón-Naranjo, Sandra Rodríguez-Sufuentes, Jose Fermoso, Maria Figols, Alba Gómez-López, Rubèn González-Colom

34 Adsorbent–photocatalyst biochar/g-C_3N_4 hybrids for CO_2 capture and VOCs removal
Andrea Medina-Fuentes, Angela Lao-Zea, Miguel G. Acedos, María José Mateos, María Luisa Ruíz, Alberto Rodríguez-López, Silvia Suárez

40 Urban environments shape the airborne microbiome
Clara Pérez-Setién, Alba Gómez-López, Jesús Muñoz, José Fermoso, Josep Roca, Javier Diéguez Uribeondo

45 Spectrum photocatalytic air disinfection for healthcare indoor environments: From pathogen inactivation to real hospital validation
Gonzalo Sánchez Domínguez, Ángela Vázquez Calvo, Mayte García Castey, Fernando Fresno, Ana Isabel Moraga-Qunitanilla, Gloria Calderita, María de Ceano-Vivas, Cristina Calvo, Antonio Alcamí, Ana Iglesias Juez

51 Influence of KOH treatment and spruce biochar on the adsorption and photocatalytic performance of TiO_2 (P25) on formaldehyde (HCHO) removal
Jouvan Chandra Pratama Putra, Silvia Suárez, Tore Sandnes Vehus, Henrik Kofoed Nielsen

58 Bioaerosol emissions from industrial biofilters may have potential implications for occupational exposure and worker health
Katarzyna Affek, Agnieszka Tabernacka, Monika Załęska-Radziwiłł, Nina Doskocz, Adam Muszyński

64 Integrated plant–microbe mechanisms driving VOC removal in botanical filtration systems
María Sol Montaluisa-Mantilla, Raquel Lebrero, Pedro García-Encina, Raúl Muñoz

71 Biological decontamination of air and surfaces using patented UV-C-based devices: Experimental evidence supporting targeted IAQ management strategies
Garcia-Gallardo Sanz MV, García Gallardo Sanz P, Gayubo Ausin S, Correira Magalahes de Soussa B, Martín Mecerreyes A., Góngora Molina R. J, Bocigas Martín C., Melero Gil B., Rovira Carvallido

77 Impact of summer outdoor pollution and heatwaves on bedroom Indoor Air Quality in social housing
Marta Sacristán-Uña, Irene Poza-Casado, Diego Tamayo-Alonso, Alberto Meiss

84 Airborne microbial communities in a judo training facility- A pilot molecular study
Nina Doskocz, Juhi Mishra, Monika Załęska-Radziwiłł, Wioletta Przystaś

89 Multi-country evaluation of indoor air across different scenarios: Results from K-HEALTHinAIR project
Otilia Boghenco, Mariana O. Corda, Alba Gómez-López, Rubèn González-Colom, Artur Badyda, Alexandra Kristian, Simon De Leede, Amy Van Grieken, Jose Fermoso, Carla Martins

95 Indoor $PM_{2.5}$ in polish residential buildings across heating system categories: Results from a two-year continuous monitoring study
Piotr Kępa, Mariusz Rogulski, Alexandra Kristian, Hanns Moshammer, Jose Fermoso Dominguez, Barbara Kozielska, Martin Lehmann, Dominik Heß, Artur Badyda

101 Coupling aerosol monitoring with airborne microbiome and resistome profiling in healthcare indoor environments
Sofya Pozdniakova, D. Ekhlas, T. Hender, Ó. González, S. Damilos, S. Saliakas, E.P. Koumoulos, J. Pagès-Oliveras, S. Santamaria, L. Mondéjar, A. Bruguera, Z. Anastopoulou, R. Fokas, A. Vantarakis, C. Karaberi, D. Fytili, X. Rodó, S.M. Soto, S. Borràs

107 From room to result: Sampling and GC-MS analysis of indoor air volatiles
R. Matesanz, G. Simón, A. Lao-Zea, M. P. Alcacera, J. Gilaranz, S. Suárez, A. Rodríguez-López

112 Air cleaning technologies for particles, gases, and microorganisms: Principles, effectiveness, and limitations
Stefan Schumacher, Anna Caspari, Ute Schneiderwind, Christof Asbach

119 Oxidative inactivation of airborne viruses using catalytic filters
P. Llanos, A. Vázquez-Calvo, A. Serrano-Lotina, A. Gómez-López, M. García-Castey, A. Alcamí, M.A. Bañares

Session 2 – Health Outcomes and Clinical Evidence Related to IAQ

126 Allergy in Children to illicit drugs, tobacco and alcohol
Alicia Armentia Medina, Sara Martín-Armentia, Sara Fernández Cortés, Ignacio Gonzalez-Rodriguez, Blanca Martín-Armentia, Maria Jose Martinez, Fernando Pineda

131 Environmental determinants of physical and cognitive health in schoolchildren
Hanns Moshammer, Alexandra Kristian, Dominika Mucha, Artur Badyda, Piotr Kępa

137 Air pollution exposure, inhaled doses, and respiratory health: A case-control study across five European cities
Johana Burbano, Apoline De Wit, Ioar Rivas, Guillaume Suarez, Sarah Koch, Andrés Alastuey, Beatriz Eguzkitza

143 Does a high air infiltration rates improve indoor air quality?
María del Mar Barbero Barrera, Luis Alou Cervera, Estefanía Sánchez-Reyes, Kevin Sabariego Moreno, Begoña Pérez-Moneo, María Aparicio

151 Attributable burden from indoor air pollution across four European countries: A multi-centre study
Mariana O. Corda, Otilia Boghenco, Alba Gómez-López, Rubèn González-Colom, Artur Badyda, Alexandra Kristian, Hanns Moshammer, Simon De Leede, Amy Van Grieken, Jose Fermoso, Carla Martins

156 Oscillometry in chronic respiratory diseases: Towards improved standardization for clinical practice
Rubèn González-Colom, Alba Gómez-López, Néstor Soler, Núria Sánchez-Ruano, Sandra Rodríguez-Sufuentes, Marta Sorribes, Emili Vela, Jordi Piera-Jiménez, José Fermoso, Josep Roca, Isaac Cano, Ramón Farre, Ebymar Arismend

162 Household air quality in chronic obstructive respiratory diseases: Actionable insights for clinical practice
Rubèn González-Colom, Alba Gómez-López, Sandra Rodríguez-Sufuentes, Néstor Soler, Núria Sánchez-Ruano, Marta Sorribes, Oguz Mulayim, María Figols, Alberto Rodríguez, Emili Vela, Jordi Piera-Jiménez, Josep Roca, Isaac Cano, Jose Fermoso, Ebymar Arismendi

Session 3 – Low-Cost Sensors and Continuous IAQ Monitoring

168 Portable air purifiers as a mitigation strategy for $PM_{2.5}$ exposure in residential wood-heating environments: A comparative case study
Alexandra Kristian, Mariusz Rogulski, Dominik Heß, Martin Lehmann, Hanns Moshammer, Artur Badyda

174 Air purifiers as a means to improve air quality in challenging environments
Dominik Heß, Martin Lehmann, Rushil Vaghasiya, Alexandra Kristian, Mariusz Rogulski, Hanns Moshammer, Artur Badyda

179 Strengths and weaknesses of air quality sensors
Hanns Moshammer, Alexandra Kristian, Cesar Mediavilla Martinez

185 Assessment of Indoor environmental quality in a windowless university classroom with low-cost multi-sensors in İzmir, Türkiye
İlknur Ayri, Buse İritepe, Sait C. Sofuoglu

189 Evaluation and monitoring of indoor environmental quality in the pathology department at Río Hortega University Hospital (Valladolid)
J.F. San José Alonso, Y. Arroyo Gomez, F.J. Rey Martínez, J.C. Cardillo Lorente

195 Design and deployment of a low-cost sensor network for continuous indoor–outdoor air quality monitoring
Maidá Domat, Enrique González-Plaza, Alfredo Menéndez-Rubiera, Alfonso Fernández-Aybar, Ignacio Rodríguez-Larrad

202 Linking human activities to indoor air pollutant peaks: Preliminary results from a diary study in polish and Austrian households
Dominika Mucha, Alexandra Kristian, Piotr Kępa, Mariusz Rogulski, Adam Muszyński, Nina Doskocz, Hanns Moshammer, Artur Badyda

206 $PM_{2.5}$ and CO_2 in polish schools: Two years of measurements
Mariusz Rogulski, Piotr Kępa, Alexandra Kristian, Adam Muszyński, Dominika Mucha, Martin Lehmann, Dominik Heß, Artur Badyda

212 Mitigating personal air pollution exposure: A 12-month trial of portable monitors
Sotirios Papathanasiou, Christos D. Argyropoulos

221 AuNP@8-MOA-based electrochemical immunosensor for passive screening of airborne aflatoxin B1-associated contamination
Mercedes Iriarte-Cela, Clara Pérez-Setién, María Figols, José Fermoso, Javier Diéguez-Uribeondo

226 Precision of MICA devices: Experimental validation under realistic indoor conditions
Amaia Irisarri, María Figols

Session 4 – Data Analytics, Artificial Intelligence and Standardised Methodologies for IAQ Assessment

231 Assessment of indoor environmental quality under real operating conditions in nearly zero-energy university classrooms using the TAIL method
Francisco Javier Rey-Martínez, Yolanda Arroyo-Gómez, Javier María Rey-Hernández, Luis Javier San José Gallego, Julio Francisco San José-Alonso

238 Continuous multi-parameter indoor air quality monitoring for operational IAQ management in hospital environments
Jose Fermoso, Sandra Rodríguez-Sufuentes, Alberto Rodríguez, Silvia Suárez, Javier Diéguez, Clara Pérez Setién-Gil, María Figols, Manel Sanz, Felipe López, Ferrán Rodríguez, Rubèn González-Colom, Isaac Cano, Josep Roca

244 Architectural guardrails for AI-assisted IAQ assessment: An agent reasoning across WELL, GO IAQS, EPBD and beyond
Miguel Escribano Hierro

251 Impact of occupancy dynamics on indoor CO_2 forecasting across real-world scenarios
Peio Garcia-Pinilla, Aranzazu Jurio, María Figols, Daniel Paternain

258 "Focus 1%" approach to indoor air quality: Translational application of targeted air purification technologies
Próspero García-Gallardo Sanz, María Victoria García-Gallardo Sanz, Sara Gayubo Ausín

Session 5 – Policy, Roadmap and Stakeholder Perspectives for IAQ

265 From awareness to action: K-HEALTHinAIR's strategic approach to stakeholder engagement and policy translation for indoor air quality
Leticia Pérez Saiz, Mireia Ferri, Maite Ferrando

270 The $PM_{2.5}$ exposure in 14 schools in the Lodz area in Poland
Wojciech Hanke, Slawomir Brzeznicki, Alexandra Kristian, Hanns Moshammer, Dominik Heß, Martyna Ziomek-Świątkiewicz, Adam Gansiniec

274 Net4CleanAir - A COST Action for indoor air cleaning technologies
María Teresa Baeza-Romero, Giorgos Panaras, Ana María Rodriguez Cervantes, Sascha Nehr, Nikos Ploskas, Ioannis Papadopoulos, Jonalda Gjoka, John Saffell, Nic Carslaw, Sofia Sousa

Welcome to the Healthy Indoor Congress

It is our great pleasure to welcome you to the Book of Abstracts of Healthy Indoors: Innovation and Research in Air Quality, held in Valladolid, Spain, on 22–23 June 2026.

Healthy Indoors was organised in the framework of the K-HEALTHinAIR project, funded by the European Union under Horizon Europe (Grant agreement 101057693), as its Final Scientific Conference. After four years of research across multiple European countries and indoor environments, the conference provided an opportunity to share and discuss some of the knowledge generated by the project on indoor air quality (IAQ), human exposure and health. However, from the outset, our ambition was to go beyond presenting the results of a single project. Healthy Indoors was conceived as an open scientific meeting, bringing together researchers, healthcare professionals, technology developers, public authorities, industry representatives and other stakeholders working towards a common objective: creating healthier indoor environments.

This broader perspective was reflected throughout the scientific programme and in the contributions collected in this volume.

The conference addressed indoor pollutants and their sources and determinants; low-cost sensing and continuous monitoring; data analytics and artificial intelligence; human exposure and health outcomes; technological and preventive interventions; and the translation of scientific evidence into standardisation, stakeholder action and public policy.

Taken together, these contributions illustrate the complexity of understanding and managing IAQ. Indoor environments cannot be considered in isolation. The air we breathe indoors is shaped by buildings and ventilation systems, human activities and behaviour, occupancy, materials and products, outdoor pollution, seasonality and, increasingly, extreme climatic events. Likewise, exposure cannot always be adequately characterised by a single measurement at a fixed location. Continuous and personal monitoring, improved analytical methods and increasingly accessible sensing technologies are opening new possibilities for understanding how exposure evolves across the different microenvironments in which people spend their daily lives.

At the same time, the conference discussions repeatedly reminded us that measuring is only the beginning. Data need context and interpretation. Sensors must be understood together with their capabilities and limitations. Pollutant concentrations need to be connected with sources, activities, ventilation, occupancy and outdoor conditions. Exposure information must ultimately be related to biological and clinical responses and, where possible, translated into an understanding of its consequences for individual and public health. The contributions presented at Healthy Indoors reflected this entire pathway, from pollutant characterisation and methodological development to exposure assessment, health outcomes and estimation of health burden.

Importantly, the programme also looked beyond the identification of problems towards prevention and action. Source control, ventilation, filtration and air-cleaning technologies, behavioural interventions and data-driven management strategies all have a role to play, but the evidence presented during the conference also showed that there is no universal solution. Effective interventions depend on the pollutant, building, occupants and environmental context, and their potential benefits must be considered alongside energy use, maintenance requirements, outdoor air conditions and possible

unintended effects. In some cases, the determinants of indoor exposure lie partly outside the building itself, reminding us that healthy indoor air also depends on wider environmental and urban policies.

A central ambition of Healthy Indoors was therefore to connect scientific evidence with action. Research can generate knowledge, technologies can provide new solutions and monitoring can make otherwise invisible exposures visible, but sustained improvements in indoor environments require the involvement of the people who occupy, operate, design and regulate them. Engagement, education, harmonised methodologies, standards, accessible evidence and appropriate policy frameworks are all necessary to translate research findings into healthier environments. This transition from awareness to participation, and ultimately to empowerment and policy action, was also a central component of the work developed within K-HEALTHinAIR.

A particularly rewarding expression of this philosophy was the Young Researchers' Session dedicated to IAQ in educational spaces. Students from IES Condesa Eylo Alfonso and IES Emilio Ferrari, in Valladolid, together with students from Primary School No. 38 named after Irena Sendler, in Warsaw, shared their own work on classroom air quality through oral presentations and posters, while students from IES Los Salados and IES Venancio Blanco also contributed to the session through poster presentations, despite being unable to attend the conference in person. Their contributions demonstrated that IAQ research and awareness should not be limited to universities, research centres or professional communities. Giving young people the opportunity to measure, analyse and discuss the air in the environments where they spend much of their daily lives can foster scientific curiosity, environmental awareness and a better understanding of the relationship between our surroundings and our health. We are especially grateful to these young researchers, their teachers and the participating schools for their enthusiasm, commitment and the quality of their contributions, which made this session a particularly valuable part of the conference.

This collaborative dimension extended beyond K-HEALTHinAIR and was particularly important in the context of the IDEAL Cluster, which has brought together European projects working on indoor air quality and health. Healthy Indoors benefited from the

participation and experience of other initiatives within this community, including EDIAQI, and provided an opportunity to continue the dialogue developed across the Cluster. The conference also shared the overarching conclusions emerging from the IDEAL Cluster final event, "The Air We Breathe", helping to connect the scientific discussions in Valladolid with the broader lessons generated through this European collaboration. This exchange illustrates one of the most valuable legacies of these initiatives: knowledge becomes more useful when projects, disciplines and stakeholders work beyond their individual boundaries.

We are particularly proud that these discussions took place in Valladolid that gave the conference a very special character. We are deeply grateful to the Real Academia de Medicina y Cirugía de Valladolid for the great honour of hosting Healthy Indoors and for generously making its facilities available for the conference. Few settings could have been more appropriate for discussing the relationship between our environment and our health. The scientific exchanges of these two days took place within walls that have witnessed a long history of medical and scientific knowledge, creating an inspiring connection between past and present research.

Our sincere gratitude also goes to the institutional representatives who took part in the Opening Ceremony: Sergio Sanz, Deputy Director General of CARTIF; Javier García Frade, President of the Royal Academy of Medicine and Surgery of Valladolid; Juan Manuel Arnáiz, Head of the Territorial Health Service of the Regional Government of Castilla y León, to whom we are particularly grateful for his personal commitment and efforts to join us on this occasion and Jesús Julio Carnero, Mayor of Valladolid, whose presence provided a warm institutional welcome to the international scientific community; Their participation gave the conference a strong institutional and scientific opening and reflected the collaborative spirit that Healthy Indoors sought to promote from the outset. We also warmly thank the Archivo Histórico Provincial de Valladolid for allowing us to use its historic courtyard for the poster and catering sessions. Together, these exceptional venues provided not only a beautiful and historically rich setting for Healthy Indoors, but also spaces for the informal conversations, exchange of ideas and new collaborations that are such an important part of any scientific meeting.

Above all, we would like to thank everyone who made Healthy Indoors possible: our invited speakers and session chairs; all authors who submitted and presented their work; the scientific reviewers; the K-HEALTHinAIR consortium and collaborating projects; the institutions and organisations that supported the event; and every participant who contributed questions, ideas and experience to the discussions. We would like to extend a very special acknowledgement to the young researchers and teachers from the participating schools, whose enthusiasm reminded us of the importance of engaging the next generation in understanding and improving the environments in which we live, learn and work. The diversity of disciplines, countries, generations and perspectives represented in Valladolid was essential to achieving the open and collaborative scientific meeting that we had hoped to create.

This Book of Abstracts provides a record of that scientific exchange, but we hope that the conversation will continue beyond these pages and beyond the conference itself. Recordings of the scientific sessions and posters presented will be made available through the K-HEALTHinAIR website, extending access to the presentations and discussions to those who were unable to join us in Valladolid and helping to preserve and disseminate the knowledge shared during the event.

Healthy indoor environments will not be achieved through a single sensor, technology, discipline, intervention or regulation. They require us to connect science, technology, health, people and policy. We hope that Healthy Indoors has made a meaningful contribution to strengthening those connections and that the knowledge, enthusiasm and collaborations shared in Valladolid will continue to support our collective efforts towards healthier indoor environments.

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Session 1 – Indoor Pollutants and Microbiome Dynamics

Microbes and PAHs in indoor air of polish schools

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Abstract

Background

Indoor air quality (IAQ) in schools is a matter of public concern, given the substantial amount of time that children aged 3 - 14 years spend in these settings, both in winter and summer (1,2). This is particularly relevant owing to children's vulnerability and high classroom occupancy rates (1,3). Children are more susceptible to environmental pollutants than adults because they inhale larger volumes of air relative to their body weight, while their tissues and organs are still developing. School-specific conditions (age and air-tightness of buildings, classroom design, ventilation rate, building and furnishing materials), location and outdoor air pollution can adversely affect IAQ and children's health (1,3). Among the various indoor air pollutants (3,4), microorganisms and polycyclic aroamatic hydrocarbons (PAHs) are particularly relevant. Elevated levels of bacteria and fungi can cause respiratory and communicable diseases, trigger asthma, headaches and allergies, and are associated with sick building syndrome and reduced wellbeing (5,6). These problems are particularly relevant in densely occupied and insufficiently ventilated schools (7). PAHs are among the most hazardous components of particulate matter (PM) and include compounds identified as carcinogenic. Their metabolites can bind to DNA or RNA, affecting replication, transcription and protein biosynthesis and cause cancer (8). In Poland, PAHs have emerged as notable air pollutants since their concentrations are the highest in Europe (9). These pollutants can penetrate indoor environments and particularly affect children, who are more vulnerable to environmental hazards than adults (7). Thus, airborne microorganisms and PAHs require thorough investigation in schools.

Objectives

This study aimed to assess seasonal variations in concentrations of PAHs and microorganisms, and to identify possible sources of these contaminants in indoor air of primary schools in central Poland.

Methodology

Samples of indoor air were taken in 5 primary schools in central Poland (3 representative classrooms and 1 outdoor sampling point in each school). To

examine seasonal variation in IAQ and the influence of outdoor pollution, sampling was performed in winter and summer (heating and hot periods, respectively). Air samples for culturable microorganisms were collected using standard impactors (MAS-100 Eco®, Merck Millipore; SAS Super IAQ®, VWR), following previously described procedures (10,11). Tryptic Soy Agar (TSA) medium was used for the enumeration of total mesophilic bacteria, incubated for 48 h at 37 °C, whereas Malt Extract Agar (MEA) was used for the enumeration of fungi, incubated for 5 days at 26 °C. To determine the concentrations of 16 PAHs crucial from the health impact point of view, respirable particles (PM_4) were first collected using GilAirPlus aspirators (Gilian, USA) on quartz filters. Then PAHs were extracted with dichloromethane and the extracts were analyzed using Clarus 500 Perkin Elmer gas chromatograph (a capillary column Restek RTX-5,) with a flame ionization detector (280°C) equipped with an autosampler (Perkin Elmer, Inc., Waltham, MA, USA), according to (8). Equivalent benzo(a)pyrene toxicity equivalent (BaPeq [ng/m3]) was calculated according to (12), Incremental Lifetime Cancer Risk (ILCR), associated with 8 years of primary schooling in Poland, was calculated depending on exposure to specific pollution sources according to (13).

Key Results

In poorly ventilated classrooms (e.g. with closed windows), the level of bacteria in indoor air reached 3000-7000 cfu/m^3 regardless of the season, and exceeded that of fungi. Bacterial contamination was lower (1000-2000 cfu/m^3) before or after the lessons (empty rooms) and in efficiently ventilated classrooms (with open windows). The fungal content indoor in summer (1000-2000 cfu/m^3) was higher than in winter (<100 cfu/m^3) and reached the outdoor levels, especially in rooms with open windows. The variability of PAHs concentrations in indoor air, as well as the mutagenicity and carcinogenicity equivalents, also reflected the changes in outdoor air concentrations. Their levels were higher in winter, in locations situated near residential areas, where the combustion of coal and wood remains the primary method of building heating. This indicates potential health risks associated with breathing indoor air during colder seasons. The biologically active PAHs (4- and more rings)

were present only in some of the analyzed summer samples and in rather low concentrations. However, in winter they were detected more often and in most cases in noticeably higher concentrations. Thus, also the mutagenicity equivalent and carcinogenicity equivalent were visibly higher in winter samples. BaP_{eq} concentrations in schools ranged from 0.001-0.4 ng/m^3 during the summer period to 0.07-4.9 ng/m^3 during the winter season. The average level of indoor air pollution in schools by PAHs was slightly lower than in homes. However, given the significantly shorter time spent in schools and the relatively short time spent outdoors (where concentrations were typically the highest), health risks are most associated with staying in homes using solid fuels for heating and in homes using other heating sources but located in housing estates where solid fuels are heavily used. Despite the highest exposure to BaP_{eq} in winter in outdoor air, where concentrations were approximately 3.5 ng/m^3, the ILCR level was relatively low, amounting to $1.1*10^{-4}$, while in schools it was $1.4*10^{-4}$ and in homes it ranged from $6.6*10^{-4}$ in homes heated using renewable energy sources or municipal heating, to $16.6*10^{-4}$ in homes heated using solid fuels.

Main Conclusions

The type and level of indoor air contamination in schools depended on a season (predominance of fungi and PAHs in summer and winter, respectively). Children were the main source of bacteria throughout the year, but the level of bacterial contamination also depended on ventilation conditions. The presence of PAHs characteristic of coal/wood combustion indicates that in the absence of internal emission sources, the external sources of PAHs in winter most likely affect IAQ. Efficient ventilation of classrooms significantly reduces bacterial contamination of indoor air, but it can be a source of fungi and PAHs in summer and winter, respectively. Due to the external origin of PAHs and fungal pollution inside schools, maintaining the air quality desirable from the point of view of public health will probably require additional air purification. Moving away from burning solid fuels for heating purposes, especially in residential sector, should contribute to a significant decrease in exposure to PAHs and to further reduce health risks.

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Assessment of volatile organic compounds in urban transitional environments: Seasonal monitoring in a metro station and public market in Barcelona

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Citation

Rodríguez-López, A., Lao-Zea, Á., Medina-Fuentes, A., Matesanz-Sanz, R., Simón-Naranjo, G., Rodríguez-Sufuentes, S., Fermoso, J., Figols, M., Gómez-López, A., González-Colom, R. Assessment of volatile organic compounds in urban transitional environments: Seasonal monitoring in a metro station and public market in Barcelona.

Abstract

Background

Urban transitional environments such as metro stations and public markets represent highly dynamic microenvironments where indoor and outdoor air interact continuously [1, 2]. These spaces are characterized by high occupant density, variable ventilation conditions and the coexistence of multiple potential emission sources, including outdoor traffic-related pollution, commercial activities, cleaning products, construction materials and human occupancy [3, 4]. Despite their relevance in terms of public exposure, comprehensive information regarding the spatial and seasonal distribution of volatile organic compounds (VOCs) in these environments remains limited.

Objective

This study aimed to characterize the occurrence, spatial distribution and seasonal variability of VOCs, aldehydes and ketones in two representative urban transitional environments in Barcelona: the Barceloneta metro station and La Concepció public market. Particular attention was given to evaluating the influence of ventilation and outdoor air infiltration on indoor air composition.

Methods

Monitoring campaigns were conducted quarterly between October 2024 and July 2025, covering a complete annual cycle. VOC sampling was performed using active sampling methods based on stainless steel tubes packed with Tenax connected to Gilian 800i pumps operating at 200 mL/min for 60 min, while aldehydes and ketones were collected using DNPH cartridges

at 500 mL/min for 60 min. Two consecutive 1-h samples were collected at each sampling point for both analyses. Samples were analysed by thermal desorption coupled with gas chromatography–mass spectrometry (TD-GC-MS) [5] and HPLC, respectively.

At the metro station, one outdoor location and two sampling points located along the platform were monitored. At the market, four locations were assessed: one outdoor reference point, a flower shop, and two indoor locations.

Results

At the metro station, VOC composition was dominated by aromatic hydrocarbons, including benzene, toluene and xylenes, together with low-molecular-weight aldehydes such as acetaldehyde and propionaldehyde. Aliphatic hydrocarbons, particularly n-hexane and n-heptane, were also frequently detected. Figure 1 shows similar concentration patterns at both platform sampling points and outdoors, indicating strong outdoor–indoor coupling. Overall, concentration profiles were relatively homogeneous across the sampling locations, suggesting a strong influence of outdoor air infiltration and ventilation processes within the station.

Benzene showed the highest toxicological relevance among the monitored compounds, reaching maximum concentrations of approximately 24 $\mu g \cdot m^{-3}$ during the warmest sampling period. Although these values exceeded the European Union annual target value for ambient outdoor air quality (5 $\mu g \cdot m^{-3}$), the measurements corresponded to short-term campaigns and therefore could not be directly compared with annual regulatory limits. Toluene, xylenes, formaldehyde, acetaldehyde and the remaining monitored aldehydes remained below available indoor air quality guideline values and occupational exposure limits [3,4,6]. In addition, compounds sucha as α-pinene, camphor and several siloxanes were identified at low or moderate concentrations, likely associated with consumer products, cleaning activities and human occupancy [7,8].

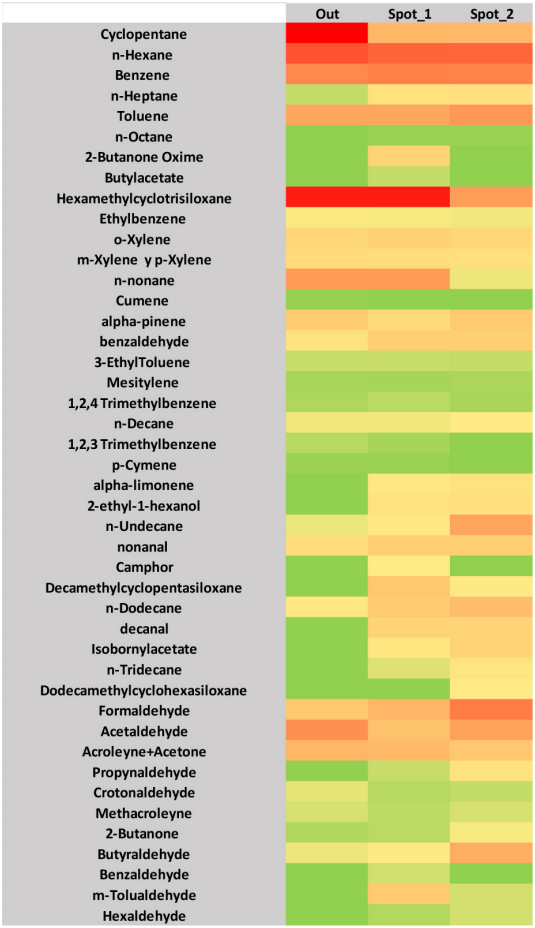
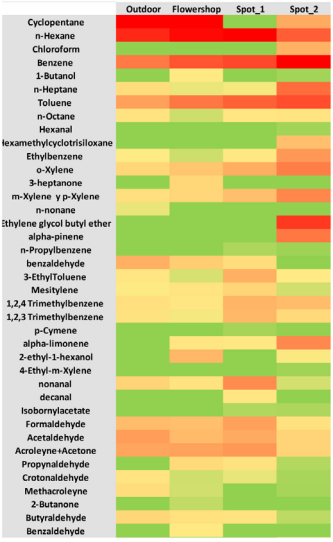


FIGURE 1

Heat map of the average concentrations of VOCs, aldehydes and ketones measured at the outdoor location and at the two platform sampling points of Barceloneta metro station.



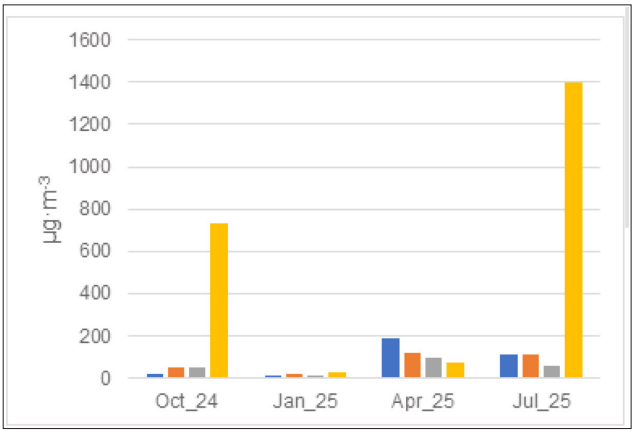


FIGURE 2
Seasonal variation of total volatile organic compound (TVOC) concentrations measured at the outdoor location, flower shop, Spot 1 and Spot 2 within Mercat de la Concepció between October 2024 and July 2025 (bottom). Annual average concentrations of individual VOCs represented as a heat map (Top).

The market environment exhibited a markedly different behaviour. The flower shop showed VOC profiles closely resembling those measured outdoors, indicating a strong influence of outdoor air due to its open configuration. In contrast, Spot 2, corresponding to the least ventilated area of the market, consistently exhibited the highest accumulation of VOCs, including aromatic hydrocarbons and aliphatic compounds such as n-hexane and n-heptane. Seasonal variations in TVOC concentrations and the annual average distribution of individual compounds are presented in Figure 2. The heat map revealed a clear spatial gradient across the market, with pollutant accumulation increasing as ventilation conditions decreased. These findings suggest that reduced air renewal favours the accumulation of pollutants originating from both outdoor infiltration and indoor commercial activities [9,10].

Conclusions

The results demonstrate the critical role of ventilation in shaping indoor VOC composition and exposure levels in urban transitional environments. While the metro station showed a strong coupling between indoor and outdoor air, resulting in relatively homogeneous pollutant profiles, the market environment exhibited distinct indoor microenvironments driven by differences in ventilation efficiency. None of the monitored compounds exceeded the available indoor air quality guideline values for the substances for which reference levels are currently available. Nevertheless, benzene remained the compound of greatest toxicological relevance due to its carcinogenic character and association with urban traffic emissions. These findings provide valuable information for the design of strategies aimed at improving indoor air quality in highly frequented public spaces.

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Adsorbent–photocatalyst biochar/g- C_3N_4 hybrids for CO_2 capture and VOCs removal

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Citation

Medina-Fuentes, A., Lao-Zea, A., Acedos, M.G., Mateos, M.J., Ruíz, M.L., Rodríguez-López, A., Suárez, S. Adsorbent–photocatalyst biochar/g-C_3N_4 hybrids for CO_2 capture and VOCs removal.

Abstract

Background

The development of sustainable materials for carbon dioxide (CO_2) capture and air pollutant removal has become increasingly important to address

climate change and air quality concerns. In addition to greenhouse gas emissions, volatile organic compounds (VOCs) are among the main contributors to atmospheric pollution and may negatively affect both environmental and human health. Consequently, there is growing interest in multifunctional materials capable of simultaneously capturing CO_2 and degrading gaseous pollutants through advanced oxidation processes.

Adsorbent–photocatalyst hybrids (APHs) have recently emerged as an attractive strategy for environmental remediation because they integrate adsorption and photocatalytic degradation within a single system (1,2). Among the different adsorbent materials available, biochars produced from biomass and organic wastes have attracted considerable attention because of their low cost, high carbon content, tunable porosity and sustainable origin. Anaerobic co-digestion (AcoD) has been widely applied as an efficient technology for the treatment of organic residues and the production of renewable energy in the form of biogas. However, this process generates large quantities of digestate, whose management remains a significant challenge. In this context, biochars derived from AcoD residues represent an interesting alternative within a circular economy framework, enabling the valorisation of waste streams into value-added materials. As photocatalytic phase, graphitic carbon nitride (g-C_3N_4) has gained increasing interest due to its visible-light activity, chemical stability and cost-effective synthesis (3). Previous studies have demonstrated the potential of biochar/g-C_3N_4 composites for environmental remediation applications (4,5).

Objective

This work aimed to evaluate the anaerobic co-digestion of sewage sludge (SS) and the organic fraction of municipal solid waste (OFMSW) through batch and semi-continuous experiments, as well as to valorise the resulting digestates into biochars for CO_2 capture applications. Furthermore, optimized biochars were combined with exfoliated graphitic carbon nitride (exf-g- C_3N_4) to develop adsorbent–photocatalyst hybrids (APHs) for the visible-light-driven degradation of volatile organic compounds (VOCs).

Methods

Batch biochemical methane potential (BMP) tests were initially performed to evaluate the anaerobic co-digestion of SS and OFMSW. Based on these preliminary results, the optimal 50:50 mixture was selected and further assessed in a semi-continuous stirred tank reactor operated under mesophilic conditions. Digestates obtained from the continuous experiment were dried and converted into biochar through pyrolysis at 500 °C for 3 h, yielding the raw biochar (B1). To improve its physicochemical properties, B1 was subsequently subjected to different post-treatment strategies: acid washing with HCl to obtain B2, chemical activation with KOH to obtain B3, and a sequential combination of acid washing and KOH activation to obtain B4. The resulting biochars were evaluated for CO_2 adsorption using thermogravimetric analysis (TGA). Finally, the optimized biochar (B4) was combined with exfoliated graphitic carbon nitride (exf-g- C_3N_4) at a 1:9 mass ratio to synthesize the hybrid material B4-exf-g-C_3N_4 (1:9), which was evaluated for the adsorption and photocatalytic degradation of gaseous trichloroethylene (TCE) under visible-light irradiation.

Results

The BMP assays (Figure 1a) demonstrated that the co-digestion of SS and OFMSW enhanced methane production compared with SS alone. Among the evaluated mixtures, the 50:50 SS ratio achieved the highest methane yield, identifying it as the most suitable composition for further studies. Although OFMSW mono-digestion achieved similar methane yields, the 50:50 SS mixture offered a better balance between methane production, process stability and the simultaneous valorisation of both waste streams.

The semi-continuous anaerobic co-digestion experiment (Figure 1b) exhibited stable performance over 300 days, confirming the robustness of the 50:50 SS ratio previously identified in the BMP assays. Biogas production progressively increased throughout the experimental period, rising from initial values below 500 mL d^{-1} to approximately 1800–2000 mL d^{-1} at

the end of the operation. This trend indicates a gradual adaptation of the microbial community to the feedstock, as well as the absence of severe inhibition phenomena during the increase in organic loading rate (OLR).

Digestates obtained from the continuous reactor were successfully transformed into biochars and further upgraded through acid washing and chemical activation. As shown in Figure 1c, the BET surface area increased

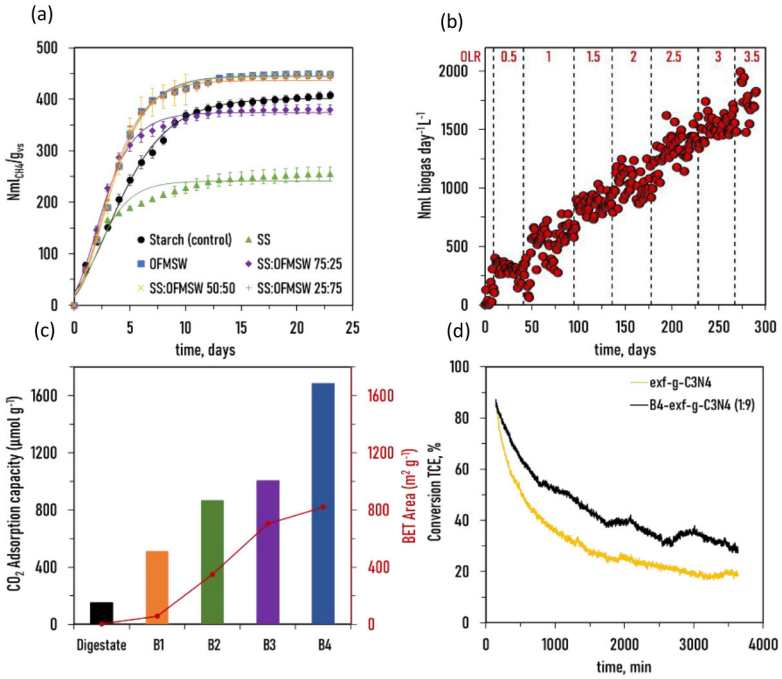


FIGURE 1
Anaerobic co-digestion of SS and OFMSW, digestate valorisation into modified biochars for CO_2 capture, and development of biochar/exf-g-C_3N_4 adsorbent–photocatalyst hybrids for VOCs degradation: **(a)** BMP assays, **(b)** semi-continuous reactor performance, **(c)** CO_2 adsorption capacity and BET surface area of biochars, and **(d)** photocatalytic degradation of TCE.

from 57 to 822 m^2 g^{-1}, while the CO_2 adsorption capacity increased from 511 to 1686 μmol g^{-1}. These results demonstrate the effectiveness of the post-treatment strategies in improving the textural properties and adsorption performance of digestate-derived biochars.

Finally, the synthesized adsorbent–photocatalyst hybrids were evaluated for the degradation of gaseous trichloroethylene (TCE). The photocatalytic results (Figure 1d) showed that the hybrid material containing biochar maintained a higher and more stable conversion over time than the reference exf-g-C_3N_4 material, demonstrating the beneficial effect of incorporating biochar into the photocatalytic system.

Conclusions

The results demonstrate the feasibility of integrating anaerobic co-digestion, digestate valorisation and photocatalytic technologies within a circular economy approach. The 50:50 SS mixture was identified as the optimal feedstock for biogas production, while the subsequent conversion of digestates into modified biochars generated materials with significantly enhanced surface area and outstanding CO_2 adsorption capacities. Furthermore, the combination of optimized biochars with exf-g-C_3N_4 produced multifunctional adsorbent–photocatalyst hybrids capable of efficiently degrading VOCs under visible-light irradiation, showing greater stability than the reference exf-g-C_3N_4 photocatalyst. These findings highlight the potential of anaerobic co-digestion residues as precursors for advanced environmental materials and contribute to the development of sustainable air pollution mitigation strategies.

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Urban environments shape the airborne microbiome

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Citation

Pérez-Setién, C., Gómez-López, A., Muñoz, J., Fermoso, J., Roca, J., Diéguez Uribeondo, J. Urban Environments shape the airborne microbiome.

Abstract

Background

Humans spend most of their time indoors, where they are continuously exposed to airborne microorganisms. However, the factors shaping airborne microbial communities across urban environments remain poorly understood.

Understanding how different urban settings influence airborne microbiomes is essential for improving our knowledge of urban ecosystem functioning and human exposure to microorganisms [1].

Objectives

This study aimed to (1) characterize airborne bacterial and fungal communities across three contrasting urban environments, (2) assess whether hospital, market, and metro environments harbor distinct airborne microbiomes, and (3) identify shared and environment-specific microbial taxa associated with each environment.

Methods

Airborne microbiome samples were collected at one hospital, one market, and one metro station in Barcelona (Spain), encompassing multiple indoor subzones and outdoor areas. The analyzed dataset comprised 46 bacterial samples (31 hospital, 10 market, and 5 metro) and 48 fungal samples (31 hospital, 12 market, and 5 metro), collected across site-specific seasonal campaigns between September 2023 and September 2025, with repeated sampling spanning different seasons at each environment. Airborne bacterial and fungal communities were characterized using Coriolis® μ bioaerosol sampling, DNA metabarcoding targeting the bacterial 16S rRNA V4–V5 region and fungal ITS2 region, and Illumina MiSeq sequencing [2]. Taxonomic assignment was performed using SILVA for bacteria [3] and UNITE for fungi [4]. Community composition was evaluated using Bray–Curtis dissimilarities, Principal Coordinates Analysis (PCoA), and PERMANOVA. The effect of urban environment was assessed across hospital, market, and metro samples, while sampling subzone/locality and seasonality were additionally evaluated within environments. Alpha diversity and taxonomic composition were also analyzed.

Results

Urban environment strongly structured airborne microbial communities. Both bacterial and fungal communities showed clear environment-related differentiation (Fig. 1 A), with environment explaining a substantial proportion

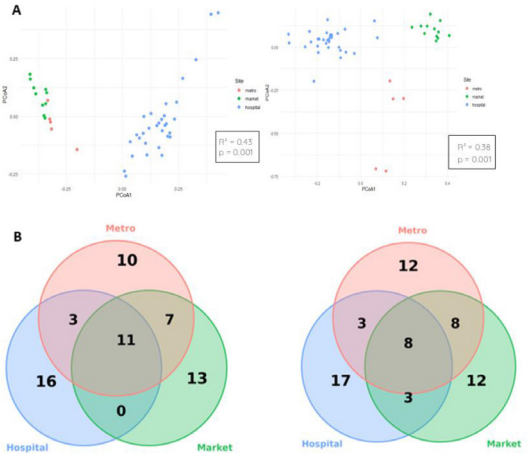


FIGURE 1
Principal Coordinates Analysis (PCoA) based on Bray–Curtis dissimilarities showing differences in airborne (left) bacterial and (right) fungal community composition among hospital, market, and metro environments. Urban environment significantly structured both bacterial (R^2 = 0.43, p = 0.001) and fungal (R^2 = 0.38, p = 0.001) communities, with distinct spatial arrangements of the three environments between microbial groups. **(A)** Eleven bacterial genera were shared among hospital, market, and metro environments, while each site also harbored unique bacterial genera. (Right) Eight fungal genera were shared across all environments, together with environment-specific fungal genera (Left). These results indicate the presence of a common airborne microbial core alongside distinct microbial signatures associated with each urban environment **(B)**.

of community variation (bacteria: R^2 = 0.43, p = 0.001; fungi: R^2 = 0.38, p = 0.001). Seasonality also significantly influenced bacterial community composition, although its effect was weaker than that of urban environment (PERMANOVA, $R^2 \approx 0.17$, p = 0.01). Although both microbial groups responded strongly to environmental differences, the spatial arrangement of hospital, market, and metro samples differed between bacterial and fungal communities. Shared and environment-specific taxa were identified across the three environments (Fig. 1 B), indicating the presence of a common airborne microbial component alongside distinct environment-associated taxa. Environment-associated taxa reflected contrasting ecological



FIGURE 2
Characteristic bacterial and fungal taxa reflected the dominant ecological sources associated with each environment, including human-associated sources in hospitals, plant-associated sources in markets, and urban dust-associated sources in metro stations.

sources (Fig. 2), including *Stenotrophomonas* and *Fusarium* in the hospital, *Arthrobacter* and *Ampelomyces* in the market, and *Ornithinimicrobium* and *Bjerkandera* in the metro.

Conclusions

Airborne microbiomes differed markedly among urban environments, identifying urban setting as a major determinant of both bacterial and fungal community composition. Bacterial communities additionally showed a weaker but significant seasonal component, indicating that airborne microbiome composition is shaped by both spatial and temporal factors. Shared and environment-specific taxa further reflected differences in local ecological sources. These findings show that different built environments generate distinct and temporally dynamic microbial exposure profiles, providing a basis for more context-specific approaches to indoor air monitoring.

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Spectrum photocatalytic air disinfection for healthcare indoor environments: From pathogen inactivation to real hospital validation

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Citation
Sánchez-Domínguez, G., Vázquez-Calvo, A., García-Castey, M., Fresno, F., Moraga-Qunitanilla, A.I., Calderita, G., de Ceano-Vivas, M., Calvo, C., Alcamí, A., Iglesias-Juez, A. Spectrum photocatalytic air disinfection for healthcare indoor environments: From pathogen inactivation to real hospital validation.

Abstract
Respiratory diseases represent one of the leading threats to public health worldwide, accounting for a substantial number of deaths each year.

Airborne transmission is a major route for the spread of respiratory pathogens, and the risk of infection is significantly higher in indoor environments, particularly in healthcare facilities and other high-occupancy spaces where cross-infection is more likely (1). While conventional ventilation and filtration systems can reduce airborne particle concentrations, they do not actively inactivate biological contaminants. Consequently, there is a growing need for innovative air sanitation technologies capable of creating safer indoor environments and contributing to the prevention of infectious disease transmission.

Microorganisms can be inactivated through oxidative stress (OS), a mechanism that damages cellular mem branes and viral structures, ultimately impairing their ability to infect host cells. In this context, we present an advanced photocatalytic air disinfection technology capable of continuously inactivating airborne pathogens through oxidative stress under illumination conditions that are safe for occupied indoor environments.

Zinc oxide (ZnO) nanoparticles exhibit antimicrobial activity through the photogeneration of reactive oxygen species (ROS) (2-4). However, their efficiency is often limited by the rapid recombination of photogenerated electron-hole pairs. To overcome this limitation, ZnO–CeO_2 nanocomposites were developed. The formation of heterojunctions between both semiconductors reduces charge recombination, while the intrinsic redox proper-ties of CeO_2 further enhance ROS generation. These characteristics make the resulting nanocomposites promising candidates for chemically active biocidal filtration systems.

To evaluate both efficacy and real-world applicability, a multi-scale experimental validation strategy was implemented. Initial antiviral activity was assessed through plaque assays performed on photocatalytic coatings. Human coronavirus HCoV-229E was tested in Biosafety Level 2 (BSL-2) facilities, while SARS-CoV-2, Human Rhinovirus (HRV), and Mpox virus were evaluated in Biosafety Level 3 (BSL-3) facilities. Viral titration assays were subsequently performed to quantify infectivity after exposure to the photocatalytic material.

The technology was then assessed under controlled laboratory conditions using aerosolized bacteriophage phi29 as a viral surrogate. These experiments were conducted in a chamber specifically designed to evaluate viral viability in airborne aerosols. The facility enables controlled bioaerosol generation, real-time monitoring of suspended particles, and bioaerosol sampling, providing a robust platform for assessing air purification technologies under well-defined environmental conditions. Following exposure, viral titration assays were used to determine the reduction in infectious viral particles, while qPCR analyses were performed to quantify the total viral concentration in aerosols and collected samples. To conduct these experiments, a prototype was developed consisting of a UV-A lamp, a nanofiber filter coated with the photocatalyst and capable of physical particle retention with low pressure drop, and a fan.

Subsequently, the technology was evaluated in a room-scale aerosol facility which reproduces realistic air dispersion patterns representative of indoor environments. Similar experiments were performed using bacteriophage phi29, enabling validation of the technology under more realistic operating conditions and facilitating assessment of scalability. As in the bioaerosol chamber experiments, both viral titration assays and qPCR analyses were conducted to evaluate reductions in infectious viral particles and total viral concentration, respectively.

Finally, the photocatalytic system was deployed and validated in a real clinical environment at Hospital Universitario La Paz. For this study, prototypes were constructed comprising a suction fan, a UV-A LED lamp, and a nanofiber filter incorporating the photocatalyst. This design represented an enhanced version of the prototype used in the bioaerosol chamber experiments, with increased airflow capacity to improve air extraction. Two prototype configurations were evaluated: (i) a photocatalytic system incorporating a nanofiber filter coated with the photocatalyst, UV-A illumination, and an extraction fan; and (ii) a control system consisting of the nanofiber filter and extraction fan without photocatalytic activation. The experimental setup additionally included a bioaerosol sampling system and

environmental sensors for continuous monitoring of indoor air conditions. The hospital validation campaign was conducted in the waiting room of the Paediatric Emergency Department over a five-day period. Air quality and microbiological parameters were monitored using a bioaerosol sampler and humidity and CO_2 sensors. Due to the low concentration of airborne viruses detected during the study period, direct assessment of viral inactivation was not feasible. Therefore, the performance of the system was evaluated through indirect microbiological indicators, including airborne bacterial and fungal concentrations. Microbiological analyses were performed according to NTP 299, while viral genetic material was analysed by RT-qPCR.

The photocatalytic material exhibited strong antimicrobial activity against a broad spectrum of pathogens, including viruses and bacteria (Figure 1). Plaque assays demonstrated reductions of up to 3 $\log_{10}$ units after 45 minutes of UV-A exposure. Within the bioaerosol chamber, a prototype air purifier incorporating the photocatalytic filter was tested under aerosolized conditions.



FIGURE 1
Photocatalytic filters with high antimicrobial efficiency validated across increasing scales, from plaque assay to bioaerosol chamber, room-scale bioaerosol facility, and real hospital environment.4

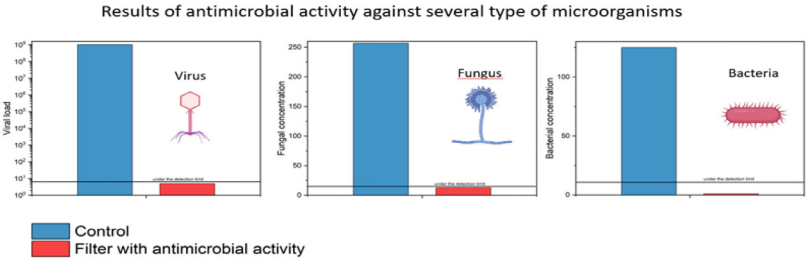


FIGURE 2
Antimicrobial performance of the photocatalytic filter against viruses, fungi, and bacteria.

The system achieved reductions of up to 5 $\log_{10}$ units in the concentration of infectious airborne viruses and up to 3 $\log_{10}$ units in viruses retained within the filter matrix, demonstrating high effectiveness under airborne transmission scenarios. Comparable results were obtained in the room-scale aerosol facility using the second-generation prototype, confirming the robustness and reproducibility of the technology under realistic indoor air dispersion conditions. Specifically, viral reductions of 5 $\log_{10}$ were achieved under same conditions (Figure 2).

In the hospital environment, the photocatalytic system achieved reductions of 100% in airborne bacterial concentrations and 100% in fungal concentrations compared with the control configuration. The system operated continuously for 6 hours without adverse effects on occupants or disruption of routine clinical activities.

Overall, the multi-scale validation strategy enabled comprehensive assessment of antiviral efficacy, operational performance, environmental integration, and scalability from laboratory testing to clinical deployment. These results demonstrate the strong potential of photocatalytic air treatment technologies as an active approach for improving indoor air quality and reducing airborne biological risks in healthcare facilities and other indoor environments.

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Influence of KOH treatment and spruce biochar on the adsorption and photocatalytic performance of TiO_2 (P25) on formaldehyde (HCHO) removal

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Citation

Putra, J. C. P., Suárez, S., Vehus, T. S., Nielsen, H. K. Influence of KOH treatment and spruce biochar on the adsorption and photocatalytic performance of TiO_2 (P25) on formaldehyde (HCHO) removal.

Abstract

Formaldehyde (HCHO) is one of the most relevant hazardous carbonyl compounds in indoor environments, particularly in buildings containing wood-based panels, adhesives, resins, coatings, and composite furnishing materials. Because HCHO can be continuously emitted at low levels and may accumulate in poorly ventilated spaces, its removal remains a central

challenge for indoor air quality management. International guidance recommends limiting indoor formaldehyde to 0.1 mg/m^3 as a 30 min average, emphasising the need for technologies capable of controlling both short-term exposure and persistent background emissions (1). Among the available abatement strategies, TiO2-based photocatalytic oxidation has attracted considerable attention because it can mineralise volatile organic compounds (VOCs) under light irradiation rather than merely transforming them into another phase (2,3). Nevertheless, practical implementation is still limited by weak adsorption of polar molecules, fast recombination of photogenerated charge carriers, sensitivity to operating conditions, and possible mismatch between pollutant uptake and photocatalytic reaction rates (3,4). Hence, hybrid adsorption-photocatalysis materials are increasingly explored to combine the pollutant-concentrating function of porous adsorbents with the oxidative activity of TiO_2.

Biochar is a prominent support for such systems because its porous carbon matrix, oxygen-containing functional groups, and tunable surface chemistry can improve VOC adsorption and interfacial contact with photocatalytic particles (5,6). Alkaline activation, particularly using KOH, can further modify pore development, surface hydroxylation, and chemical reactivity. However, the effect of KOH treatment is not necessarily linear. A treatment condition that increases HCHO adsorption may not produce the highest photocatalytic removal if it changes the accessibility of TiO_2 active sites, residual potassium content, or surface charge-transfer behaviour. Recent work on KOH-modified TiO_2 has shown that potassium and hydroxyl-related surface species may enhance formaldehyde oxidation by improving charge separation, oxygen activation, and electron mobility, but the extent of modification remains critical (7). This study, therefore, investigated how KOH concentration and spruce biochar incorporation influence the adsorption and photocatalytic degradation of gaseous HCHO on TiO_2 (P25)-based materials.

A chemical mixing approach was used to prepare five materials: KOH-treated spruce biochar (Bsp-K1), KOH-treated TiO_2 (P25) prepared using different

KOH concentrations (P25-K1 and P25-K2), and TiO_2 (P25) incorporated with KOH-treated spruce biochar (Bsp@P25-K1 and Bsp@P25-K2). In this notation, K1 and K2 correspond to 1 M and 0.5 M KOH, respectively. Adsorption and photocatalytic tests were conducted in a continuous gas-phase reactor using a total flow rate of 900 mL min-1 and an inlet HCHO concentration of 15 ppm. Photocatalytic degradation was evaluated under UV-A irradiation at an irradiance of 5.3 mW cm^{-2} and a gas residence time of 0.43 s. Adsorption capacity was used to evaluate HCHO uptake, whereas HCHO removal efficiency and photodegradation rate were used to assess photocatalytic performance.

The results revealed that KOH treatment and biochar incorporation controlled HCHO removal through distinct and partly competing mechanisms. The adsorption results (Fig. 1), shows that KOH treatment

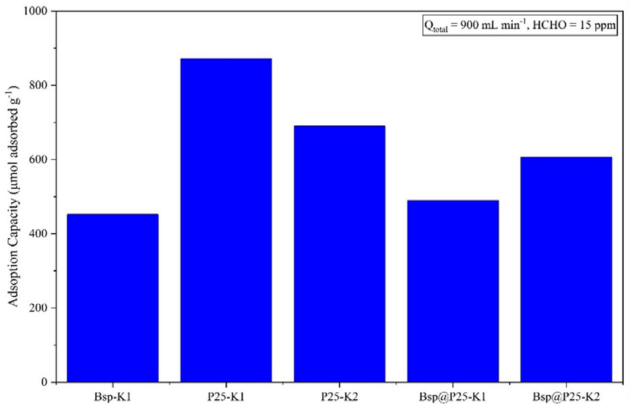


FIGURE 1
HCHO adsorption capacity of the prepared samples. Bsp-K1 denotes KOH-treated spruce biochar prepared using 1 M KOH, P25-K1 and P25-K2 denote TiO_2 (P25) treated with 1 M and 0.5 M KOH, respectively. Bsp@P25-K1 and Bsp@P25-K2 denote TiO_2 (P25) incorporated with KOH-treated spruce biochar prepared using 1 M and 0.5 M KOH, respectively.

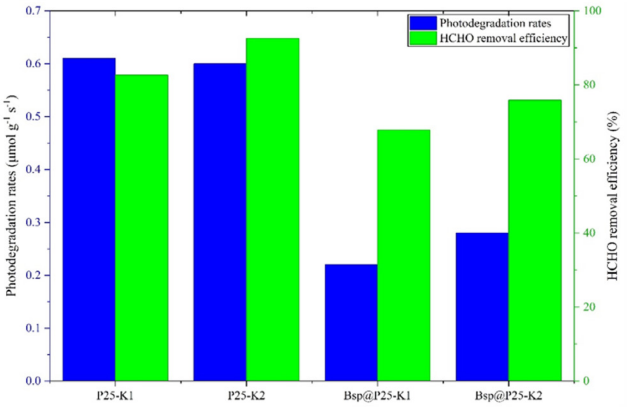


FIGURE 2

Photocatalytic activity for HCHO degradation over the prepared samples. Operation conditions: Qtotal = 900 mL min-1, [HCHO] = 15 ppm, residence time (tr) = 0.43 s, UV-A irradiance (I) = 5.3 mW cm-2. P25-K1 and P25-K2 denote TiO_2 (P25) treated with 1 M and 0.5 M KOH, respectively. Bsp@P25-K1 and Bsp@P25-K2 denote TiO_2 (P25) incorporated with KOH-treated spruce biochar prepared using 1 M and 0.5 M KOH, respectively.

strongly affected the HCHO uptake of the prepared materials. For P25, increasing the KOH concentration from 0.5 M to 1 M enhanced HCHO adsorption, with P25-K1 exhibiting the highest adsorption capacity among the investigated samples. However, the biochar-containing composites show a different trend, as Bsp@P25-K2 displayed higher HCHO adsorption than Bsp@P25-K1. This indicates that stronger alkaline treatment favoured HCHO uptake on P25, whereas moderate KOH treatment was more suitable for the spruce biochar-P25 composite system. Under UV-A irradiation, the photocatalytic results presented in Fig. 2 show that P25-K2 achieved the highest HCHO removal efficiency, while P25-K1 exhibited a comparable photodegradation rate but lower overall removal efficiency. For the composite materials, Bsp@P25-K2 outperformed Bsp@P25-K1 in both HCHO removal efficiency and photodegradation rate, confirming that 0.5 M KOH provided a more favourable balance between adsorption and photocatalytic oxidation.

The lower overall performance of Bsp@P25-K1 is consistent with its lower HCHO adsorption capacity compared with Bsp@P25-K2 (Fig. 1), as well as its lower HCHO removal efficiency and photodegradation rate under UV-A irradiation (Fig. 2). These results suggest that treatment with 1 M KOH did not produce the most favourable surface and interfacial characteristics for the biochar-P25 composite. Excessive alkaline modification may have reduced pore accessibility or altered the interfacial contact between biochar and TiO_2, thereby limiting HCHO capture and its subsequent availability at photocatalytically active sites. In contrast, Bsp@P25-K2 appears to provide a more favourable balance between HCHO adsorption and photocatalytic oxidation.

In addition, the comparison between P25-only and biochar-containing samples shows that the role of KOH depends on the material architecture. Direct modification of TiO_2 with KOH mainly alters the photocatalyst surface. By contrast, in biochar-containing composites, KOH treatment may also alter the pore structure and surface chemistry of the biochar, as well as the interfacial contact between biochar and TiO_2. Material design should therefore consider both the properties of the individual components and their interfacial interactions under continuous gas-flow conditions. This distinction is important for developing materials with potential indoor applications.

Overall, the study demonstrates that KOH concentration is a critical parameter for tuning TiO_2 (P25)-based and spruce biochar-incorporated photocatalysts for formaldehyde abatement. For P25, 1 M KOH favoured adsorption, whereas 0.5 M KOH was more beneficial for UV-A photocatalytic removal. For the biochar-P25 composites, 0.5 M KOH provided the best combined performance, improving adsorption, HCHO removal efficiency, and photodegradation rate relative to the 1 M composite. These findings highlight the importance of balancing surface activation, pollutant adsorption, and photocatalytic accessibility in hybrid materials. However, the experiments were conducted at an inlet HCHO concentration of 15 ppm, which is substantially higher than concentrations typically encountered

in occupied indoor environments, and the effects of relative humidity and temperature were not evaluated. Accordingly, the results should be interpreted as a comparative assessment under the tested conditions rather than as direct evidence of performance in real buildings. Future studies should validate the best-performing materials at lower, indoor-relevant HCHO concentrations while systematically varying relative humidity and temperature, because these factors may affect adsorption equilibrium, surface reactions, and photocatalytic kinetics. Such validation is necessary before the practical application of these materials in coatings and wood-based surfaces for indoor formaldehyde control can be assessed.

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Bioaerosol emissions from industrial biofilters may have potential implications for occupational exposure and worker health

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Citation

Affek, K., Tabernacka, A., Załęska-Radziwiłł, M., Doskocz, N., Muszyński A. Bioaerosol emissions from industrial biofilters may have potential implications for occupational exposure and worker health.

Abstract

Biofiltration is widely applied for the treatment of odorous and polluted waste gases generated by industrial facilities due to its relatively low operational costs and high efficiency in removing volatile pollutants (1,2).

However, despite the filtration of non-biological suspended particles, biofilters themselves may become sources of bioaerosol emissions (3) Such emissions may contribute to outdoor air pollution and may also affect the microbial quality of nearby indoor or semi-enclosed environments, with potential implications for occupational exposure and worker health. Although numerous laboratory studies on biofiltration have been performed, there is still limited information regarding bioaerosol emissions from semi-technical and technical-scale systems operating under real industrial conditions (4). Building on previously published experimental data on bioaerosol emissions from industrial biofilters, the present contribution revisits these findings from an occupational exposure perspective, considering their potential implications for nearby indoor and semi-enclosed work environments.

The aim was to examine whether biofilters can be sources of airborne microorganisms and under which circumstances this could become relevant for occupational indoor air quality. Particular attention was paid to culturable airborne bacteria and fungi, quantified as colony-forming units (CFU/m^3), to consider the potential impact of these emissions on nearby indoor and semi-enclosed work environments.

Three identical semi-technical scale biofilters were operated in Poland at: (i) a mechanical–biological treatment plant of municipal solid waste (MBTP), (ii) a wastewater treatment plant (WWTP), and (iii) a food industry plant (FIP). Two biofilter bed materials were tested alternatively: a mixture of stumpwood chips and pine bark (CB), and a mixture of stumpwood chips, pine bark, and compost from green waste (CBC). Waste gas, treated gas, and ambient air samples were collected using MAS-100 and SAS Super ISO impactors. Airborne bacteria and fungi were enumerated using standard culture-dependent methods on TSA and RBC media, respectively, and results were expressed as CFU/m^3.

The microbial abundance in waste gases strongly depended on the industrial source (Figure 1-2). The highest microbial concentrations were

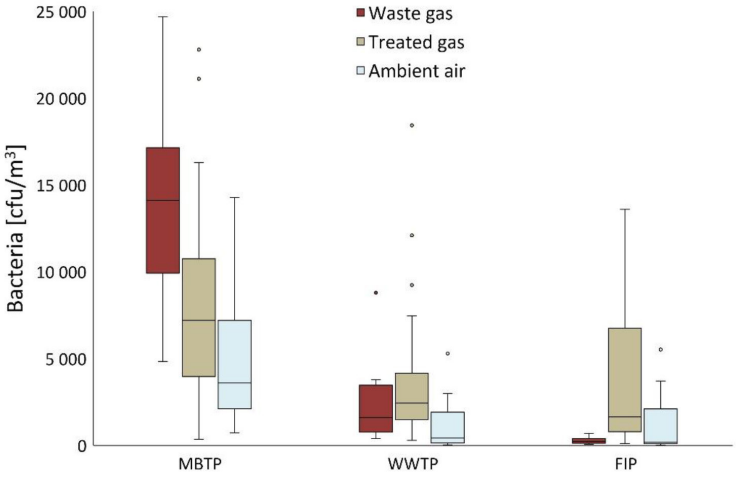


FIGURE 1
Bacterial concentrations (CFU/m^3) in waste gases before and after treatment in biofilters with CB beds composed of stumpwood chips and pine bark at the mechanical–biological treatment plant (MBTP), wastewater treatment plant (WWTP), and food industry plant (FIP). The line within the box indicates the median; circles denote outliers.

observed in gases from the MBTP, whereas the lowest were detected at the FIP. The results demonstrated that biofilters could either reduce or increase bioaerosol emissions depending mainly on the microbial load of inlet gases. In the MBTP system, where inlet microbial concentrations were high, biofilters reduced bacterial and, in some cases, fungal concentrations in treated gases. For example, the CB bed reduced the median bacterial concentration approximately twofold. In contrast, in the WWTP and especially in the FIP, where microbial concentrations in waste gases were substantially lower, treated gases frequently contained higher concentrations of airborne microorganisms than inlet gases, indicating microbial emission from the biofilter system. Similar observations were previously reported

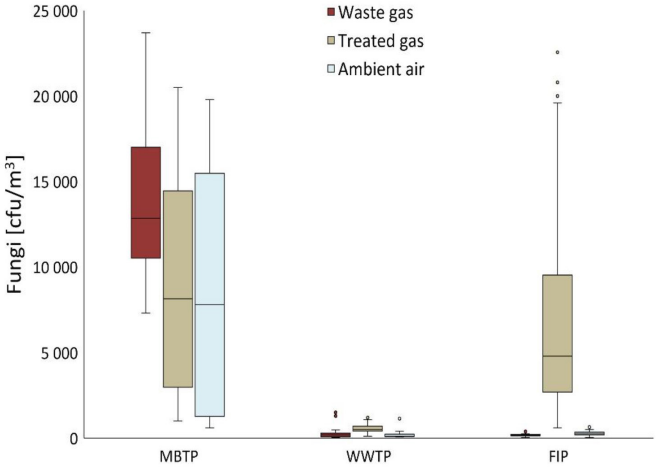


FIGURE 2
Fungal concentratons (CFU/m^3) in waste gases before and after treatment in biofilters with CBC beds (stumpwood chips, pine bark, and green-waste compost) at MBTP, WWTP, and FIP. The line within the box indicates the median; circles denote outliers.

for industrial biofilters treating waste gases from food-processing and wastewater facilities (1,5,6). In several cases, fungal concentrations in treated gases exceeded 4000–8000 CFU/m^3 despite much lower fungal concentrations in incoming gases. Moreover, microbial concentrations in treated gases were consistently higher than in ambient air collected upwind from the installations.

The findings indicate that the microbial characteristics of incoming waste gases are the primary factor determining the final bioaerosol emission from biofilters. High microbial loads in inlet gases may mask the contribution of microorganisms released from the biofilter itself, whereas under low inlet microbial loads, biofilters may become net emitters of airborne bacteria and fungi. This may be particularly relevant in the case of close-by indoor or semi-enclosed workspaces where microorganisms emitted from biofilters

may contribute to the microbial load of workplace air. Increased exposure to bioaerosols may be associated with respiratory irritation or allergic responses, particularly in susceptible individuals; however, the health relevance of such exposure depends on the composition and characteristics of the emitted microbial community. Further microbial identification and characterization of potentially pathogenic species would be necessary to better evaluate the potential health relevance of the emitted bioaerosols. This study highlights the importance of considering bioaerosol emissions during the design and operation of industrial biofiltration systems, not only in the context of outdoor air quality, but also indoor air quality in the workspace and occupational exposure.

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Integrated plant–microbe mechanisms driving VOC removal in botanical filtration systems

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Citation

Montaluisa-Mantilla, M.S., Lebrero, R., García-Encina, P., Muñoz, R. Integrated plant–microbe mechanisms driving VOC removal in botanical filtration systems.

Abstract

Indoor air quality (IAQ) has become a major environmental and public health concern due to the large amount of time people spend indoors

and the continuous emission of volatile organic compounds (VOCs) from building materials, furniture, cleaning products, personal care products, and other indoor sources (1). Exposure to VOCs has been associated with a wide range of adverse health effects, from sensory irritation to more severe respiratory and neurological disorders. Botanical filtration has emerged as a promising nature-based solution for indoor air treatment by combining the remediation potential of plants and their associated microbial communities. Previous studies have demonstrated that plants can remove VOCs through adsorption, absorption, metabolic transformation, and rhizospheric degradation processes (2). However, the relative contribution of plant foliage, roots, and root-associated microorganisms to VOC removal remains insufficiently understood. Therefore, this study aimed to elucidate the mechanisms involved in VOC removal by botanical filtration systems and quantify the contribution of different plant compartments and rhizospheric microorganisms to the removal of representative indoor VOCs.

Five plant species commonly used in indoor botanical filters *(Epipremnum aureum, Syngonium podophyllum, Spathiphyllum wallisii, Dieffenbachia, Monstera adansonii*) were evaluated under controlled laboratory conditions. Acetone, toluene, α-pinene, o-xylene, and limonene were selected as model VOCs because they represent compounds with different physicochemical properties frequently detected in indoor environments. Three experimental series were conducted. The first investigated VOC removal exclusively by plant foliage using a PETG chamber simulating an indoor environment, where roots were physically isolated from contaminated air. The second experiment evaluated VOC removal by isolated root systems and whole plant cuttings comprising leaves, stems, and roots. The third assessed the role of root-associated microorganisms by comparing VOC removal in systems containing intact roots and systems inoculated with microorganisms extracted from the rhizosphere (Figure 1). VOC concentrations in the gas phase were monitored by GC-FID, and removal efficiencies were determined from triplicate experiments.

The results revealed substantial variability in VOC removal depending on both the plant species and pollutant characteristics. In the foliar

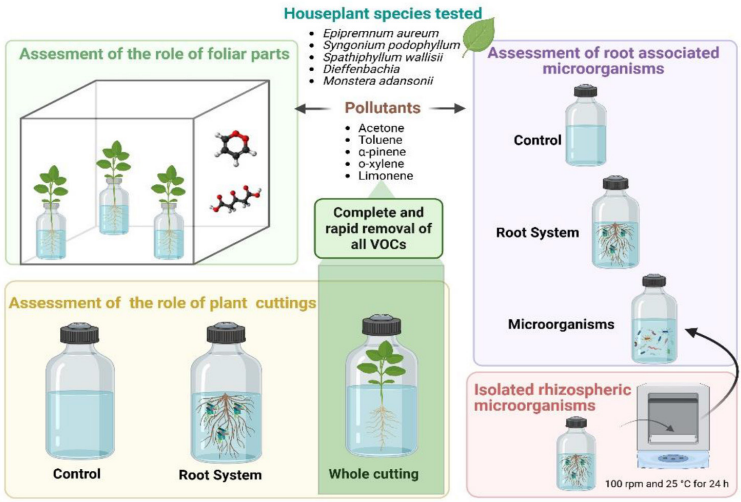


FIGURE 1
Graphical abstract of the experimentation.

experiments, acetone exhibited the highest removal efficiencies across all species. *Dieffenbachia* achieved the best performance, removing more than 55% of the initial acetone concentration within five days, whereas the abiotic control accounted for only 16% removal after six days. *Syngonium podophyllum* and *Monstera adansonii* also exhibited relatively high acetone removal efficiencies, approaching 40%. In contrast, all plant species showed comparatively low removal efficiencies for toluene, with the highest values observed for *Epipremnum aureum* and *Dieffenbachia* at approximately 25%, only slightly exceeding the abiotic control. Similar trends were observed for α-pinene and o-xylene, where removal efficiencies were generally low and often comparable to abiotic conditions. In the case of limonene, all plant species achieved removal efficiencies above 30%, slightly outperforming the abiotic control. The differences observed among VOCs were strongly influenced by their physicochemical properties. Toluene, α-pinene, and o-xylene are hydrophobic compounds with a strong tendency to remain

in the gas phase, limiting their interaction with plant tissues. Toluene is characterized by a log K_{ow} of approximately 2.7, low water solubility, and high vapor pressure, which restricts diffusion through leaf cuticles and stomata (3). Likewise, α-pinene presents a high hydrophobicity (log $K_{ow} \approx 4.8$) and low water solubility, favoring gas-phase partitioning and reducing foliar uptake (4), while o-xylene exhibited similar behavior due to its moderate hydrophobicity and limited affinity for aqueous phases (5). In contrast, limonene showed comparatively higher foliar removal despite its hydrophobic nature, likely due to its affinity for lipid-rich plant tissues such as cuticles and cellular membranes (6). Acetone displayed a completely different behavior due to its high hydrophilicity, which promoted rapid partitioning into aqueous media and potentially masked plant-mediated removal mechanisms (7).

Experiments involving whole plant cuttings demonstrated substantially greater VOC removal efficiencies than those obtained with foliage alone. Complete removal of toluene, α-pinene, o-xylene, and limonene was achieved within approximately 20–115 h depending on the plant species and compound evaluated. Bottles containing whole plant cuttings consistently exhibited significantly faster VOC removal rates than systems containing roots alone ($p < 0.05$). These findings demonstrate the importance of the synergistic interaction between the phyllosphere and rhizosphere. While foliage acts as the first barrier for pollutant interception through adsorption on epicuticular waxes and stomatal uptake, roots contribute to pollutant uptake and support rhizospheric microbial communities capable of transforming and degrading VOCs. This integrated action improves overall removal performance and supports previous findings indicating that roots may account for the most of VOC removal in phytoremediation systems (8,9).

Root-associated microorganisms also played a key role in VOC attenuation. Similar removal profiles were observed between systems containing intact roots and systems inoculated with extracted microbial communities, indicating a substantial microbial contribution to pollutant removal. In most cases, systems containing intact roots exhibited slightly faster removal rates, indicating that the interaction between roots and microorganisms

enhances overall remediation performance. Rhizosphere-associated microorganisms can utilize VOCs as carbon and energy sources, thereby promoting pollutant degradation and increasing the efficiency of botanical filtration systems (10,11). Previous studies have identified members of the Actinobacteria phylum as effective degraders of aromatic hydrocarbons and other VOCs commonly found in indoor environments (12,13). Although the absence of microbial characterization prevented the definitive attribution of VOC removal to biodegradation processes, the results strongly indicate that microbial activity represents an important component of VOC attenuation.

Overall, this study demonstrated that VOC removal in botanical filtration systems results from the interaction of physical adsorption, plant uptake, metabolic transformation, and microbial degradation. While foliage alone contributed to VOC attenuation, the highest removal efficiencies were achieved when both aerial and belowground plant compartments were simultaneously involved. The results highlight the importance of selecting plant species with extensive foliage and root systems and promoting active rhizospheric microbial communities to maximize VOC removal. These findings provide new mechanistic insights into botanical biofiltration and support the development of more efficient nature-based technologies for improving indoor air quality.

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Biological decontamination of air and surfaces using patented UV-C-based devices: Experimental evidence supporting targeted IAQ management strategies

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Abstract

Background

Indoor air quality (IAQ) is increasingly recognized as a major determinant of human health, given that individuals spend most of their time in enclosed environments (1–3). Airborne microorganisms constitute an important component of indoor pollution and contribute to the transmission of respiratory infections, environmental contamination, and deterioration of indoor environmental quality (4,5). Although ventilation and mechanical filtration remain the primary strategies for IAQ management, their effectiveness against biological contamination may be limited in environments characterized by continuous microbial generation, high occupancy, or insufficient air renewal. Consequently, growing interest has emerged in complementary technologies capable of actively reducing microbial contamination in both air and surfaces (6,7).

Ultraviolet-C (UV-C) radiation has been extensively investigated for microbial inactivation and environmental decontamination. However, implementing UV-C-based technologies in occupied indoor environments presents important challenges related to exposure safety, treatment effectiveness under realistic operating conditions, and the reliable interpretation of experimental results (6–8). The evaluation of biological decontamination systems requires careful consideration of factors such as UV-C source stabilization, aerosol dynamics, sampling methodologies, and passive particle deposition phenomena, all of which may influence apparent removal efficiencies (8,9).

Objectives
To experimentally evaluate the microbiological efficacy of a patented UV-C-based technology for the decontamination of air and surfaces under controlled laboratory conditions, and to assess its potential role within targeted indoor air quality management strategies.

Methodology
Experimental studies were conducted using a proprietary UV-C device developed by HHIT and protected by industrial property rights. The system incorporates UV-C emitters operating at 253.7 nm and was specifically designed to enable safe application of photolytic and photocatalytic processes for air treatment in occupied environments and surface decontamination in unoccupied spaces.

Two representative bacterial species were selected as biological indicators: *Leuconostoc mesenteroides* (Gram-positive) and *Escherichia coli* (Gram-negative). Aerosolized microbial suspensions with concentrations ranging from 10^7 to 10^8 CFU/mL were generated under controlled laboratory conditions and introduced into the system inlet. Airborne microorganisms were quantified through active air sampling at predefined intervals using microbiological collection equipment, followed by culture-based enumeration on selective media. Comparative experiments were performed with UV C treatment activated and deactivated.

Particular attention was paid to methodological aspects that may influence efficacy assessment. Experimental protocols incorporated stabilization periods for both UV-C emission and aerosol generation before sampling. In addition, the potential contribution of passive aerosol deposition within the device was considered in order to distinguish active microbial inactivation from physical retention mechanisms. These controls were implemented to improve the reliability, reproducibility, and interpretability of the results (8,9).

Surface decontamination assays were also conducted using inoculated substrates exposed to treatment under controlled conditions. The methodology

was developed not only to evaluate biological reduction performance but also to contribute to the standardization of testing approaches for biological decontamination technologies.

Key Results

Operation of the UV-C system resulted in substantial reductions in airborne microbial concentrations. For *Leuconostoc mesenteroides*, reductions greater than 3 log units were achieved, whereas *Escherichia coli* demonstrated reductions exceeding 4 log units. Airborne microbial concentrations decreased from values above 10^4 CFU/m^3 to levels below 10^2 CFU/m^3 within a few minutes of treatment. In contrast, control experiments performed without UV-C activation showed persistence or progressive increases in microbial concentration.

Significant reductions were also observed on contaminated surfaces subjected to treatment. These findings demonstrate effective microbial inactivation in both airborne and surface applications under controlled laboratory conditions.

Beyond efficacy results, the testing programme highlighted the importance of controlling UV-C source stabilization, aerosol stabilization, and internal deposition effects when evaluating biological decontamination systems. The study confirmed that these factors can significantly influence measured performance and should therefore be considered in future standardized methodologies for the assessment of UV-C-based technologies.

The experimental programme also supported the development of an additional patent associated with the testing methodology and technological implementation, reflecting the translational nature of the work from laboratory evaluation to practical application.

Main Conclusions

The evaluated UV-C technology demonstrated high efficacy for the targeted reduction of microbiological contamination in both air and surfaces

under controlled laboratory conditions. The results support its use as a complementary strategy to conventional ventilation and filtration systems within indoor air quality management programmes.

A relevant outcome of the project was the development of a reproducible experimental methodology for evaluating UV-C air decontamination systems, including source stabilization, aerosol stabilization, active air sampling, surface monitoring and differentiation between biological inactivation and physical retention mechanisms.

These findings support the integration of UV-C-based technologies within targeted IAQ management frameworks, particularly in healthcare facilities, public buildings, and other indoor environments where biological contamination represents a relevant exposure pathway.

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Impact of summer outdoor pollution and heatwaves on bedroom Indoor Air Quality in social housing

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Sacristán-Uña, M., Poza-Casado, I., Tamayo-Alonso, D., Meiss, A. Impact of summer outdoor pollution and heatwaves on bedroom Indoor Air Quality in social housing.

Abstract

People spend most of their time indoors (1), with dwellings representing the primary occupied spaces, and bedrooms accounting for the longest occupancy periods. This is consistent with the occupancy scenarios defined in the Spanish Technical Building Code (CTE), Basic Health Document DB

HS3 "Indoor Air Quality"; which assumes an occupancy period of 8 hours sleeping (2), making bedrooms critical spaces for assessing occupants' exposure to indoor pollutants. These conditions highlight the importance of Indoor Air Quality (IAQ) and the health risks associated with indoor air pollution, as recognised by The World Health Organization (WHO) (3, 4) and the European Union (UE) (5, 6).

IAQ study has traditionally focused on winter conditions, considering this season the most critical due to short ventilation cycles, especially in buildings with occupant-dependent natural ventilation. Occupants often limit ventilation due to comfort requirements and energy-saving considerations, since outdoor air flows need to be conditioned. This behaviour increases the concentration of indoor-generated pollutants (7).

However, Outdoor Air Quality (OAQ), traditionally considered better than IAQ, may deteriorate during extreme summer climate events. Heat stress, wildfires and desert dust, among others, are responsible of OAQ deterioration. During these events, outdoor Particulate Matter (PM) concentrations increase significantly and become a risk factor because it constitutes approximately 90% of the particulate mass in wildfire smoke and can penetrate deep into the respiratory and cardiovascular systems (8). For this reason, the summer period cannot be ignored and must be evaluated for a comprehensive IAQ assessment (7, 9).

In Spain, a large proportion of the social housing stock was built during the rapid urban growth of the mid-20th century. These buildings often present deficient thermal behaviour, inadequate ventilation, and outdated construction systems, conditions that can compromise Indoor Environmental Quality (IEQ) during climate-related extreme events.

This paper examines IAQ conditions during multi-hazard summer events in the master bedrooms of a representative set of dwellings located in La Rondilla, a social housing neighbourhood in Valladolid, Spain. Valladolid is classified as BSk (cold semi-arid climate) according to the Köppen-Geiger

classification (10) and as climate zone D2 according to CTE, Basic Document DB HE "Energy saving", corresponding to a D winter severity and a 2-summer severity (11).

For this purpose, indoor CO_2 and PM concentrations were monitored in 22 master bedrooms, selected for monitoring because they represent the most occupied spaces within dwellings. Measurements were carried out between June and September 2025, with particular attention to heatwaves and episodes of elevated outdoor pollution, including regional wildfires and desert dust events. These dwellings share similar typological and construction characteristics and, importantly, lack a ventilation system, relying instead on occupant-controlled window opening.

Low-cost sensors were used to monitor CO_2 and PM concentrations, also recording other IEQ parameters: indoor temperature, relative humidity, formaldehyde (HCHO), Total Volatile Organic Compounds (TVOC), carbon monoxide (CO), ozone (O_3), and nitrogen dioxide (NO_2). To obtain a representative profile, sensors were installed in each master bedroom for an average period of 6 days during the summer campaign.

Indoor concentrations were related to significant climate events using OAQ data obtained from the Valladolid Municipal Air Pollution Control Network (12). Since all monitored dwellings were located within the same neighbourhood, the Poniente Bridge monitoring station was selected as the most representative outdoor pollutant data due to its proximity to La Rondilla.

This data (Figure 1) recorded significant fluctuations in OAQ during summer 2025. Outdoor PM2.5 and PM10 concentrations showed several peaks associated with the identified extreme weather events.

Exploratory individual monitoring of the master bedrooms provided data regarding different environmental hazards and their impact on IAQ.

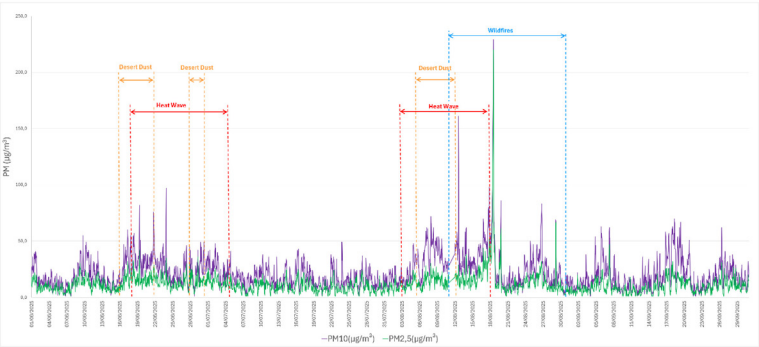


FIGURE 1

PM values measured, from the 1st of June to the 30th of September 2025, by the Municipal monitoring station in Poniente's bridge in Valladolid and weather events.

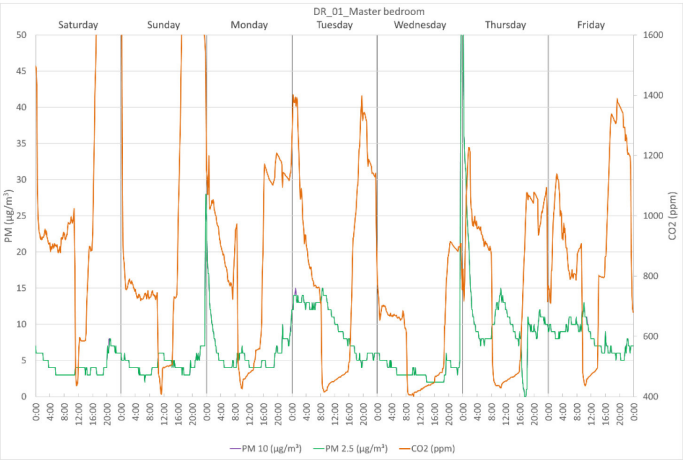


FIGURE 2

Levels of PM and CO_2 measured in dwelling 01 (August 02-08, 2025) in master bedroom.

Preliminary results indicate that increases in indoor PM concentrations were closely associated with window-opening periods, identified by decreases in indoor CO_2 levels. When ventilation began and CO_2 concentrations declined, indoor PM levels initially increased due to the entry of particulate matter from the outdoor environment although this pattern evolves on time (Figure 2).

The monitoring of 22 social housing dwellings in La Rondilla (Valladolid) during the summer of 2025 provides critical evidence on the vulnerability of aging Mediterranean residential stock to multi-hazard climate events. During heatwaves, occupants tend to open windows to mitigate thermal stress (13). However, this practice eliminates the building envelope's protective barrier, leading to the entrance of outdoor pollutants. This issue is critical as the building envelope is the primary barrier against outdoor smoke and dust during extreme events (14). Although remaining indoors is a primary health recommendation during heatwaves, its effectiveness is compromised in social housing lacking cooling systems or controlled ventilation systems equipped with air filtration units (13,14).

Preliminary results show a recurrent trend across the 22 monitoring dwellings: indoor PM levels tend to increase as CO_2 concentrations decrease, indicating periods of natural ventilation through window opening. However, some bedrooms showed different patterns, with PM levels increasing during natural ventilation periods and continuing to rise even when windows appeared to remain closed, suggesting the presence of indoor PM sources.

This interaction between outdoor pollution and ventilation behavior suggests that residents of La Rondilla are exposed to a double risk: thermal discomfort from overheating and deteriorated IAQ resulting from incoming PM from outdoors. These findings reveal a conflict between thermal adaptation and IAQ in naturally ventilated dwellings.

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Airborne microbial communities in a judo training facility: A pilot molecular study

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Citation

Doskocz, N., Mishra, J., Załęska-Radziwiłł, M., Przystaś, W. Airborne microbial communities in a judo training facility: A pilot molecular study.

Abstract

Indoor sports facilities represent dynamic indoor environments where intensive human activity may influence the emission, resuspension, and redistribution of airborne microorganisms. Human movement, contact with training surfaces, and limited air exchange may contribute to rapid changes in airborne microbiome structure (1,2). Despite increasing interest in indoor microbiomes, studies investigating short-term microbial dynamics in sports facilities remain limited.

The aim of this study was to characterize airborne bacterial and fungal communities in an indoor judo training facility and to evaluate microbiome

changes associated with occupancy-related activity. Particular attention was paid to microbial diversity, community restructuring, and relationships between microbiome composition and environmental parameters.

The study was conducted in a judo training hall located on the campus of the Silesian University of Technology in Gliwice, Poland, during regular facility use in the autumn–winter season. Air samples were collected before training sessions (PRE), after the first training session (POST1), and after the second training session conducted on the same day (POST2). Bioaerosol samples intended for molecular analyses were collected using a Coriolis® μ cyclonic air sampler (Bertin Technologies, France). Bacterial communities were analyzed based on sequencing of the V3–V4 region of the 16S rRNA gene, whereas fungal communities were characterized using the ITS1 region. Bioinformatic analyses were performed in the QIIME 2 environment using the DADA2 pipeline. Alpha diversity was evaluated using the Shannon diversity index, while beta diversity was assessed using Principal Coordinates Analysis (PCoA) and PERMANOVA. Correlations between microbial diversity and occupancy, CO_2 concentration, temperature, and relative humidity were also analyzed.

The results demonstrated occupancy-related changes in airborne bacterial and fungal communities. Bacterial alpha diversity increased after training sessions, particularly in POST2 samples, indicating greater diversity and complexity of airborne bacterial communities with increasing training intensity. Positive correlations were observed between bacterial Shannon diversity and occupancy intensity ($\rho \approx 0.66$) as well as temperature ($\rho \approx 0.65$), whereas weaker associations were observed for CO_2 concentration and relative humidity. Fungal communities also demonstrated occupancy-associated variability and dynamic shifts in community composition between sampling stages. Although fungal diversity patterns were more heterogeneous than those observed for bacteria, several POST samples exhibited elevated Shannon diversity values, suggesting increased fungal community complexity following training activity (Figure 1).

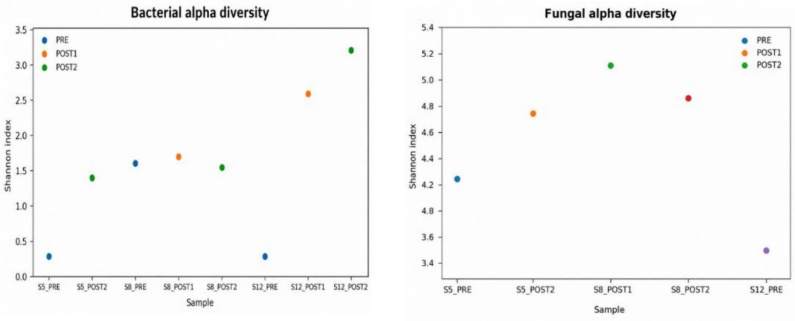


FIGURE 1
Alpha diversity (Shannon index) of bacterial and fungal communities in air samples collected before (PRE) and after training sessions (POST1, POST2) in the investigated judo facility.

Taxonomic composition analysis revealed clear differences between PRE and post-training samples. PRE samples were dominated by environmental bacterial genera, particularly Acinetobacter and Brucella, whereas post-training samples showed increased contributions of human-associated genera, including Micrococcus, Cutibacterium, Corynebacterium, and Rhodococcus. Dominant fungal genera included Penicillium, Fusarium, Mycena, and Ossicaulis, with noticeable fluctuations in relative abundance across sampling stages (Figure 2). PCoA analysis demonstrated partial clustering of bacterial communities according to sampling stage, with PRE samples forming more compact clusters and post-training samples showing greater dispersion and variability. In contrast, fungal communities demonstrated weaker separation and greater heterogeneity between samples, suggesting a stronger influence of environmental background sources and settled dust reservoirs on fungal bioaerosol composition (3).

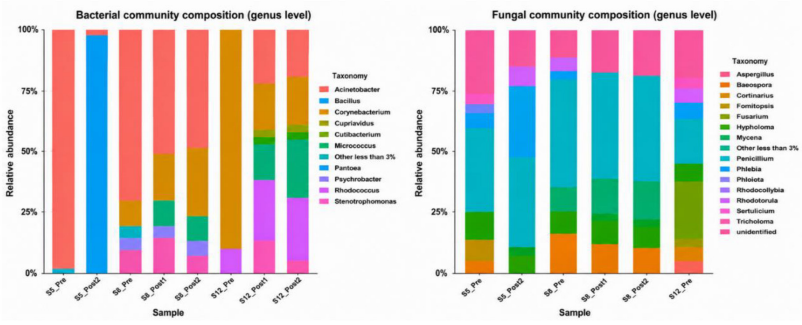


FIGURE 2
Relative abundance of dominant bacterial and fungal genera in air samples collected before (PRE) and after training sessions (POST1, POST2) in the investigated judo facility.

The study demonstrated that occupancy-related activity and training intensity influenced the structure and diversity of airborne microbial communities in the investigated sports facility, with distinct response patterns observed for bacterial and fungal communities. The obtained results indicate that occupancy intensity may represent one of the major factors shaping airborne microbiomes in indoor sports environments (1,4). Furthermore, the study confirms the usefulness of high-throughput sequencing approaches for investigating dynamic changes in indoor airborne microbiomes.

As a pilot study based on a single sampling campaign, the observed patterns should be confirmed through additional measurements conducted across different seasons and sports facilities. The changes in airborne microbial communities observed during intensive occupancy may also be relevant from the perspective of biological exposure and indoor air quality. The increased contribution of human-associated bacterial taxa after training highlights the role of occupants as an important source of airborne microorganisms, whereas the presence of environmentally associated fungal taxa indicates additional contributions from outdoor sources and

resuspended material. These findings emphasize the importance of adequate air exchange and effective ventilation in high-occupancy sports facilities, particularly during intensive physical activity, and support further research linking microbial community dynamics with indoor air quality management.

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Multi-country evaluation of indoor air across different scenarios: Results from K-HEALTHinAIR project

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Citation

Boghenco, O., Corda, M.O., Gómez-López, A., González-Colom, R., Badyda, A., Kristian, A., De Leede, S., Van Grieken, A., Fermoso, J., Martins, C. Multi-country evaluation of indoor air across different scenarios: Results from K-HEALTHinAIR project.

Abstract

Background

People spend approximately 80 to 90% of their time indoors, making indoor air quality (IAQ) a major public health factor (1). Poor IAQ can increase the risk of respiratory issues, heart disease, cognitive impairments, and cancer. This study, within the K-HEALTHinAIR project, aims to evaluate potential exposure risks across different scenarios such as homes, schools, and hospitals across four countries.

Methods

Data were collected using low-cost sensors to monitor carbon dioxide (CO_2), particulate matter below 10 µm and 2.5 µm diameter (PM_{10}, $PM_{2.5}$, respectively) and formaldehyde. The data analysis consisted in calculating the daily average levels of pollutants for each scenario. Additionally, for specific locations (e.g., schools) the average pollutant levels were calculated as well for designated time periods that reflect typical working or activity hours, thus understanding the conditions during peak occupancy times. Alongside, a risk analysis was carried out using the frequency of exceedance (%) of guideline concentrations as a proxy for risk. Guideline values considered for the analysis are presented in Table 1.

TABLE 1: Guidelines considered for comparison of monitoring data

Pollutant	Setting	Period	Guideline levels	References' source
CO_2	School	During use	950 ppm	Healthy Schools Requirements Specification (NL) (2)
	Indoor Spaces/all buildings	During use	900 ppm	Multiple sources

(*Continued*)

(*Continued*)

Formaldehyde	School	During use	30 μg/m^3	Healthy Schools Requirements Specification (NL) (2)
	Residential	During use	30 μg/m^3	Programme of Requirements Healthy Homes (NL) (3)
	Indoor spaces/all buildings	8h	100 μg/m^3	Portugal (4)
	Indoor Spaces (vulnerable populations, schools, hospitals, senior homes)	24h	50 μg/m^3	Poland (5)
$PM_{2.5}$	All buildings	24-hour	15 μg/m^3	WHO 2021 (6)
		8-hour	25 μg/m^3	Portugal (4)
PM_{10}	Indoor spaces/all buildings	24-hour	45 μg/m^3	WHO 2021 (6)
		8-hour	50 μg/m^3	Portugal (4)

Results

For schools, during operating hours, exceedances of CO_2 guidelines increased substantially when compared to the 24h average, highlighting the impact of classroom occupancy. Analysis of exceedances showed high annual CO_2 exceedance in schools, particularly in Austria (41%) and Poland (34%), which rose further during winter (48% and 41%, respectively) when reduced ventilation leads to increased CO_2 accumulation. Austrian schools experienced more frequent low-level CO_2 exceedances, while Polish schools tend to show a greater share of exceedances in the

higher concentration ranges during operating hours. Regarding PM_{10} exceedances in schools, for Austrian schools a very low frequency was observed, while Polish schools experienced noticeably higher exceedance frequencies (1.7% vs 7.8%, respectively). Regarding $PM_{2.5}$ exceedances in schools, results indicate that $PM_{2.5}$ is a much more significant indoor air quality concern in Polish schools (26%) than in Austrian schools (7.6%). The persistence of exceedances highlights the influence of elevated fine-particle concentrations in the Polish locations and suggests that $PM_{2.5}$ mitigation measures may be particularly beneficial in these schools.

For homes, exceedances of CO_2 guidelines were highest in Poland, where concentrations exceeded guideline values during approximately 13–25% of the monitored period, followed by Austria (8–11%), Spain (4–12%) and the Netherlands (<4%). Most exceedances were of low magnitude (≥1/<1.5 times the guideline value) and increased during winter months, highlighting the importance of ventilation practices and occupancy patterns. Homes with wood-based heating systems generally showed the highest exceedance frequencies, while differences associated with smoking status, cooking fuels and cooling systems were less pronounced. Regarding PM_{10} exceedances, they were generally highest in Poland, where concentrations exceeded guideline values for approximately 3–10% of the monitored time, followed by Spain (1–8%), Austria (1–7%), and the Netherlands (<2%). Exceedances were strongly influenced by smoking, wood-based heating systems, and winter conditions, with most occurring within the lower exceedance categories. Regarding $PM_{2.5}$ exceedances, it showed the highest exceedance frequencies reaching approximately 15–25% in Poland, 8–20% in Spain, 8–15% in Austria, and generally below 5% in the Netherlands. Homes with smoking occupants, wood-heated dwellings, and poorly ventilated indoor environments consistently exhibited the highest exceedance frequencies, particularly during winter. Regarding formaldehyde exceedances, it varied substantially across countries and settings, with the highest frequencies observed in selected Polish homes (up to 66%), whereas exceedances were generally lower in Spain, Austria, and the Netherlands (typically <15%). Unlike PM, formaldehyde exceedances were more strongly associated with indoor emission sources such as building materials, furnishings, consumer products.

For hospitals, it was consistently demonstrated good indoor air quality conditions during the study. Exceedance frequencies for CO_2, PM_{10}, $PM_{2.5}$, and formaldehyde were generally very low, reflecting the effectiveness of ventilation systems, filtration technologies, and environmental management procedures.

Conclusions

For CO_2, exceedances were primarily related to occupancy and ventilation effectiveness rather than direct emission sources. Schools represented the setting where CO_2 exceedances were most consistently observed, particularly during operating hours and winter periods. Among the pollutants assessed, $PM_{2.5}$ emerged as the most important concern across scenarios. Homes and some schools displayed the highest exceedance frequencies, particularly during winter months. In residential settings, smoking was identified as one of the strongest determinants of PM_{10} and $PM_{2.5}$ exceedances, with homes occupied by smokers consistently recording the highest frequencies and most severe exceedance categories. Similarly, wood heating was associated with elevated $PM_{2.5}$ concentrations, especially in Poland, where wood-heated homes showed the highest exceedance frequencies across multiple pollutants. In contrast, electric-heated homes generally exhibited lower particulate matter exceedances. This study demonstrates that indoor air quality remains highly variable across environments and is strongly influenced by occupant activities, heating practices, ventilation conditions, and pollutant sources. Fine particulate matter emerged as the most widespread exposure concern, while formaldehyde represented a relevant issue in selected settings. Together, these findings provide a robust evidence base for targeted interventions aimed at reducing indoor pollutant exposure and improving public health across diverse indoor environments.

Acknowledgements

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Indoor $PM_{2.5}$ in polish residential buildings across heating system categories: Results from a two-year continuous monitoring study

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Citation

Kępa, P., Rogulski, M., Kristian, A., Moshammer, H., Fermoso Dominguez, J., Kozielska, B., Lehmann, M., Heß, D., Badyda, A. Indoor $PM_{2.5}$ in polish residential buildings across heating system categories: Results from a two-year continuous monitoring study.

Abstract

Background

Indoor air quality (IAQ) is a major determinant of population health, as people in high-income countries spend most of their time indoors, with homes representing the dominant microenvironment for daily pollutant exposure. Combustion-based residential heating is a key source of indoor fine particulate matter ($PM_{2.5}$), particularly in Central Europe, where combustion-based heating remains widespread. Poland is a particularly informative setting: it relies more heavily on solid fossil fuels for residential space heating than any other EU Member State, accounting for approximately 28% of space-heating energy (1). While the contribution of solid fuel combustion to outdoor $PM_{2.5}$ is well documented, continuous, long-term indoor measurements stratified by heating system remain comparatively scarce (2-4).

Objectives

This study aimed to characterise indoor $PM_{2.5}$ concentrations in Polish residential buildings across three heating-system categories over two full years, to describe their seasonal and diurnal patterns, and to identify the building-related and source factors that drive variability within each heating category.

Methods

Continuous indoor $PM_{2.5}$ monitoring was conducted in 27 residential buildings in the Warsaw metropolitan area from January 2024 to December 2025, within the framework of the K-HEALTHinAIR Horizon Europe project (Grant Agreement No. 101057693). Buildings were stratified into three heating categories: solid fuel (n=4), natural gas (n=10), and non-combustion — electric, district, or renewable (n=13). $PM_{2.5}$ was measured at one-minute intervals using Kaiterra Sensedge Mini sensors and analysed as hourly and daily means. Building and neighbourhood characteristics — construction period, thermal-retrofit status, ventilation, cooking fuel, monitor placement, and nearby combustion and traffic sources — were obtained from occupant questionnaires and installation visits. The relative contribution of heating type versus building- and time-related factors to the total variance of indoor

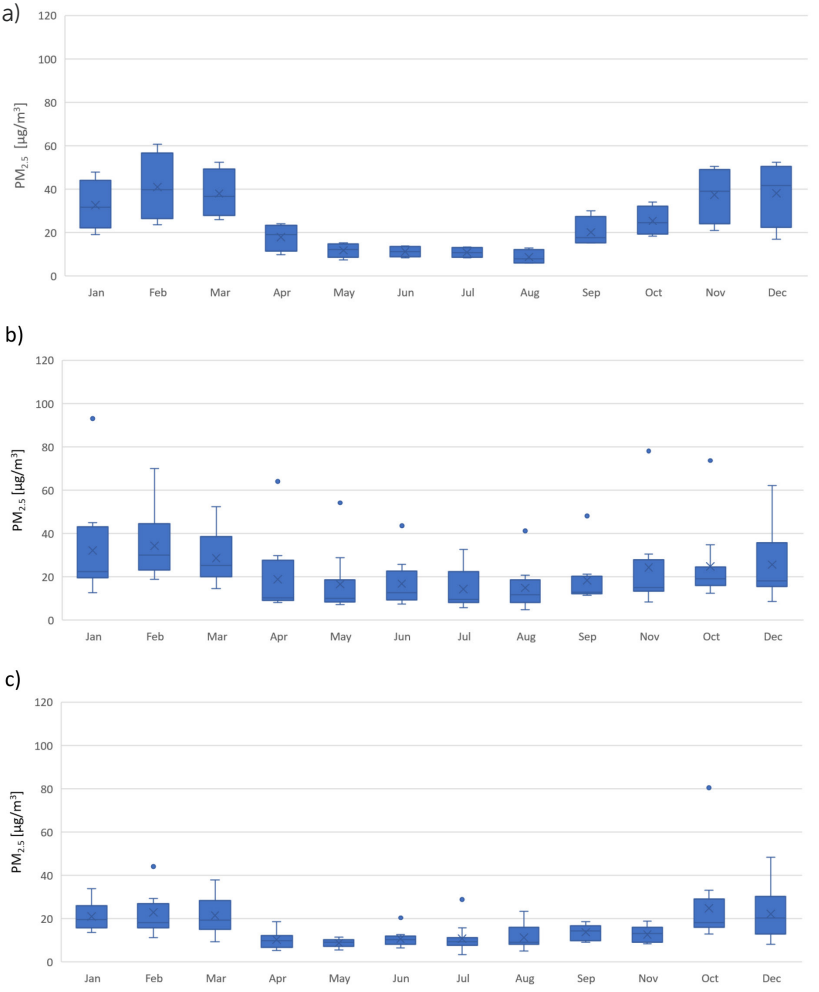


FIGURE 1
Seasonal variation in mean daily $PM_{2.5}$ concentrations in: **(a)** solid fuel-heated buildings, **(b)** gas-heated buildings, **(c)** non-combustion heated buildings.

$PM_{2.5}$ was assessed by variance partitioning (nested analysis of variance), and differences between heating categories were tested with the Kruskal–Wallis test and Dunn's post-hoc test with the Holm correction.

Results

A gradient in mean hourly $PM_{2.5}$ concentrations was observed across heating types, decreasing from solid-fuel homes (26.4 μg/m^3) through gas-heated homes (22.8 μg/m^3) to non-combustion homes (15.8 μg/m^3). Solid-fuel homes showed approximately four-fold winter-to-summer variation, compared with two-fold variation in the other categories, and all categories exceeded the WHO annual air quality guideline (5 μg/m^3) several-fold (Figure 1).

Diurnal patterns showed pronounced evening peaks in solid-fuel homes, consistent with heating cycles, and irregular peaks in gas-heated homes linked to cooking activities. Episodic peak hourly concentrations exceeded 1,000 μg/m^3 in the gas and non-combustion categories and approached this level in solid-fuel homes, reaching approximately 3,500 μg/m^3 in one gas-heated home associated with indoor tobacco smoking.

Variance partitioning showed that heating type set a seasonally varying baseline: its contribution to indoor $PM_{2.5}$ variance was substantial during the heating season and negligible in summer. In a balanced comparison of four buildings per category, the share of variance attributable to heating type exceeded 20% in midwinter (December–February) and fell to 3.2% or below in summer, and between-category differences were statistically significant in the coldest months (Kruskal–Wallis, $p < 0.001$) but indistinguishable in mid-summer. Across the full sample, differences between individual buildings within the same category accounted for more variance than the heating category itself. The larger source of within-category variability was therefore non-heating, building-level: residual on-site combustion such as a supplementary fireplace, the presence of a cooking area in the monitored room, and infiltration from neighbouring solid-fuel use or traffic. Consequently, some non-combustion-heated homes reached concentrations comparable to combustion-heated dwellings.

Conclusions

The small number of solid-fuel dwellings (n = 4) limits the precision of between-category comparisons and should be taken into account when interpreting the results.

Heating-system type is a major determinant of residential $PM_{2.5}$ exposure in Poland, setting a seasonally varying baseline that is most pronounced in winter. However, building characteristics, occupant behaviour, and outdoor air quality substantially shape indoor concentrations within each heating category, so that heating technology alone does not fully determine exposure. Effective mitigation therefore requires integrated strategies that address both heating technology and the broader building- and neighbourhood-level determinants of indoor air quality.

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Coupling aerosol monitoring with airborne microbiome and resistome profiling in healthcare indoor environments

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Citation

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Abstract

Indoor air quality assessment in healthcare environments is still largely centred on physicochemical parameters, while biological particles remain underrepresented despite their relevance for infection prevention, microbial exposure assessment and antimicrobial resistance surveillance. Built-environment microbiomes are shaped by occupancy, ventilation, outdoor inputs and building-specific sources (1), and hospital air has been shown to contain clinically relevant microbial signatures detectable by metagenomic approaches (2). However, biological data are rarely interpreted together with real-time aerosol dynamics.

In this pilot study, we applied an integrated aerosol-microbiome monitoring framework to characterize airborne microbial communities, viable bacteria, antimicrobial resistance determinants and particle dynamics in two healthcare-associated indoor environments in Greece: the KHFH Elderly Care Centre in Trikala and Thriassio General Hospital in Elefsina. The overall study design, analytical workflow and main findings are summarized in Figure 1.

Air samples were collected using high-volume PM_{10} filtration for shotgun metagenomics and culture-based microbiology, together with gelatin-filter sampling for targeted respiratory virus detection. Aerosol dynamics were monitored in parallel using particle instruments and low-cost multiparametric sensors recording particulate matter fractions, CO_2, temperature and relative humidity.

The two environments showed distinct aerosol regimes. The elderly care centre displayed relatively stable particle profiles, whereas hospital rooms

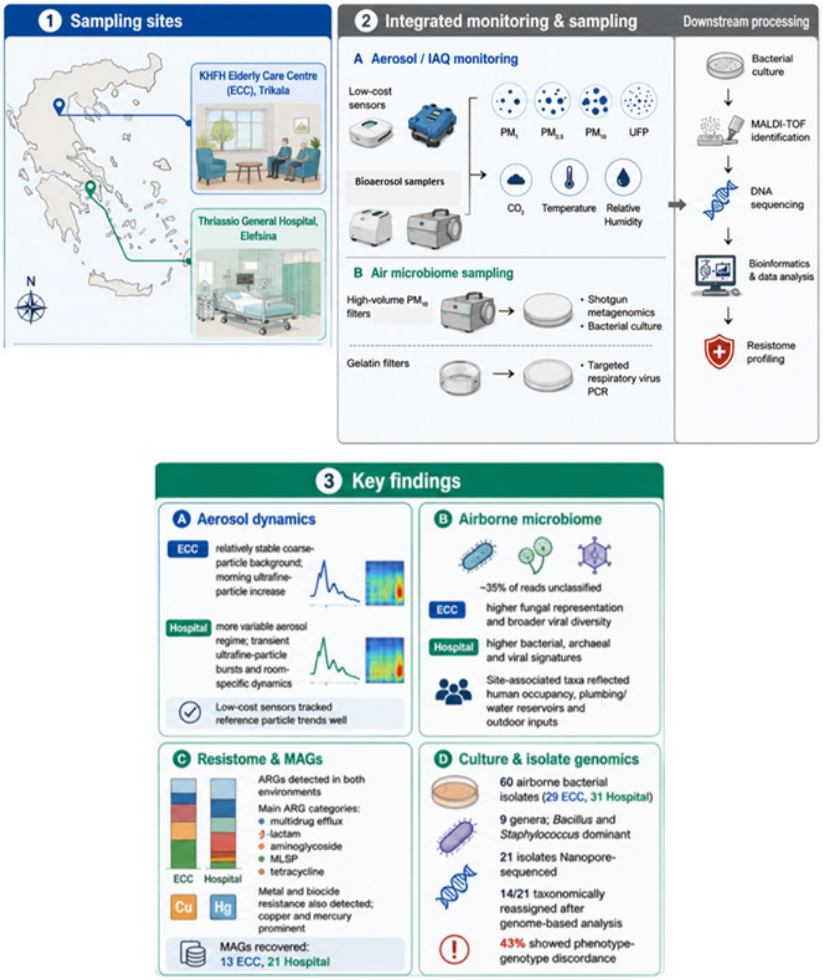


FIGURE 1
Integrated aerosol–microbiome monitoring workflow and key findings from two healthcare-associated indoor environments.

showed more variable aerosol behaviour, including ultrafine particle bursts and transient particle events consistent with occupancy and routine indoor activity. These physical patterns provided essential context for interpreting the biological signals detected in air samples.

The campaign covered two healthcare-associated indoor environments over four consecutive days: the KHFH Elderly Care Centre in Trikala, sampled on 30–31 May 2023, and Thriassio General Hospital in Elefsina, sampled on 1–2 June 2023. Sampling was performed in one ECC common room and three hospital rooms: a doctor's office, a nurses' station and the emergency reception area. 7 PM_{10} air-filter (four ECC samples and three hospital samples) were analysed by shotgun sequencing and 15 million reads per sample, corresponding approximately to around 4 GB per sample was generated. Shotgun metagenomics detected bacterial, fungal, archaeal and viral signatures consistent with mixed human-associated, plumbing-associated and outdoor sources. Across samples, bacterial reads represented the dominant classified fraction, while approximately 35% of reads remained unclassified. Alpha diversity did not differ significantly between ECC and hospital air samples ($p = 0.27$), whereas Bray–Curtis beta diversity separated ECC and hospital microbial communities (PERMANOVA, $P < 0.01$). The ECC microbiome showed higher fungal representation and broader viral diversity, whereas hospital samples showed higher relative contributions from archaeal, bacterial and viral components. Human adenovirus was detected by targeted qPCR in both ECC and hospital gelatin-filter samples, while SARS-CoV-2, influenza A virus, RSV A/B and rhinovirus were not detected during the campaign.

Resistome profiling identified genes linked to multidrug efflux, and genes associated with β-lactam, aminoglycoside, tetracycline and macrolide–lincosamide resistance. Non-antibiotic resistance determinants were also detected, particularly, metal and biocide resistance determinants, with

copper and mercury resistance showing the highest relative abundances. Metagenome assembly reconstructed 34 medium- to high-quality MAGs, including 13 from ECC samples and 21 from hospital samples, with completeness ranging from 72.5% to 100% and contamination below 3.1%. These findings are consistent with growing evidence that airborne environments can act as reservoirs and dispersal routes for antimicrobial resistance genes (3,4).

Culture-based analyses recovered 60 viable airborne bacteria (29 from ECC and 31 from hospital samples) with heterogeneous antimicrobial susceptibility profiles, including multidrug-resistant phenotypes. The isolate collection was dominated by *Bacillus* and *Staphylococcus*, with additional genera including *Aerococcus*, *Pseudomonas, Pantoea, Lactobacillus, Micrococcus, Lysinibacillus* and *Escherichia*. Long-read Oxford Nanopore sequencing of 21 selected isolates enabled strain-level taxonomic reassignment and linked resistance determinants, plasmid markers and mobile genetic elements to specific bacterial genomes. Importantly, phenotype–genotype discordance was frequent, indicating that detection of resistance genes alone is insufficient to predict antimicrobial susceptibility in airborne isolates.

This pilot study demonstrates the value of combining aerosol physics, environmental sensing, shotgun metagenomics, culture-based microbiology and isolate genomics for comprehensive indoor air characterization in healthcare settings. The results support the inclusion of biological indicators in routine IAQ monitoring and highlight the need for longitudinal surveillance frameworks that integrate particle dynamics with microbial and resistome profiling to better assess airborne exposure and antimicrobial resistance risks indoors.

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From room to result: Sampling and GC-MS analysis of indoor air volatiles

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Citation
Matesanz, R., Simón, G., Lao-Zea, A., Alcacera, M.P., Gilaranz, J., Suárez, S., Rodríguez-López, A. From room to result: Sampling and GC-MS analysis of indoor air volatiles.

Abstract

Background

Given that individuals spend more than 90% (1) of their time indoors, indoor air quality (IAQ) represents one of the main determinants of human exposure to airborne pollutants and has become a major focus of environmental health research. Reliable assessment of indoor environments is therefore essential to support exposure evaluation, source identification and risk assessment.

Accurate characterization of volatile organic compounds (VOCs) in indoor environments remains a significant analytical challenge. VOCs concentrations

are often highly variable in space and time, while sample contamination, storage conditions and analytical artefacts may substantially affect data quality. Consequently, the reliability of IAQ studies depends not only on the analytical instrumentation employed but also on the robustness of the entire methodological chain, from sample collection to laboratory analysis.

Objective

This work presents a comprehensive methodological framework for the determination of VOCs in indoor air using thermal desorption tubes and gas chromatography–mass spectrometry (TD-GC-MS). The protocol was developed to ensure data quality, traceability and comparability across monitoring campaigns while minimizing potential sources of uncertainty associated with sampling, transport, storage and analysis.

Methodology

The proposed methodology encompasses all critical stages of the monitoring process. VOCs sampling was performed using stainless-steel thermal desorption tubes packed with hydrophobic porous sorbents suitable for the collection of a broad range of volatile organic compounds. Prior to sampling, thermal desorption tubes were conditioned by passing a continuous flow of high-purity helium (200 $mL \cdot min^{-1}$) through the sorbent bed at 300 °C for one hour. This treatment effectively removed residual contaminants and reduced background signals, thereby ensuring the suitability of the tubes for trace-level VOCs analysis.

Both active and passive sampling approaches can be implemented within the framework, following internationally recognized procedures including ISO 16000-6 (1) and US EPA TO-17 method (2). For active sampling, calibrated pumps operating at controlled flow rates were used to guarantee representative air volumes and reproducible sampling conditions.

Particular attention was devoted to sample preservation and traceability. Immediately after collection, tubes were hermetically sealed using brass caps equipped with PTFE ferrules to prevent contamination and analyte losses.

Samples were subsequently stored under refrigerated conditions at temperatures close to –10 °C and transported in sealed containers isolated from potential emission sources. Chain-of-custody procedures were applied throughout the process to maintain full sample traceability from collection to analysis.

Laboratory analyses were performed using thermal desorption coupled with gas chromatography–mass spectrometry (TD-GC-MS). VOCs were analysed using a PerkinElmer TurboMatrix™ 650 Automated Thermal Desorber coupled to an Agilent 6890 gas chromatograph equipped with an Agilent 5973 mass selective detector. Prior to chromatographic separation, compounds retained on the sorbent tubes were thermally desorbed at temperatures between 250 and 300 °C and subsequently concentrated in a cryogenically cooled focusing trap maintained at sub-ambient temperature. The desorbed analytes were then transferred to the gas chromatograph and separated on an HP-5MS capillary column (30 m × 0.25 mm × 0.25 µm, Agilent Technologies), featuring a low-polarity stationary phase composed of 5% phenyl-methylpolysiloxane. Following chromatographic separation, compounds were introduced into the mass spectrometer, where electron impact ionization (70 eV) generated characteristic mass spectra that enabled compound identification and quantification. The combination of thermal desorption and GC-MS provides high sensitivity and selectivity for the determination of trace-level VOCs in indoor air samples, while minimizing sample handling and potential analyte losses (4).

Quality assurance and quality control procedures were integrated throughout the workflow. These included conditioning verification, blank analyses, flow-rate calibration, storage controls and analytical performance checks designed to minimize contamination, improve reproducibility and ensure data reliability.

Results and Discussion

The proposed framework provides a standardized and reproducible approach for indoor VOCs characterization, addressing many of the methodological challenges commonly encountered in IAQ investigations. The combination

of rigorous sorbent tube preparation, controlled sampling conditions, strict sample preservation procedures and TD-GC-MS analysis contributes to the generation of high-quality datasets suitable for exposure assessment and source apportionment studies.

The protocol is particularly advantageous for long-term monitoring campaigns and multi-site studies, where methodological consistency is essential to ensure comparability of results. Furthermore, the use of solvent-free thermal desorption techniques minimizes sample handling and reduces the risk of analyte loss compared with conventional extraction-based approaches.

The implementation of this methodology within indoor air monitoring campaigns has demonstrated its suitability for detecting a wide range of VOCs at environmentally relevant concentrations while maintaining analytical robustness and operational practicality.

Conclusions

Reliable characterization of indoor air pollutants requires a holistic approach that extends beyond analytical instrumentation alone. The methodology presented here integrates tube conditioning, sample collection, preservation, traceability and TD-GC-MS analysis into a unified quality-assurance framework. By reducing uncertainty throughout the analytical chain, the protocol supports the generation of robust and comparable VOCs datasets, thereby strengthening the scientific basis for IAQ assessment, exposure evaluation and environmental health research. Moreover, the standardized worklow provides a practical framework for harmonized IAQ monitoring campaigns, facilitating the comparability of VOC measurements across different sampling campaigns, sites and laboratories.

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Air cleaning technologies for particles, gases, and microorganisms: Principles, effectiveness, and limitations

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Schumacher, S., Caspari, A., Schneiderwind, U., Asbach, C. Air cleaning technologies for particles, gases, and microorganisms: Principles, effectiveness, and limitations.

Abstract

Background

In industrialized countries, people spend most of their time indoors (1), where exposure to airborne pollutants may adversely affect health (2). These pollutants can be broadly classified into particulate matter, gaseous contaminants, and microorganisms. While natural ventilation is often sufficient when outdoor air quality is good, it may be ineffective or energetically unfavourable due to elevated outdoor pollution, building

characteristics, climatic conditions, noise, or security concerns. In such situations, ventilation systems and portable air cleaners can complement natural ventilation. However, no single technology is equally effective for all indoor pollutants, and the benefits of air cleaning must always be balanced against limitations such as energy demand, maintenance requirements, and the potential formation of by-products.

Particulate Pollutants

The performance of particle-removing air cleaners is commonly assessed by the Clean Air Delivery Rate (CADR), determined in standardized chamber tests from the decay of airborne particle concentrations. The CADR corresponds to the product of particle removal efficiency and airflow rate. Consequently, effective air cleaning requires a balance between high filtration efficiency and sufficient airflow.

Most commercial air cleaners rely on non-woven fibrous filters (3). Electret filters are particularly common because electrostatic interactions complement mechanical collection mechanisms (4), enabling higher removal efficiencies at a given pressure drop and thus higher airflow rates at comparable power consumption and noise levels. Their main disadvantage is that the electrostatic charge may decay over time owing to particle loading, humidity, or exposure to solvent vapours, highlighting the importance of long-term performance testing (5). In contrast, uncharged HEPA filters (e.g., classes H13 and H14 according to EN 1822) are less susceptible to ageing effects but exhibit substantially higher pressure drops, often reducing airflow or increasing energy consumption and noise (6), which limits their practical advantages in air cleaners.

Electrostatic precipitators (ESP) represent an alternative approach (7).Particles are charged by an ionizer and subsequently collected on oppositely charged plates. Owing to their low pressure drop, ESPs can achieve high airflow rates at similar power consumption, while reusable collector plates reduce the need for consumable filter media. However, their performance depends

on particle electrical mobility, and ionizers may generate ozone as an undesirable by-product (8). Additional activated carbon filters are therefore often required, partly offsetting these advantages. Stand-alone ionizers, which rely solely on particle deposition onto room surfaces, generally provide limited and poorly controlled particle removal and are therefore not recommended as a primary air-cleaning strategy.

Gaseous Pollutants

For the removal of gaseous pollutants, particularly volatile organic compounds (VOC), household air cleaners predominantly rely on adsorption using activated carbon (AC) (9). Alternative adsorbents such as zeolites and metal–organic frameworks (MOF) have attracted research interest but remain largely absent from consumer devices.

The effectiveness of activated carbon depends on the amount of adsorbent, its accessibility, and the contact time between air and adsorbent surface. Dense carbon beds, which provide high capacities and long service lives, are mainly used in professional applications because of their large space requirements and pressure drops. Household devices typically employ either honeycomb structures with limited contact between air and adsorbent or activated carbon incorporated into non-woven media, which provide improved initial removal but lower adsorption capacities. A general limitation of activated carbon is its strong dependence on pollutant properties (10). For example, it is comparatively ineffective for small, highly polar molecules such as formaldehyde. Impregnation with reactive compounds, such as amines, can improve the removal of specific pollutants through chemisorption but may reduce the adsorption capacity for others by partially blocking the pore structure (11). Consequently, adsorbent selection generally represents a compromise between broad-spectrum performance and the efficient removal of specific target compounds.

Alternative technologies aim to decompose pollutants rather than adsorb them. These include plasma-based systems (12) and photocatalytic oxidation (PCO) (13). While these approaches may avoid the need for adsorbent

replacement, incomplete oxidation and the generation of reactive species can result in undesirable by-products (14). Therefore, their evaluation should include not only pollutant removal efficiencies but also the monitoring of ozone emissions and secondary reaction products.

Microbiological Pollutants

Microorganisms such as bacteria, viruses, and fungi, as well as the respiratory droplets carrying them, are airborne particles. Consequently, the same technologies used for particulate matter, particularly fibrous filters and ESPs, are also effective for bioaerosol removal (6). Concerns that microorganisms retained on filters may proliferate or become re-entrained into the air are generally of minor relevance under proper operating conditions. The lack of nutrients and sufficient moisture limits microbial growth on filter media, while small particles are strongly bound to fibre surfaces. The added benefit of antimicrobial filter treatments or UV irradiation of filter surfaces should therefore be critically assessed.

Some air cleaners instead rely exclusively on the inactivation of microorganisms, most commonly by UV-C irradiation, without physically removing them from the air (15). UV-C has proven effective against a broad range of microorganisms and offers advantages such as low pressure drop and the absence of disposable filters. However, inactivation depends critically on the delivered radiation dose, which varies among microorganisms and may be influenced by shielding effects of surrounding droplets or particles. Consequently, the performance of UV-based systems is less readily generalizable than filtration-based approaches, which are largely independent of the biological nature of the collected material. In addition, it must be ensured that occupants are not exposed to harmful UV radiation and that the devices do not generate ozone or other undesirable by-products.

Conclusions

Overall, no single air-cleaning technology can be considered universally superior, as its effectiveness depends on the pollutants to be removed and the conditions under which the device is operated. Thus, the most

appropriate technology should always be based on the target pollutant(s), the intended application, and the specific indoor environment. In addition to pollutant removal efficiency, factors such as energy consumption, maintenance requirements, noise, long-term performance, and the potential formation of harmful by-products should be considered when selecting an air-cleaning technology.

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Oxidative inactivation of airborne viruses using catalytic filters

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Citation

Llanos, P., Vázquez-Calvo, A., Serrano-Lotina, A., Gómez-López, A., García-Castey, M., Alcamí, A., Bañares, M.A. Oxidative inactivation of airborne viruses using catalytic filters.

Abstract

Background

Lower respiratory infections are currently ranked by the World Health Organization (WHO) as the fifth leading cause of death worldwide (1). Respiratory pathogens are transmitted mainly through three routes: inhalation, direct deposition, and contact. Airborne transmission by

inhalation occurs when small infectious respiratory particles (IRPs) (2) remain suspended in the air and are inhaled by a susceptible individual, potentially depositing anywhere along the respiratory tract. Direct deposition involves larger particles expelled with sufficient momentum to follow a semi-ballistic trajectory and land directly on exposed mucosal surfaces, such as the mouth, nose, or eyes. Finally, contact transmission occurs through direct physical interaction or via contaminated surfaces (fomites) (3–5). Among these routes, airborne transmission plays a critical role in the spread of respiratory diseases, particularly in indoor environments, where pathogens represent a major concern in poorly ventilated spaces and sensitive facilities such as hospitals. The small size of pathogens (1–100 μm for fungi, 0.1–10 μm for bacteria, and 0.01–1 μm for viruses) enables their transport through aerosol droplets (6). The aerodynamic behavior of aerosols is influenced by several factors, including emission velocity, the number of emitted droplets, particle size distribution, and ambient relative humidity. In particular, particles smaller than 10 μm can remain suspended in the air for several hours and therefore propagate through air currents(7). Although a wide range of air purification technologies is currently available, many of them still present important limitations related to energy consumption, operational complexity, or the generation of potentially harmful by-products. In this context, we have developed and patented (WO2025196358) ceramic catalytic filters that can be integrated into indoor air-cleaning devices and are capable of efficiently inactivating a broad spectrum of pathogens, including HCoV-229E, SARS-CoV-2, RV-B14, *Escherichia Coli*, and *Staphylococcus Aureus*, by oxidative stress under mild operating conditions (temperatures below 40 °C).

Objectives

The main Objective of this research is to develop ceramic catalysts capable of inactivating airborne pathogens and suitable for direct integration into ventilation and air-treatment systems in the form of catalytic filters.

Methods

Catalysts were synthesized by incipient wetness impregnation, and the antimicrobial activity of the catalytic filters was subsequently evaluated.

The antimicrobial performance was initially assessed using plaque assays. Virucidal activity was determined against human coronavirus 229E (hCoV-229E), severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), human rhinovirus 14 (RV-B14), and bacteriophage ϕ29 by quantifying plaque-forming units (PFU) before and after contact with the catalytic material. In parallel, bactericidal activity was evaluated against *Escherichia Coli* and *Staphylococcus Aureus* through the quantification of colony-forming units (CFU). To further investigate the inactivation mechanism, the contribution of copper species and reactive oxygen species (ROS) was examined using hCoV-229E as a model virus. The assays were performed in the presence of EDTA, as a Cu^{+}/Cu^{2+} chelating agent, as along with Tiron and mannitol, as ROS scavengers. These compounds were added before incubation of the virus with the catalytic material, and the results were compared with those obtained in the absence of additives. This approach enabled evaluation of the relative contribution of copper species and oxidative pathways to viral inactivation.

Subsequently, in accordance with the planned scale-up strategy, preliminary tests were conducted in an aerosol chamber. The evaluated catalytic filters consisted of ceramic monoliths produced by extrusion and coated with the selected active phase (CuI) through immersion in a catalytic solution. Unlike conventional filtration systems, these reactive filters were designed to inactivate pathogens rather than retain them.

Aerosols were generated using a modified Counterfog® SDR-F05A device and continuously monitored using an SPS30 sensor from Sensirion. The aerosol was recirculated for 1 h, after which the remaining virus present in the chamber air was recovered. The viability of bacteriophage ϕ29 was determined by plaque assays, while viral retention was evaluated through quantification of DNA copies by qPCR. Catalyst durability was investigated through consecutive operating cycles without intermediate regeneration treatments and by assessing catalytic performance after one year of storage.

Key Results

Among the synthesized catalysts, copper-based materials demonstrated the most effective broad-spectrum antimicrobial activity against all tested viruses and bacterial species. These catalysts exhibited antiviral reductions of approximately 4 $\log_{10}$ PFU·mL^{-1}, with viral titers in most cases falling below the detection limit (5 PFU·mL^{-1}) after 1 h of contact at room temperature. Similar reductions of up to 4 $\log_{10}$ CFU·mL^{-1} were observed for *E. coli* and *S. aureus*.

Furthermore, plaque assays performed against hCoV-229E in the presence of chelating and scavenging agents revealed a significant decrease in virucidal activity. These findings indicate that both Cu^{+} species and superoxide anions contribute to pathogen inactivation (Figure 1).

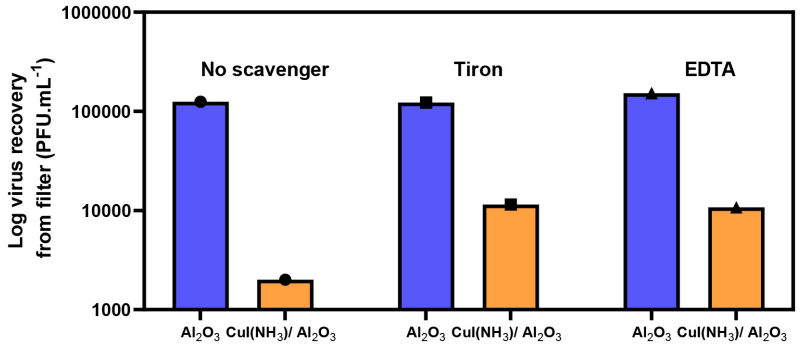


FIGURE 1
Log virus recovery after 10 min exposure to catalytic ceramic filters against HCoV-229E at room temperature following treatment with TIRON and EDTA.

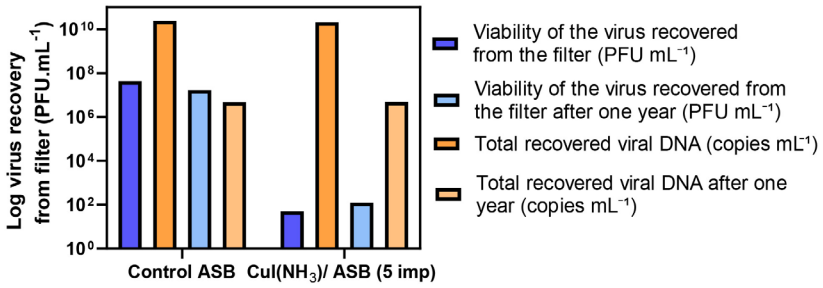


FIGURE 2
Viability and viral DNA recovery of aerosolized bacteriophage ϕ29 after exposure to fresh and one-year-aged catalytic ceramic filters.

In aerosol chamber experiments, reductions of up to 8 log units were achieved at room temperature, demonstrating the effectiveness of the catalytic filters under realistic airborne conditions. The catalysts also exhibited remarkable stability, maintaining their antimicrobial performance after multiple operation cycles without regeneration and after one year of storage, highlighting their potential for long-term practical applications (Figure 2).

Main Conclusions

The developed ceramic catalysts demonstrated a high capacity for pathogen inactivation under ambient conditions, achieving reductions below the detection limit after 1 h of contact. This represents a significant advantage over other air-purification technologies, which depend on UV activation, release harmful species or demand high energy. Overall, these results highlight functional ceramic catalysts as a promising technology for advanced bioaerosol control and improved indoor air quality.

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Session 2 – Health Outcomes and Clinical Evidence Related to IAQ

Allergy in children to illicit drugs, tobacco and alcohol

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Citation

Armentia Medina, A., Martín-Armentia, S., Fernández Cortés, S., Gonzalez-Rodriguez, I., Martín-Armentia, B., Martinez, M.J., Pineda, F. Allergy in children to illicit drugs, tobacco and alcohol.

Abstract

Background

Illicit drugs, tobacco, and alcohol contain allergens that can trigger, inadvertently affecting children living with consumer relatives.

Allergic sensitization and hypersensitivity associated with cannabis have been previously described (1–4), as well as reactions associated with opioids (5,6), cocaine (7), and alcohol (8.9).

Objective

This real-life study is aimed to evaluate the presence of sensitization to illicit drugs (cannabis, opium derivatives, and cocaine), tobacco, and allergens derived from alcoholic beverages in children (10).

Methods

Children (0-14 years) with severe allergic symptoms and domestic exposure to drugs, tobacco, or alcohol were included. Prick, specific IgE, molecular analysis, and Dot Blot assays were performed (10). We tested 46 aeroallergens and food, pure

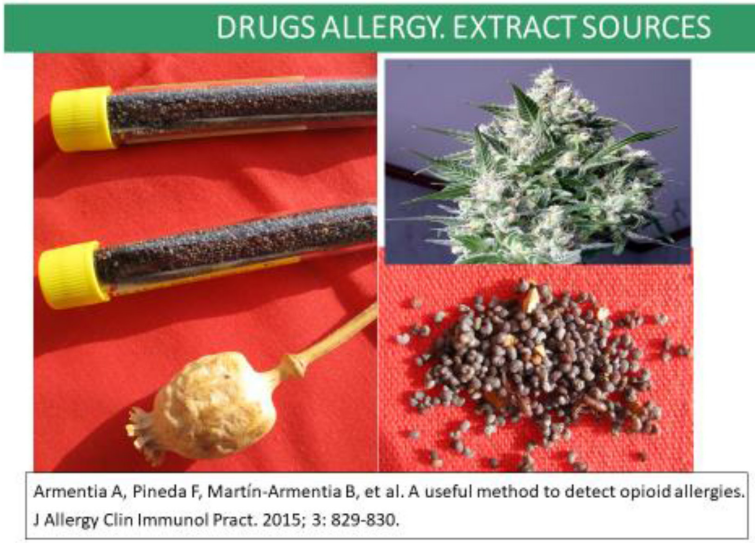


FIGURE 1
Sources used for the preparation of allergenic extracts from illicit drugs, including opium poppy seeds and capsules and Cannabis sativa. Adapted from Armentia et al. (2015) (6).

cocaine, coca leaf extract, opium, *Papaver somniferum* seeds, cannabis, tomato, tobacco, latex, malt, hops, and lipid transfer proteins (LTPs) from grapes (Figure 1).

Results

Of the 150 selected patients, 134 completed the study. Among them, 21 tested positive for cannabis, 18 for tobacco, 17 for malt, 13 for hops, 12 for grape LTPs, 10 for cocaine, 6 for opioids A significant association was found between drug, tobacco, and alcohol exposure and the development of severe allergic symptoms ($p < 0.001$) (10). Specific relationships were observed: cocaine ($p < 0.009$) and tobacco ($p < 0.05$) were associated with severe asthma. Malt and cannabis sensitization ($p < 0.001$) were linked to anaphylaxis, with additional

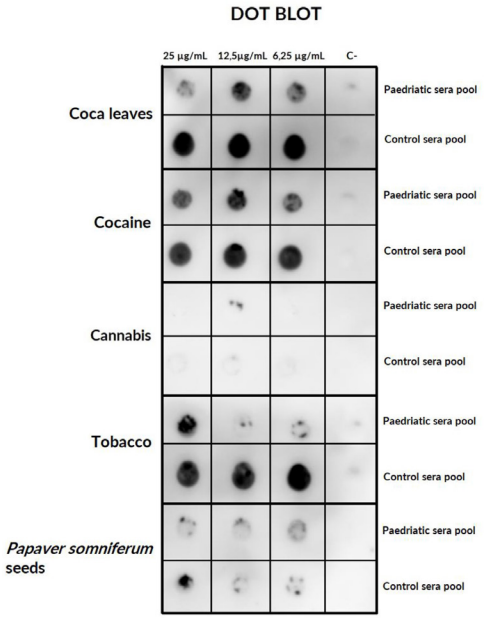


FIGURE 2
Inmunolobulin E (IgE) dot blot. Each dot represents the allergenic study sample (coca tea, cocaine, cannabis, tobacco leaves and opium seeds. The intensity of the dot is directly proportional to the binding of IgE from the serum pool to the study sample.

associations found for hops ($p < 0.003$) and grape LTP ($p < 0.006$). Molecular assays revealed binding of the IgE from these paediatric patients to the tested samples (Figure 2).

Conclusions
Atopic children should be considered at risk of developing hypersensitivity to allergens from illicit drugs, tobacco, and alcohol. This possibility should not be overlooked or underestimated. It is possible to use environmental drug detectors in homes to detect patients at risk of sensitization.

In summary, the key findings were:

- Variable intensity of reactivity was observed between different samples and patients.
- Allergic responses were identified to the following allergens:
  - **Tobacco leaves** and **opium seeds** → Strong IgE binding
  - **Cocaine** and **beer** → Moderate reactivity
  - **Cannabis** and **coca tea** → Less intense or absent reactivity

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Environmental determinants of physical and cognitive health in schoolchildren

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Citation
Moshammer, H., Kristian, A., Mucha, D., Badyda, A., Kępa, P. Environmental determinants of physical and cognitive health in schoolchildren.

Abstract

Introduction

Because of increased vulnerability of children during growth and development and because their longer remaining life expectancy that increases their risk of experiencing long-term consequences of exposure, environmental exposures in children are very relevant. School-children are a rather homogenous group of possible participants in environmental health studies: at least younger school-children have not started smoking yet, they have not suffered any occupational exposures, and their past environmental history is comparably short and therefore accessible through parents' questionnaires. At school-age effects of early life exposures are already visible and exposures during school-age are already forming their future fates. We found school-children willing and dedicated study participants that

are easily accessible provided the school authorities help with recruitment and the distribution of information and questionnaires to children and their parents. Environmental and health history of school-children are still sufficiently short so that parents are able to report most relevant facts in detailed questionnaires. Similar to their children, they are mostly eager to support the research and are interested in the scientific findings. Thus, participation rate is usually sufficient for robust findings.

Methods

In various studies mostly in primary schools (age about 6-10 years) throughout Austria, we have evaluated different environmental exposures and have assessed the health of the children through different methods and indicators. All children in the same class-room are exposed to a similar class-room environment. Because epidemiological studies depend on a sufficient exposure gradient, our primary focus was first on the home environment about which we obtained information through questionnaires mostly. These questionnaires focused on early life exposures like smoking in pregnancy or smokers at home in the first years of life, and on current exposures including mould at home, location at a busy road (e.g., asking "if you cannot open the window at night because of traffic noise") or use of pesticides and other chemicals at home. Other microenvironments like the way to school and the mode of transport also matter. Regarding school environment, we compared multiple class-rooms and schools and we measured allergens, endotoxin, air quality and chemical contaminants in schools. We also compared urban to rural schools and investigated the orientation of the classroom window to understand effects of indoor microclimate and direct sunlight. Physical health was most often assessed by spirometry, mental health by tests of concentration and reaction time.

Results

Among the many results we present the effect of smoking in pregnancy (Figure 1) (1) and of living with a smoker and how this exposure is mitigated by the protective effect of breast-feeding (2). We demonstrate the effects of cooking with gas and of mould exposure (3, 4). We also found that

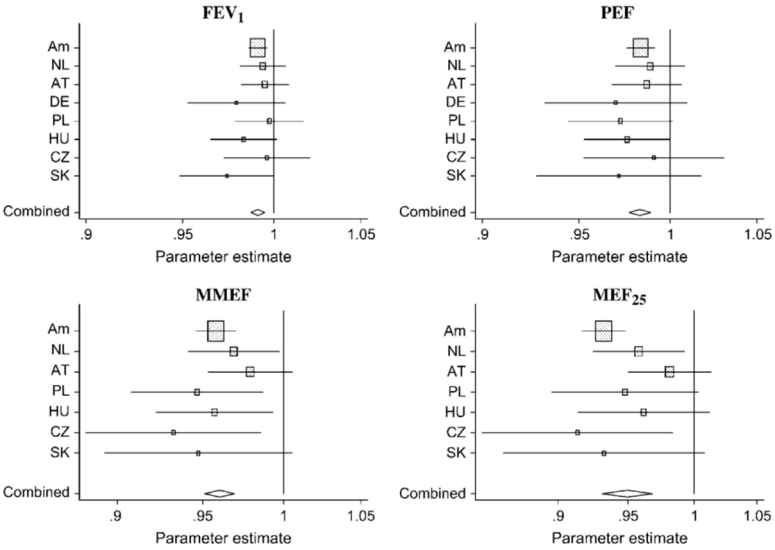


FIGURE 1
Effect of maternal smoking during pregnancy on childhood lung function: A meta-analysis.

formaldehyde in the classroom air and endotoxin in the settled dust affect lung-function negatively (Figure 2). Organophosphorus flame-retardants in the dust affect cognition. Cognition is further affected by room temperature and ventilation rate. While early life exposure to a diverse microbiome might likely protect against later development of asthma and allergies, exposure to higher levels of bacteria (measured through endotoxin in settled dust) in the school has a negative effect on respiratory health (5) and exposure to mould early in life increases the risk of asthma later (6).

We demonstrate that active mobility (walking or cycling) instead of passive mobility (brought by car) on the daily way to school improves physical and mental health (4). The way to school only takes up a short time of daily routine. But exposure on the streets can be substantial and with active

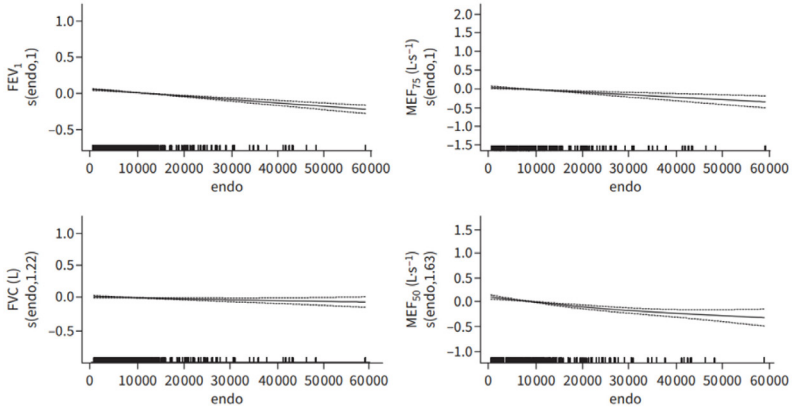


FIGURE 2
Effect of endotoxin in settled dust of classrooms on lung function of children, a multi-country study.

mobility (walking, cycling) ventilation rate will increase thus increasing internal exposure even stronger. Thus, home environment, the way to school, and the school environment act together to shape the health of the children. This is true for long-time somatic health but also for general wellbeing and for mental health including school performance and learning ability.

Conclusion

In multiple campaigns we were able to demonstrate relevant effects of environmental exposures both at home and in the school setting on health and well-being of school-children. School-children are the future of our societies and they deserve the best available environment for their upbringing. Parents, schools, and the society as a whole should stay committed to that goal.

School-age is a developmental period where future behaviour and health trajectories are formed. Life-style, diets, mobility patterns and interests are

shaped and can be influenced by local environmental opportunities and restraints. Thus, the childhood environment extends far beyond the mere physiochemical environment usually considered.

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Air pollution exposure, inhaled doses, and respiratory health: A two-panel study across five European cities

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Abstract

In urban environments, traditional fixed ambient monitoring stations provide an incomplete representation of individual daily environmental

exposure across highly diverse microenvironments (1). This physical and spatial limitation is particularly significant given that modern urban residents spend approximately 90% of their daily lives in indoor environments (2–4), a behavioral trend extensively confirmed by human activity pattern studies in Europe (5).

Even though most exposure occurs indoors, standard environmental regulatory systems rarely account for the indoor environment. Crucially, indoor environmental dynamics are heavily influenced by dwellers´ behaviors and activities, structural housing characteristics, and socioeconomic factors, creating a critical knowledge gap in our understanding of true individual exposure levels (6). Furthermore, population dynamics, such as commuting routines, multi-modal transport usage, and varying daily activities, further complicate the precise determination of personal exposure (6). Consequently, conventional macro-level air quality and noise assessments fail to capture these individual-level nuances (1), justifying the paradigm shift proposed within the HARMONIE project: a personal exposure, context-aware, multi-sensor assessment framework essential for determining the specific contribution of indoor environments and the integrated exposure across environments to adverse health outcomes.

The specific aim of this sub-study within the broader HARMONIE framework is to fully characterize **Indoor Environmental Quality (IEQ).** This multidimensional assessment comprises Indoor Air Quality (IAQ)—specifically measuring oxidative potential (OP), fine particulate matter ($PM_{2.5}$), ultrafine particles (UFP), lung deposited surface area (LDSA), black carbon (BC), nitrogen oxides (NO_x), and ozone (O_3)—alongside structural ventilation adequacy via carbon dioxide (CO_2) and carbon monoxide (CO) concentrations, thermal comfort, and ambient noise levels, all of which directly affect human physiological and psychological well-being (2,7). This sub-study seeks to evaluate how these environmental stressors, acting individually or in combination, impact human biological responses and lung function. To achieve this, human participation is indispensable to non-invasively validate the real-world interactions between localized environmental exposure and direct respiratory health impacts.

The project prioritizes susceptible groups—specifically children and older adults—who are disproportionately vulnerable to urban pollution and systemic environmental stressors. The **central hypothesis of this project posits that acute and short-term exposure to elevated indoor concentrations of these specific pollutants are associated with increased pulmonary oxidative stress and reduction in lung function.** Concurrently, the study aims to prospectively evaluate the short to medium-term (over 6-months) epidemiological impact of these distinct exposures on the clinical control of asthma in children and of chronic obstructive pulmonary disease (COPD) in the older adults.

To evaluate these environmental and health factors, the **HARMONIE project will employ a panel study design consisting of two sub-panels: healthy individuals and individuals with chronic respiratory disease.** This repeated-measures design enables the continuous tracking of exposure and health outcomes across individuals over time. **The study will enroll 15 sick persons and 15 healthy persons across 30 distinct households within each of the five participating pilot cities, establishing an aggregate cohort of 150 households across Europe**. For the purposes of this protocol, "children" are defined as individuals aged 7 to 14 years with and without physician-diagnosed asthma, while "older adults" are defined as individuals aged 65 years and older with and without clinically confirmed COPD.

The five urban pilot sites are strategically distributed to capture geographical, meteorological, and environmental variation across Europe:

- Barcelona (Spain): Focusing on the older adult population (≥65 years) affected by COPD.
- Lausanne (Switzerland): Focusing on the older adult population (≥65 years) affected by COPD.
- Barakaldo (Spain): Focusing on the pediatric population (7–14 years) diagnosed with asthma.

- Gävle (Sweden): Focusing on the pediatric population (7–14 years) diagnosed with asthma.

- Sarajevo (Bosnia and Herzegovina): Focusing on both the pediatric and older adult populations, currently under definition.

This sub-study utilizes a **dual-track data collection framework over a one-week monitoring window per household. Track one gathers Objective indoor environmental data** using high-precision sensors and portable monitors: Bettair sensor for criteria pollutants, Unisanté online analyzer for oxidative capacity, microAeth MA200 for black carbon, Naneos Partector for UFP/LDSA, and TSI IAQ-Calc 7545 for CO/CO_2 and ventilation. Simultaneously, personal NO_2, geolocation, and accelerometry data are continuously recorded. Geolocation estimates out-of-home ambient exposure via HARMONIE spatial-temporal models, while accelerometry estimates minute ventilation. These are integrated with real-time concentrations to compute the Inhaled Dose of Air Pollutants (IDoAP). Concurrently, a technician conducts a baseline home characterization survey. **Track two collects subjective participant data**, capturing real-time perceptions of temperature, ventilation, noise, and crowding via a mobile application to provide a participant-centered perspective.

To accurately establish the Indoor/Outdoor (I/O) relationship, data are complemented by direct home outdoor measurements, where identical monitoring instrumentation will be secured on the immediate exterior elements of the residence, such as balconies or window sills. By integrating direct indoor-outdoor measurements, localized outdoor air pollution modeling, geolocation tracking, and dynamic physical activity levels, the study will calculate and contrast explicit exposure metrics and **IDoAP values for indoor-specific periods versus total daily routines.**

The health outcomes of interest will be assessed on the final day of the one-week intensive exposure window. The primary health markers include the oxidative potential in exhaled air (OPEA), spirometry-based lung function

(FEV_1 and FVC). To capture long-term chronic impacts, a weekly digital questionnaire will be administered over a prospective 6-month follow-up period to all case participants to track real-world exacerbations and overall clinical control of their respective chronic illnesses. Extensive covariates—including age, sex, height,weight, passive smoking exposure, and detailed 7-day activity logs—will be compiled.

This sub-study introduces two innovative approaches to advance environmental health. First, it goes beyond traditional exposure assessments based on outdoor concentrations. It does so by estimating integrated exposure across multiple microenvironments and the Inhaled Dose of Air Pollutants (IDoAP), combining environmental monitoring with physical activity. Second, it bridges exposure and health outcomes through concurrent assessments of OPEA, a novel biomarker, and spirometry. This case-control protocol will provide a high-resolution dataset linking microenvironmental exposures with biological responses and health. These findings will deliver crucial epidemiological evidence to calibrate HARMONIE predictive models, offering urban planners and health authorities a robust framework to transition toward healthy, resilient environments.

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Does a high air infiltration rate improve indoor air quality?

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Barbero Barrera, M.M., Alou Cervera, L., Sánchez-Reyes, E., Sabariego Moreno, K., Pérez-Moneo, B., Aparicio, M. Does a high air infiltration rate improve indoor air quality?

Abstract
Construction techniques are influenced by societal changes as well as advancements in regulations. In Europe, 85% of buildings were constructed before 2000 and commonly exhibit poor energy performance. With regard to energy efficiency, four different periods can be identified in Spain:

i) Until 1940–1950, when traditional construction systems and materials, mainly mineral-based, were used;

ii) From 1960 to 1980, when buildings were primarily constructed with concrete structures and increasingly reduced envelopes. The 1973 energy crisis led to the approval of the first energy standard in 1979;

iii) From 1980 to 2006, when the use of thermal insulation became compulsory, with limitations regarding envelope thermal transmittance;

iv) From 2006 to the present, when several regulations have been following successive energy efficiency directives, aiming to reduce buildings' energy dependence and limit greenhouse gas (GHG) emissions.

These regulations improve energy efficiency by reducing thermal transmittance and air infiltration rates. The Spanish Technical Building Code limits thermal envelope air permeability according to building compactness and window airtightness depending on climatic zones. However, do these energy efficiency standards take indoor air quality into account? Does improving energy efficiency necessarily imply better indoor air quality?

Environmental quality has a significant influence on physical activity, social relationships, mental health, and neurological development. Schools are particularly relevant environments for children., where learning conditions influence their physical and mental well-being (2, 3). Moreover, school buildings have a high retrofit potential to reduce energy consumption and ensure adequate thermal conditions for students. In Spain, non-residential buildings account for 13% of total floor area but are responsible for 42% of final energy consumption (4). However, energy retrofits that do not consider future climate scenarios may lead to worse thermal conditions than before intervention (5). But what about indoor air quality?

This study aims to analyze the relationship between building air infiltration rates, indoor biological air pollutants, and reported health outcomes among schoolchildren, comparing schools with different construction characteristics.

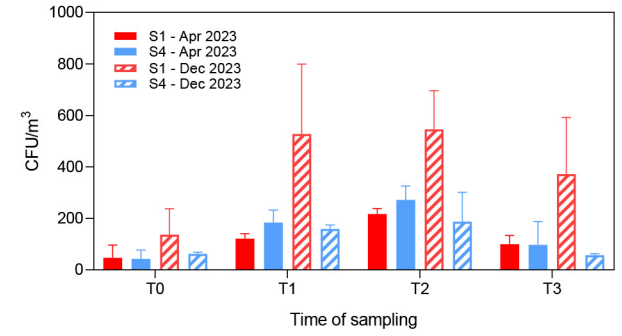
A holistic assessment was conducted in two classrooms from two schools: one built before the first energy efficiency regulation (1968), referred to as S1, and another built after it (2001), referred to as S4. Air infiltration was measured according to UNE EN ISO 9972:2019 (UNE, 2019), with a

Minneapolis Blower Door system. The results showed 4.3 h^{-1} for S1 and 9.7 h^{-1} for S4. Contrary to expectations, the newer building exhibited higher air infiltration rates. To evaluate the influence of infiltration on indoor air quality, biotic contaminants (bacteria, fungi and pollen) and abiotic parameters (VOCs, ultrafine particles, PM, CO_2, temperature and relative humidity) were monitored (6). For bacterial and fungal analysis, two indoor air samples were collected at four times: before school starts (T0), before the break and window opening (T1), at the start of afternoon classes (T2), and after the end of classes (T3) using a Millipore Air Tester® (M Air T) impactor (7). Pollen was measured with a Burkard personal volumetric air sampler at T0 and T2. These data were then cross-analyzed with health questionnaires completed by the students' families after each campaign, to explore associations between IAQ and reported symptoms.

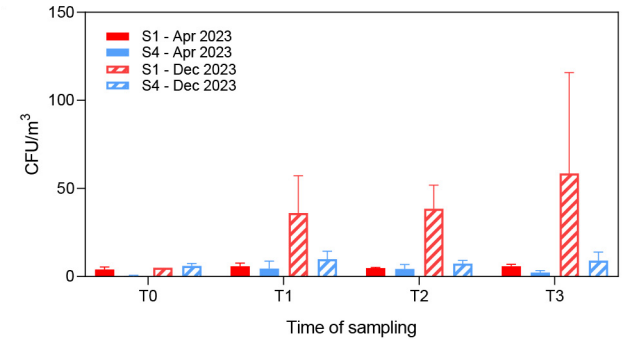
Abiotic pollutants showed similar values (Table 1) regardless of the construction period, highlighting their dependence on indoor activities (6). These values are consistent with previous studies (8, 9). No significant differences were observed in pollen levels.

TABLE 1: Abiotic concentration of pollutants

		TVOCs (ppb)	UFP (pt/cm^3)	$PM_{0.3}$ (pt/cm^3)	$PM_{2.5}$ (pt/cm^3)	CO_2 (ppm)	T(ºC)	HR (%)
S1	April	105	8135.03	25.19	21.45	1123.28	23.89	29.52
	Dec.	12	5747.78	696.80	49.05	2048.46	19.91	61.82
S4	April	98	8426.14	14.78	20.06	1071	26.88	28.16
	Dec.	13	6331.83	229.25	26.20	1897.70	20.44	55.04



a)



b)

FIGURE 1
Mean counts (CFU/m³) in indoor air samples throughout the day from the two schools and campaigns (April and December 2023). **(A)** Mean bacterial counts; **(B)** Mean fungal counts.

However, bacterial and fungal counts differed notably (Figure 1): S1 showed higher concentrations than S4 during occupied periods (T1 and T2) and even after classes (T3). Wang et al. (10) demonstrated that higher air exchange

rates can mitigate the effect of occupant density on indoor bacterial levels. In our study, S1 showed infiltration rates (4.3 h^{-1}), within the range reported for Mediterranean housing (7.1 h^{-1}) and the NBE CT-79 buildings (6.8 h^{-1}) (11). S4 showed 9.7 h^{-1}, consistent with CTE-HE buildings (average 8.9 h^{-1}) (11).

Lower infiltration rates are known to improve energy efficiency (12), but they also reduce air renewal, which may explain the increased CO_2, $PM_{0.3}$ and bacterial concentrations observed in S1, particularly in December. Bacterial and fungal concentrations increased throughout the day during winter, especially in S1.

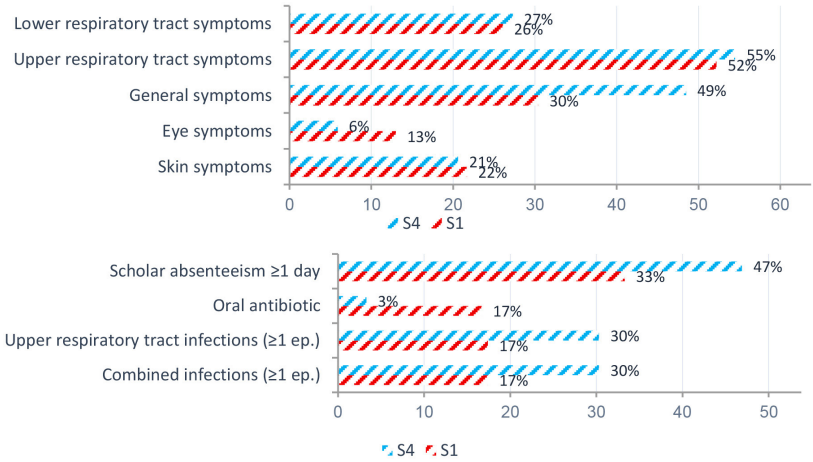


FIGURE 2
Symptoms and infections. **(A)** Symptoms prevalence by group. Percentage of students with ≥1 symptom in each category. December 2023. n = 23 (S1), n = 33–34 (S4). No statically significant differences were observed in any of the analyzed symptoms. **(B)** Infections, use of medicines or school absenteeism together with the types of infections. Upper respiratory tract infections affect only the upper respiratory tract, whereas combined infections also involve the lower respiratory tract, including pneumonia. Percentage of students affected. December 2023.n = 23 (S1), n = 30–34 (S4). Percentages were calculated over the total number of children with valid data for each variable. No statistically significant differences were observed.

From a health perspective, detected microbial levels were generally below pathological thresholds, suggesting no clear association with reported diseases (Figure 2).

There was no clear relationship between the higher fungal concentration observed in some campaigns (December, S1 and T3) and diseases. Concentrations were only slightly above 100 spores/m^3; *Alternaria spp.* has been linked to allergic asthma and rhinitis above this threshold. However, it was not the only type of fungus detected.

One of the main findings was that newer buildings are not necessarily more airtight than older ones Furthermore, although current regulations aim to improve energy efficiency by reducing air infiltration, this approach may have unintended consequences for indoor air quality, including increased microbial concentrations. These results highlight the importance of achieving an appropriate balance between airtightness, ventilation, energy performance and occupant health in the design and refurbishment of school buildings. However, this analysis was based on only two schools. Further research involving a larger and more diverse sample of buildings is needed to confirm the robustness and generalizability of these results.

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Attributable burden from indoor air pollution across four European countries: A multi-centre study

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Abstract

Background

Individuals spend nearly 90% of their time indoors, whether at home, at work, or in public spaces like schools, hospitals, and public transport, thus poor indoor air quality (IAQ) has become a significant concern (1). Indoor environments are often more complex and variable than outdoor ones, as the sources and concentrations of pollutants can differ widely across different buildings and even within various areas of the same building. Indoor air pollution emerges as a critical public health issue recognised globally, which poses a significant risk for several leading causes of death and disease. According to the World Health Organization (WHO), more than 3 million people die prematurely each year due to indoor air pollution (2). Both outdoor and indoor air pollution continue to contribute to several health-related conditions, such as cardiovascular diseases, like stroke and ischemic heart disease (IHD), respiratory diseases, such as chronic obstructive pulmonary disease (COPD) and asthma, cognitive impairments and even cancers (2). Household air pollution deserves particular attention, being responsible for an estimated 2.9 million deaths in 2021, including over 309 000 deaths of children under the age of 5 (3). This is attributable to the inefficient combustion of fuels and the utilisation of technologies in and around the home that are themselves sources of pollution. The combustion of such fuels and technologies results in the release of pollutants that are health-damaging, including fine particulate matter ($PM_{2.5}$) that can penetrate deep into the lungs and bloodstream, damaging multiple organs.

Methods

As part of the European K-HEALTHinAIR project, the health burden attributable to indoor air pollution was estimated using a comparative risk

assessment framework. Indoor levels of $PM_{2.5}$, PM_{10}, and formaldehyde were measured across four European countries participating in the project. Baseline health data, including years of life lost (YLLs) and years lived with disability (YLDs), were obtained from the Global Burden of Disease Study 2023, while exposure–response functions for mortality and morbidity were derived from robust epidemiological evidence (4). YLLs and YLDs for respiratory, cardiovascular, metabolic, and neurological outcomes attributable to indoor $PM_{2.5}$ exposure were estimated by multiplying the population attributable fraction (PAF) by the corresponding baseline health values. Attributable disability-adjusted life years (DALYs) were subsequently calculated as the sum of attributable YLLs and YLDs.

Results

Across all countries and exposure scenarios, $PM_{2.5}$ produced the highest estimated health burdens, substantially exceeding those associated with PM_{10} and formaldehyde. Poland presented the largest overall burden, particularly under the household scenario, where $PM_{2.5}$ exposure was associated with approximately 457,374 from ischaemic heart disease (IHD), 340,464 from stroke, 216,671 from diabetes, 180,566 from lung cancer, and 47,593 from dementia. PM_{10} in the same scenario accounted for lower but still substantial burdens (78,028 for IHD, and 47,184 for lung cancer). Under the school scenario in Poland, $PM_{2.5}$-related IHD reached 414,589, together with stroke (273,152), and lung cancer (191,888). Spain also showed elevated household $PM_{2.5}$ burdens, notably for ACM (635,343 DALYs), IHD (147,859), stroke (111,936), and lung cancer (116,017), whereas Austria reported markedly lower values (62,449 DALYs for ACM; 27,045 for IHD). In the Netherlands, only household $PM_{2.5}$ estimates were available, indicating around 7,700 DALYs from COPD. Formaldehyde exposure was predominantly linked to asthma, with lower burden (approximately 6,365 DALYs in Poland, 8,758 in Spain, and 1,732 in the Netherlands).

Conclusions

The results demonstrate that cardiovascular outcomes, particularly IHD and stroke, together with diabetes, account for much of the attributable burden.

These findings align with the growing body of epidemiological evidence showing that particulate matter affects multiple physiological systems beyond the respiratory tract. $PM_{2.5}$ was identified as the dominant driver of the indoor air pollution–related health burden, reinforcing the need for targeted mitigation strategies in residential and school environments. Findings support the urgent need for improved indoor air quality management, particularly in homes and schools, where the greatest burdens were observed. At the same time, they highlight the importance of generating more robust scientific evidence to reduce current uncertainties and strengthen future indoor air quality policies and interventions. In conclusion, the results of the K-HEALTHinAIR project provide strong evidence that indoor air pollution continues to represent a significant public health challenge across Europe.

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Oscillometry in chronic respiratory diseases: Towards improved standardization for clinical practice

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Citation
González-Colom, R., Gómez-López, A., Soler, N., Sánchez-Ruano, N., Rodríguez-Sufuentes, S., Sorribes, M., Vela, E., Piera-Jiménez, J., Fermoso, J., Roca, J., Cano, I., Farre, R., Arismendi, E. Oscillometry in chronic respiratory diseases: Towards improved standardization for clinical practice.

Abstract

Background

Oscillometry is a non-invasive pulmonary function technique that assesses respiratory system mechanics during spontaneous breathing by applying small pressure oscillations at the mouth and measuring the resulting respiratory response. Unlike forced spirometry, which requires a sustained and technically demanding expiratory manoeuvre, oscillometry requires minimal patient cooperation and can therefore be performed in patients with different levels of functional capacity and in non-specialist, community, or home-based settings. Oscillometry provides complementary information to forced spirometry by characterizing respiratory system resistance and reactance. In particular, reactance-related measures such as X_5 and the area of reactance (AX) may provide information on peripheral airway and lung mechanical abnormalities, including small airway dysfunction. This is of particular interest in chronic respiratory diseases such as COPD, asthma, and bronchiectasis, in which abnormalities of the small airways may contribute to respiratory impairment but may not be fully captured by conventional spirometric measurements. Despite increasing clinical and research interest and the availability of international technical standards, the broader

implementation of oscillometry remains challenging. Interpretation involves multiple parameters, measurement quality can be affected by artefacts and intra-session variability, and the clinical meaning of changes over time is not always straightforward. These challenges are particularly relevant when oscillometry is considered for repeated or longitudinal monitoring, including community- and home-based assessment. Within the EU project KHEALTHinAIR, oscillometry was incorporated into the follow-up of the Barcelona Pilot cohort to explore relationships between indoor air quality (IAQ) and small airway dysfunction not detectable by forced spirometry.

Objective

To investigate refinements in oscillometry analysis and reporting aimed at improving repeatability, interpretability, and clinical applicability.

Methods

In 170 patients with COPD (n=89, 52%), asthma (n=59, 35%), or bronchiectasis (n=22, 13%), oscillometry, forced spirometry and symptom assessments were obtained at baseline, mid-term and final follow-up over a median 602 days. Separately, intra-individual repeatability was assessed in dedicated analyses using daily measurements over two weeks and monthly measurements over six months. Three oscillometry-related domains were evaluated: (1) intra-breath analysis, comparing inspiratory and expiratory phases; (2) modelling strategies to derive a single composite oscillometry score; and (3) intra-individual variability. Outcomes were assessed across three clinical scenarios: bronchodilator response, longitudinal follow-up, and community-managed exacerbations.

Results

Intra-breath analysis showed differences between inspiratory and expiratory phases, consistent with respiratory hysteresis. However, ΔX_5 and ΔAX showed substantial day-to-day variability in the daily repeatability analyses, with coefficients of variation (COV) of 200% and 70%, respectively. Multiple signal spikes were also observed in a subset of recordings, suggesting potentially avoidable artefacts and the need for improved signal-quality control.

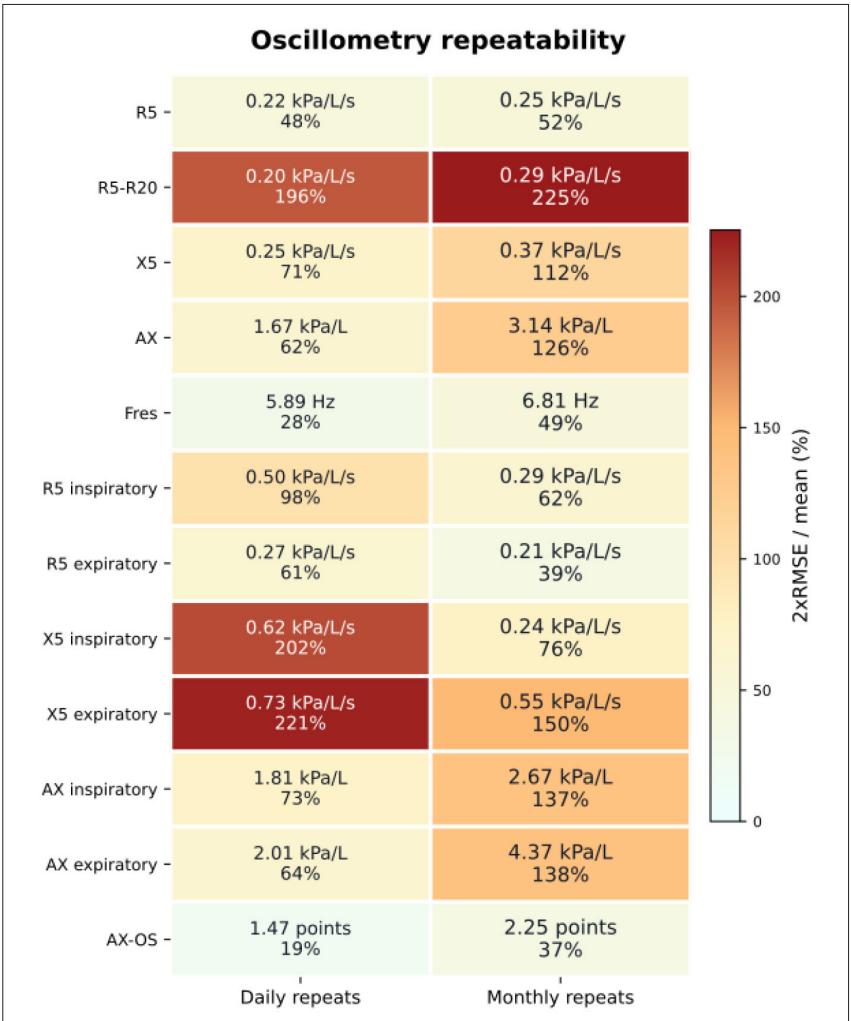


FIGURE 1
Heatmap displaying daily and monthly intraindividual variability results, expressed as 2RSME and Coefficient of Variation (COV%), for the different oscillometry parameters assessed in the current study.

To simplify the interpretation of oscillometry, several candidate modelling strategies were evaluated. AX-OS was the best-performing candidate composite index. It is a 0–10 score derived from the AX z-score and calibrated against spirometric impairment, with higher values indicating a greater probability of lung function impairment. AX-OS showed good discrimination for spirometric impairment (AUC 0.895) and a more compact repeatability profile than conventional oscillometry variables. In the daily repeatability analysis, AX-OS showed a COV of 19% (Figure 1). These findings suggest that a composite score based on AX may provide a more consistent and clinically interpretable summary of oscillometry measurements. In the bronchodilator-response assessment, AX-OS decreased following bronchodilator administration, while home-based oscillometry was feasible during community-managed exacerbations within the nurse-led hybrid care model. [1-5].

Conclusions

The findings support: (1) the implementation of specific strategies to reduce intra-session variability in oscillometry, particularly through optimization of AX-derived measures; and (2) simplified clinical reporting approaches. Composite indices such as AX-OS demonstrated superior repeatability and responsiveness across the three clinical scenarios assessed. AX-OS may improve interpretability and longitudinal assessment; however, remains an exploratory index derived and internally validated in a single cohort, and independent validation in larger multicentre studies is required before routine clinical adoption.

Trial Registration

NCT06421402.

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Household air quality in chronic obstructive respiratory diseases: Actionable insights for clinical practice

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Citation
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Abstract

Background

Inhalation of airborne irritants is a major driver of disease onset and progression in susceptible individuals. In some regions (e.g., Asia and the Andes), indoor air pollution related to traditional cooking practices represents a major risk factor for respiratory disease among non-smokers. In contrast, in Western countries, household indoor air quality (IAQ) has received considerably less attention than outdoor air quality (OAQ). Consequently, household IAQ profiles and their health impact in patients with chronic respiratory diseases and multimorbidity remain insufficiently characterized.

Objective

This study aimed to: (1) characterize household IAQ profiles and their determinants; (2) explore associations between IAQ and clinical outcomes; and (3) develop practical recommendations to improve household IAQ.

Methods

This prospective observational study included 205 participants from the Barcelona cohort, followed over a two-year period (2024–2025). Home IAQ was monitored using low-cost sensors (LCS) (MICA, inBiot) in patients recruited from two clinical programs: (1) a community-based program (n=152, 77%) including patients with COPD, bronchiectasis, or asthma and associated co-morbidities; and (2) a hospital-based Severe Asthma Unit (n=53, 23%). Household IAQ monitoring included CO_2, formaldehyde, $PM_{2.5}$, PM_{10}, temperature, humidity, and total volatile organic compounds (VOCs). IAQ data were interpreted according to the Global Open Air Quality Standards (GO-AQS). OAQ data (AerisWeather platform), were available for indoor–outdoor analyses. Household environmental characteristics were assessed using an observational checklist. Longitudinal clinical data included health status, clinical events, lung function testing (spirometry and oscillometry), pharmacological treatment, and healthcare resource utilization across care settings. Associations between IAQ and subsequent clinical burden were analyzed using adjusted logistic regression models.

Results

The final study population comprised 162 patients (community-based program: 74%; severe asthma program: 26%). Median follow-up was 616 days (IQR 397–715). Mean household IAQ values exceeded low-risk GO-AQS thresholds for $PM_{2.5}$ in 71 homes (44%), CO_2 in 16 homes (10%), and formaldehyde in 16 homes (10%). Distinct day–night pollutant patterns were observed for CO_2, formaldehyde, and $PM_{2.5}$. Associations between IAQ and OAQ were characterized, and seasonal effects were also explored. Smoking inside the home emerged as the strongest determinant of poor IAQ, being associated with markedly higher $PM_{2.5}$ levels compared with non-smoking households (daytime: +188%; nighttime: +211%) (Figure 1). In addition, parquet flooring was significantly associated with higher nighttime

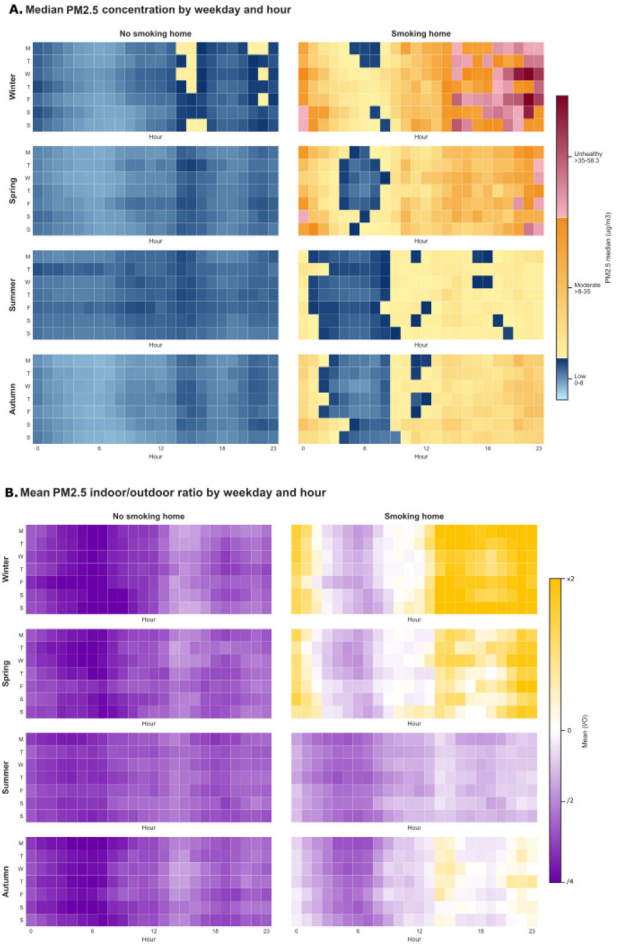


FIGURE 1

Temporal, seasonal, and source-related PM2.5 patterns according to household smoking status. Panel A: median indoor PM2.5 concentrations by weekday and hour, stratified by season and smoking. Panel B: mean indoor-to-outdoor (I/O) PM2.5 ratio.

formaldehyde concentrations (+21%). Health status–related variables showed consistent associations with baseline morbidity, previous severe exacerbations, and healthcare resource utilization; however, no significant associations were observed between poor household IAQ and subsequent clinical burden [1-4].

Conclusions
A substantial proportion of households showed chronic exposure to indoor air pollutants. LCS proved useful for identifying key determinants and temporal patterns of poor household IAQ, thereby supporting the development of targeted preventive strategies with potential benefits for respiratory health. Further research addressing the human exposome and the long-term health effects of chronic indoor pollutant exposure is warranted.

Registration
NCT06421402.

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Session 3 – Low-Cost Sensors and Continuous IAQ Monitoring

Portable air purifiers as a mitigation strategy for $PM_{2.5}$ exposure in residential wood-heating environments: A comparative case study

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Citation

Kristian, A., Rogulski, M., Heß, D., Lehmann, M., Moshammer, H., Badyda, A. Portable air purifiers as a mitigation strategy for $PM_{2.5}$ exposure in residential wood-heating environments: A comparative case study.

Abstract

Residential wood combustion represents an important source of indoor particulate exposure in many homes, particularly where combustion appliances are located close to occupied living spaces. Fine particulate matter ($PM_{2.5}$) emitted from residential wood-burning systems is of concern because of its well-established associations with adverse respiratory and cardiovascular health outcomes and its contribution to household exposure under everyday living conditions (1–4). Indoor $PM_{2.5}$ concentrations in wood-heated homes may vary substantially according to source proximity, building layout, room-to-room air mixing, occupant activities, and air-cleaner operation characteristics. Real-world studies have shown that wood-stove use can lead to pronounced indoor particle accumulation events in occupied homes, highlighting the importance of source location and household-specific conditions in shaping exposure patterns (5,6). Portable air purifiers are increasingly used as a practical exposure mitigation strategy in residential environments, and previous studies have shown that portable HEPA-based as well as combined filtration systems can reduce indoor $PM_{2.5}$ concentrations under real-world conditions (7–10). However, evidence remains limited for comparative residential scenarios in which baseline exposure conditions differ according to the location of the wood-heating source relative to the living area.

The present work aimed to evaluate the effect of portable air purifier operation on indoor $PM_{2.5}$ concentrations in two residential wood-heating environments with contrasting exposure conditions and to compare whether the relative reduction in $PM_{2.5}$ differed between households. The study additionally examined purifier performance under two filter configurations, namely HEPA-only and combined HEPA/activated carbon filtration, under occupied real-world residential conditions. Continuous indoor air quality monitoring was conducted in two households using sensor devices (*Kaiterra Sensedge Mini*) with one-minute temporal resolution. Household 1 represented a higher-exposure setting, with a wood-burning stove located on the same level as the living area, whereas household 2 represented a

lower-exposure setting, with the wood-based heating system located in the basement. In both households, purifier performance was assessed during sequential operation with HEPA-only and HEPA/activated carbon filters and compared with corresponding periods from the previous year without purifier operation. For both intervention periods, 138 days were included in the comparison. $PM_{2.5}$ was selected as the primary outcome variable because it is the main particulate pollutant associated with residential wood smoke and the principal target of portable air cleaning technologies (2,3,7-10). The two households further differed in purifier operating level, room size, purifier placement, spatial layout, door status, and cooking frequency, all of which were considered relevant contextual factors in the interpretation of between-household differences.

Portable air purifier operation was associated with substantial reductions in indoor $PM_{2.5}$ concentrations in both households. In Household 1, mean $PM_{2.5}$ concentrations during the HEPA comparison period decreased from 32.08 $\mu g/m^3$ in the 2024 reference period to 9.31 $\mu g/m^3$ during filter operation in 2025, corresponding to a relative reduction of 70.99%. During the combined-filter comparison period, mean $PM_{2.5}$ concentrations decreased from 70.24 $\mu g/m^3$ to 9.60 $\mu g/m^3$, corresponding to a relative reduction of 86.33%. In Household 2, mean $PM_{2.5}$ concentrations during the HEPA comparison period decreased from 5.67 $\mu g/m^3$ to 1.65 $\mu g/m^3$, corresponding to a relative reduction of 70.86%. During the combined-filter comparison period, concentrations decreased from 9.06 $\mu g/m^3$ to 2.82 $\mu g/m^3$, corresponding to a relative reduction of 68.84%. Differences between baseline and intervention periods were statistically significant in both households for both filter configurations (all Mann–Whitney U tests, $p < .001$). Comparison between households therefore showed nearly identical relative reductions during HEPA-only operation, but a markedly greater relative reduction in Household 1 than in Household 2 during operation with the combined HEPA/activated carbon filter, with a between-household difference of 17.49 percentage points.

The intervention was additionally associated with a marked reduction in the daily share of time spent above the $PM_{2.5}$ threshold of 15 µg/m^3 (3). The mean daily exceedance shares above this threshold decreased from 0.32 to 0.10 and from 0.57 to 0.11 in Household 1, corresponding to reductions of 68.75% and 80.70% during HEPA and combined-filter operation, respectively. In Household 2, corresponding exceedance shares decreased from 0.06 to 0.01 and from 0.17 to 0.03, corresponding to reductions of 83.33% and 82.35%. These differences were statistically significant for both households and both filter configurations ($p \leq .005$). Taken together, the results indicate that portable air purifier operation reduced not only average $PM_{2.5}$ concentrations but also the duration of elevated exposure periods in both residential settings.

The findings suggest that portable air purifiers may provide a feasible strategy for reducing indoor $PM_{2.5}$ exposure in residential wood-heating environments, while also highlighting that observed effectiveness may be shaped by residential context and by the selected outcome metric. In particular, source location relative to occupied space, purifier operating level, room size, purifier placement, and the degree of spatial separation or air mixing between rooms may all influence the extent of measurable improvement. The higher purifier operating level used in Household 1 may also have contributed to the stronger reduction observed for mean $PM_{2.5}$ during the combined-filter period. At the same time, the threshold-based analyses indicate that reductions in elevated exposure durations were in several cases comparable across households and, for selected thresholds, even greater in Household 2. The study is limited by its case-study design, the inclusion of only two households, and the potential confounding introduced by year-to-year comparison. Nevertheless, the study provides ecologically relevant evidence from occupied residential settings that are often underrepresented in controlled filtration studies, indicating that the benefits of portable air purification in wood-heated homes are context-dependent.

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Air purifiers as a means to improve air quality in challenging environments

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Citation
Heß, D., Lehmann, M., Vaghasiya, R., Kristian, A., Rogulski, M., Moshammer, H., Badyda, A. Air Purifiers as a means to improve air quality in challenging environments.

Abstract
Densely occupied spaces such as school classrooms often suffer from elevated airborne particle concentrations, as many people share a confined volume of air over several hours. Natural ventilation is the simplest remedy, but weather, outdoor pollution, and noise frequently make it impractical. In these cases, portable air purifiers with high-efficiency particulate air (HEPA) filtration offer an effective alternative for reducing indoor particle levels.

Yet the benefit achieved depends strongly on correct operation, including proper sizing, placement, fan mode, and timely filter maintenance. This presentation shares findings on how air purifiers can be operated reliably to deliver consistent, measurable improvements in air quality.

This study evaluates how air purifiers contribute to reducing particle and gaseous concentrations within a room, and how potential user faults can influence their effectiveness. The user errors examined include wet filters, incorrect flow direction, low bypass, and a hole or cut in the filter element, each of which can significantly reduce the performance of the device. In addition, the investigation assesses the usability of low-cost sensors from Kaiterra and Inbiot for monitoring air quality. Finally, the noise pollution generated by the air purifiers during operation has been investigated in relation to its performance, since acceptable sound levels are essential in a learning environment.

As a first measure to assess the effectiveness of air purifiers, controlled experiments were conducted. For this, the mixing chamber of a HVAC test system from Topas ALF 114, usually used for air filter evaluation accord ing to ISO 16890/ EN 779, has been repurposed as testing chamber. For this experimental series, the chamber has been sealed to form a closed system. Two particle sources have been added, one generating courser KCl particles, the other finer DEHS droplets. All particles generated were smaller than 10 µm, but DEHS has a higher fraction of <1mm. The particle concentration is measured by the two low-cost sensors (Kaiterra Sensedge Mini and InBiot MICA) as well as a lab grade particle counter (Klotz Abakusmobil Air). For each experimental run, the air purifier (MANN+HUMMEL SQ500) is set to a specific power setting (Level 1 to 4 and auto) and run until no particles are detected by the sensors. Then, a burst of particles is introduced for 10s and the air purifier keeps running until the concentration is near zero again. The decay curve is measured and recorded.

The Clean Air Delivery Rate (CADR) is then calculated using the following equation:

$$CADR = (k - k_n) \times V$$

$$with\ k = -\frac{ln(\frac{Cend}{C0})}{tend - t0}$$

with k (kn) being the velocity constant of the (natural) decay, V the Volume of the mixing chamber, time t and particle concentration C at the start (0) and the end (end) of the experiment. The CADR can then be put into relation to noise pollution or electrical power demand.

Firstly, the results show that the inherent recirculation of air through the air purifier led to really robust operation (compare Figure 2). Even with a 15cm cut in the filter element, the CADR is not affected much. Over all investigated error modes, a maximum deviation in CADR of 12% has been identified without a clear pattern if the CADR is increased or decreased. Therefore, we assume fluctuations are of statistical nature. Interesting to note is, that the wet filters did not lead to water penetration to critical electric components, somewhat protecting the AP from introduces liquids.

Considering the energy consumption the pattern is pretty clear: There is a more or less linear correlation between the CADR per electrical power and the power level. In terms of electricity consumption, the optimal operation therefore is clearly to run the air purifier at the highest level for a shorter amount of time (compare Figure 1).

We get similar results when investigating the CADR per noise emission: When dividing the CADR by the emitted noise power in W (not the logarithmic dB value), we get a similar result than with the power consumption. When running the AP at full power for a shorter amount of time it will emit less sound energy than with a lower power setting (compare Figure 1) However, as noise is highly subjective, we did see complaints for the higher power levels, that can exceed 60 dB. Therefore, still the best course of action is to run the AP at the highest acceptable level to obtain minimal cleaning time.

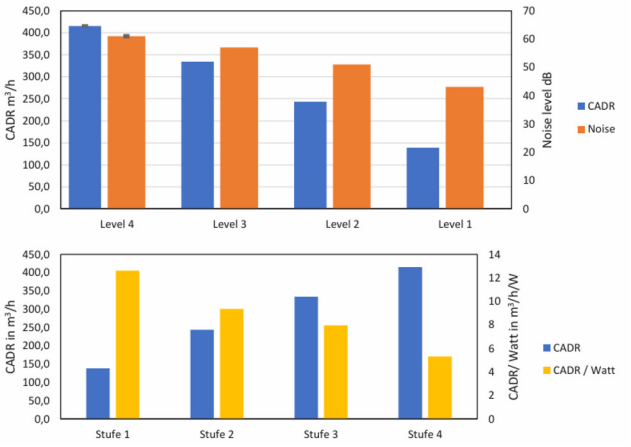


FIGURE 1
CADR in ratio to the electrical power (top) or noise emission (bottom).

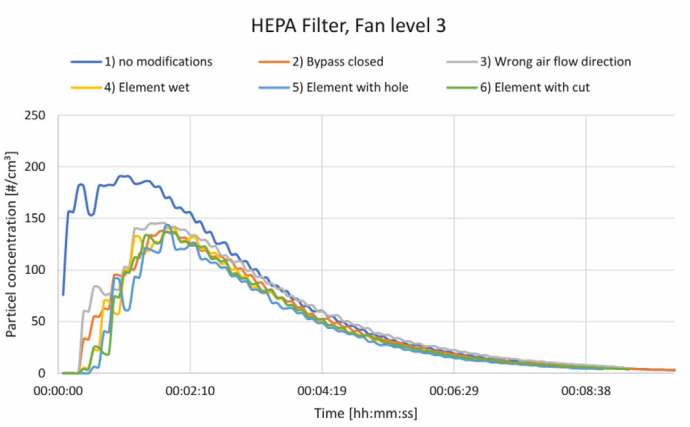


FIGURE 2
Decay curve for various error modes for power setting 3 of the AP.

In regards to the performance of the low-cost sensors, the experiments show, that trends and qualitative analyses can be successfully detected by the sensors. However out of the box absolute values are not accurate enough to obtain scientific significance, as the sensors assume a mean density of the particles to obtain the $\mu g/m^3$ value displayed and recorded. As the particle system in these experiments is well known, we could obtain this mean density accurately and with a conversion factor we could successfully fit the low-cost sensor data with the lab equipment. Therefore, with proper calibration, the low-cost sensors can yield value above trends and qualitative analyses.

The experiments conducted show, that air purifiers can be operated in challenging environments prone to mis use and unintended damage without compromising the air quality by a lot. The power consumption is best minimized by running at high power settings, e.g. when there is noise present anyways, such as in brakes. In quiet phases, the AP has to be kept down, but a pre cleaning in anticipation of a quite phase could be helpful here.

Strengths and weaknesses of air quality sensors

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Citation
Moshammer, H., Kristian, A., Mediavilla Martinez, C. Strengths and weaknesses of air quality sensors.

Abstract

Background

Every indoor space potentially has its own specific sources of pollutants that can affect indoor air quality. Therefore, no two indoor spaces are alike. While outdoor air quality can be assessed with relatively few monitors, a separate measuring device would be required for each indoor space. This necessitates cost-effective and user-friendly sensors that provide information for research, education, public awareness campaigns, and ultimately, regulations, such as those governing building product standards, ventilation standards, or smoking bans, in public indoor spaces.

Methods

Within the framework of the EU-funded project K-HEALTHinAIR, we investigated the performance of cost-effective and user-friendly sensors from various manufacturers: Kaiterra Sensedge Mini, inBiot MICA plus, and TSI AirAssure. Measurements were conducted in schools and private households in Austria over a period of three years. Depending on the sensor

type, the measurement data was recorded every minute or every 5 or 15 minutes. Hourly data on outdoor air quality were also collected. Correlations and relationships between indoor and outdoor air data, between different indoor air quality indicators, and between different sensors were examined. In addition, spot samples were taken from indoor air and analysed by GC-MS for volatile organic compounds (VOC). Sums of volatile organic compounds (VOCs) were compared to the same-time sensor readings of total VOC (TVOC). Historical trends in the VOC spectrum from building products were analysed from more than 1000 measurement data over more than 20 years from Austria.

Results 1

The temperature and relative humidity data appear to be accurate. CO_2 levels, which serve as an important indicator of ventilation, are reliable. Parallel measurements by different sensors are highly correlated. CO_2 levels are strongly affected by ventilation rates. In the homes and classrooms examined, ventilation rate was controlled by opening or closing windows. In the Alpine climate, windows are more likely opened during warmer periods and therefore, CO_2 levels were negatively correlated with outdoor temperature (−4.6 ppm per 1° increase).

Results 2

Trace concentrations of more complex gaseous pollutants or particles still pose a challenge for existing sensors. Because these are passive devices without a mechanical pump or airflow, the sensors rely on natural indoor air circulation and therefore do not achieve the same precision as expensive active measuring devices. Electrochemical measurement methods are not fully specific. For example, the formaldehyde sensor also reacts to other aldehydes or amides. The VOC sensor reacts to various volatile organic compounds with varying sensitivities, preventing a reliable estimate of the total VOC concentration.

Correlations of TVOCs values between sensors were usually poor. Kaiterra reported two different TVOC values with the second one based on an

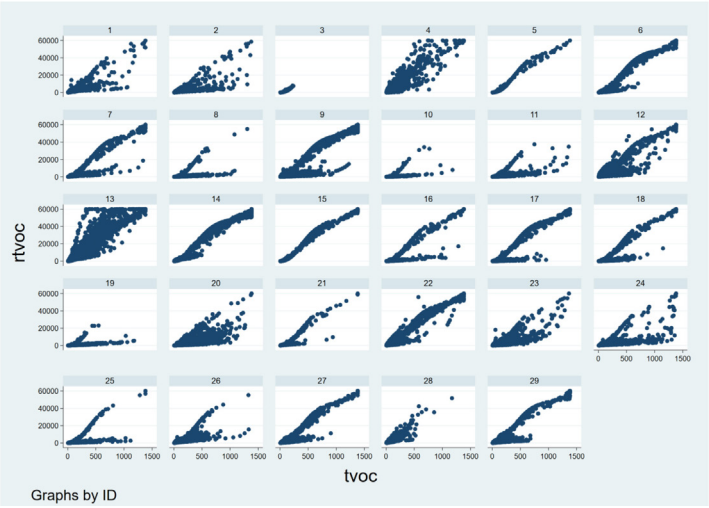


FIGURE 1
Correlation between "old" and "new" TVOC levels in 29 homes.

"improved formula". The formula seems to include the sensor signal plus temperature and humidity data, because in linear regression of the old on the new TVOCs value, these parameters are also significant. The new value usually reports a more plausible magnitude (0 – 1500 µg/m^3) compared to the old value (0 – 60,000 µg/m^3), but both values show practically no correlation with the sum of VOCs collected at the same time period. The new and old TVOCs value are correlated with each other, but there appears to be deviation from linearity (Figure 1).

According to Kaiterra, TVOC sensors have been calibrated to represent the 22 VOC mixture suggested by Molhave et al. (e.g., 1). But it is likely that the VOC spectrum in building products has changed substantially in the last 30 years. To demonstrate that we performed a principal component analysis (PCA) of the historical data and investigated the association between the

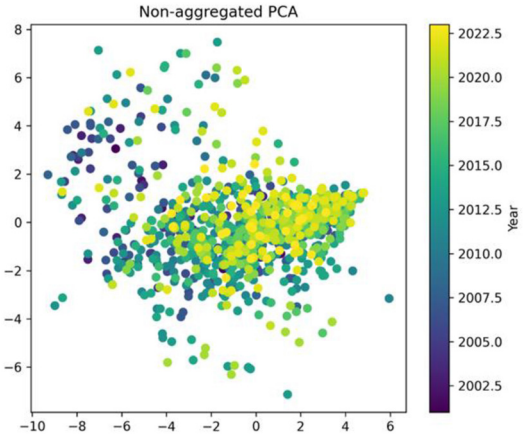


FIGURE 2
Principal Component Analysis of VOC spectra by year of measurement.

first component (which explained about 50% of the variance) and the year of measurement (Figure 2). We found a weak though highly significant correlation indicating a temporal shift in the VOC spectrum and providing proof that the Molhave mixture is no longer representative of current exposures.

Results 3

The particle sensor appears to count the number of particles, but manufacturers convert the sensor signal into a mass concentration. Not surprisingly, PM10 and PM2.5 are therefore highly correlated with each other (r=0.99). Indoor PM levels depend on outdoor levels, are affected by ventilation rate and by indoor humidity, are higher in smokers' households and, in winter, in homes using solid fuels. Air filtration devices lower PM levels consistently.

Discussion

Any sensor signal can be relevant. For assessing health effects, particle count is often more informative than particle mass, as many small particles have

stronger biological effects and penetrate deeper into the respiratory tract (2, 3). Different VOCs differ substantially in their toxicological profile. Any single sensor technology (in the case of Kaiterra a Multi-pixel metal oxide sensor) responds to a certain chemical reaction which might, e.g., be based on some oxidisation process. This chemical reaction, although it might not be representative of all existing VOCs, might by itself also have a direct health relevance. Therefore, the relevance of this sensor signal should be analysed rather than that of a spurious TVOCs value.

Sensor manufacturers should provide the raw sensor data, not just derived values, which are inevitably less accurate. Although calibration measures may hinder the user-friendliness of applications, regular calibration should be possible to verify sensor validity and control for potential drift. While sensors still need improvement in terms of reliability and precision, they are already well-suited for educational and awareness-raising purposes. For example, we observed very high particle concentrations in smokers' homes. Demonstrating these high levels prompted the smokers to at least change their behaviour and smoke outdoors. This led to a significant reduction in particulate matter pollution; however, smokers' households still exhibit significantly higher particle concentrations than non-smokers' households.

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Assessment of indoor environmental quality in a windowless university classroom with low-cost multi-sensors in İzmir, Türkiye

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Citation
Ayri, İlknur., İritepe, Buse., Sofuoglu, Sait C. Assessment of indoor environmental quality in a windowless university classroom with low-cost multi-sensors in İzmir, Türkiye.

Abstract
Educational facilities represent unique indoor environments characterized by high occupant density and prolonged exposure durations. Students and educators typically spend up to six–eight hours daily in classrooms, rendering these spaces among the most consistently occupied within the institutional sector (1,2). Sustained exposure to sub-optimal environmental conditions over such periods can substantially increase health risks, elevate absenteeism rates, and reduce overall learning efficiency (3–5). Therefore, a comprehensive understanding of the parameters governing these microenvironments is essential.

Indoor air quality (IAQ) plays a critical role in influencing student health, well-being, and academic performance. Students who spend extended periods

in enclosed spaces are particularly susceptible to inadequate ventilation and indoor air pollution, especially in mechanically ventilated classrooms where air exchange relies entirely on the system. Despite growing attention to IAQ, spatial variations within classrooms remain largely unexplored.

This study investigates IAQ in a windowless university classroom (capacity: 72 students; dimensions: 9.0 × 6.7 × 3.5 m) relying solely on mechanical ventilation, examining pollutant dynamics and spatial gradients under varying occupancy conditions. A four-week monitoring campaign was conducted using Atmocube low-cost sensors during low- and high-occupancy periods. Parameters measured included CO_2, particulate matter (PM), volatile organic compounds (VOCs), formaldehyde, noise, light, temperature, and humidity. Correlation and spatial analyses were performed to characterize IAQ patterns.

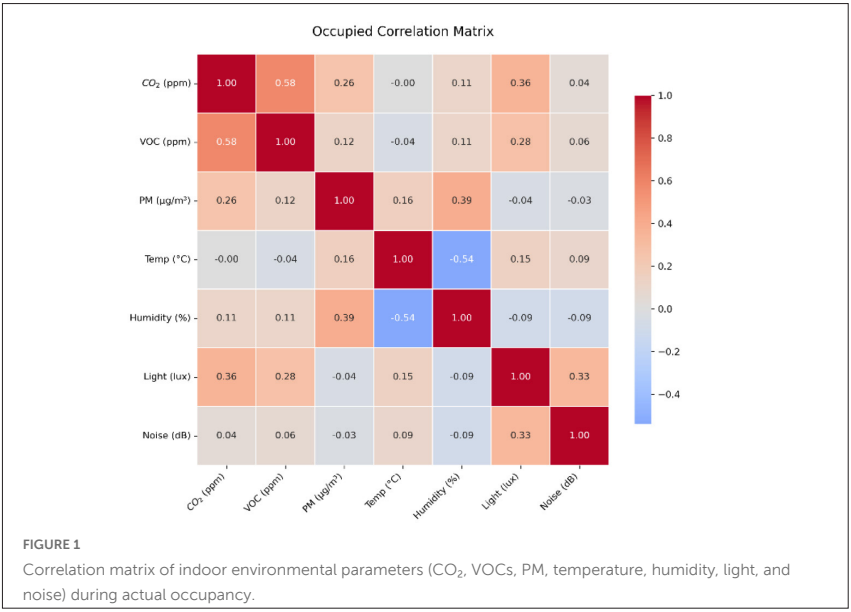


FIGURE 1
Correlation matrix of indoor environmental parameters (CO_2, VOCs, PM, temperature, humidity, light, and noise) during actual occupancy.

Pollutant levels increased notably during occupied periods. The average CO_2 concentrations rose from 442 ppm to 830 ppm (88% increase), with peaks exceeding 2000 ppm, indicating insufficient ventilation. The mean PM levels increased from 2.2 μg/m^3 to 4.5 μg/m^3 (100% increase), with peaks exceeding 12 μg/m^3. During unoccupied periods, strong correlations between VOCs and temperature (r = 0.84) and temperature and humidity (r = -0.84) indicated thermal-driven conditions (Fig. 1). Occupancy weakened these relationships, introducing moderate correlations between CO_2 and VOCs (r = 0.58), reflecting human-related emissions. Spatial analysis revealed IAQ gradients, with areas near the door meeting ASHRAE Category II standards, degrading to Category III toward the back (Fig. 2).

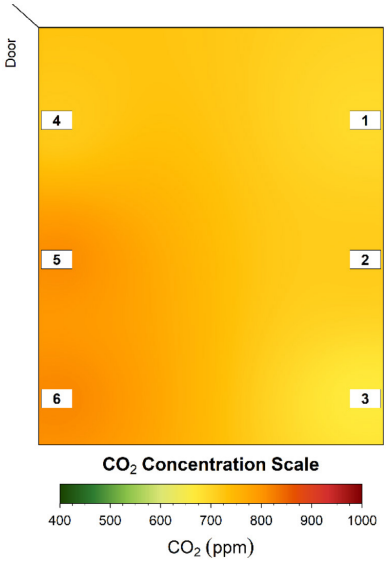


FIGURE 2
Spatial distribution of indoor CO_2 concentrations during actual occupancy (heat map).

Even in mechanically ventilated environments, existing systems may fail to adequately maintain IAQ during occupancy.

Findings emphasize the critical need for evaluating ventilation performance in association with spatial variation in IAQ and occupant comfort in enclosed educational spaces.

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Evaluation and monitoring of indoor environmental quality in the pathology department at Río Hortega University Hospital (Valladolid)

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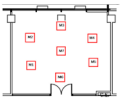
Citation

San José-Alonso, J.F., Arroyo Gomez,, Y., Rey-Martínez, F.J., Cardillo Lorente, J.C. Evaluation and monitoring of indoor environmental quality in the pathology department at Río Hortega University Hospital (Valladolid).

Abstract

This study was conducted over two weeks. This paper presents a one-day monitoring of contaminant concentration levels in the sample processing

TABLE 1: Pollutant concentration measurement results

	Gases	M1	M2	M3	M4	M5	M6	M7
	CO_2 (ppm)	444,6	382,0	469,6	395,0	419,5	437,2	435,4
	CO (ppm)	4,7	5,9	6,3	6,6	6,7	6,9	7,1
	HCHO (ppb)	0	0	0	0	0	0	0
	NO_2 (ppm)	0	0	0	0	0	0	0
	O_3 (ppm)	1,0	1,0	1,0	1,0	1	1	1
	VOC (ppb)	253,9	202,6	202,4	188,8	190,9	274,3	189,6

room of the Pathology Department at the Río Hortega University Hospital (HURH) in Valladolid. The analysis focuses on average concentration levels recorded at 15-minute intervals, obtained with an indoor air quality probe that captures data through eight smart sensors. These sensors measure temperature, relative humidity, and the concentration of volatile organic compounds, nitrogen dioxide, carbon dioxide, formaldehyde, ozone, and carbon monoxide. The study examines the relationship between these concentrations and four key factors: the operational status of the laboratory's fume hoods, the number of occupants in the room, their spatial distribution, and the type of activity being performed. Table 1 presents concentration values measured at seven different locations within the room.

The Pathology laboratory at HURH (Figure 1) processes approximately 20,000 biopsy samples annually (1). The department employs around 30 staff members, including 14 laboratory technicians, 9 pathologists, and administrative personnel. The activities conducted in these facilities involve the handling of chemical substances and biological samples(2-4), which can generate significant levels of indoor air pollution. If ventilation systems are inadequate, these pollutants may pose health risks to workers (5-9). Among the chemicals commonly used during sample preparation are formaldehyde (formalin), nitric acid, formic acid, ethanol, toluene, xylene, Harris hematoxylin, and eosin (10-12).



FIGURE 1
The Pathology laboratory at HURH.

The study began by defining the indoor environmental quality requirements for grossing rooms in pathology departments. To establish these criteria, a comprehensive review of international standards and guidelines was conducted, including Spanish regulations (UNE, RITE, and EsSalud), as well as American (ASHRAE), German (DIN), French (NF), and British standards. The most stringent requirements for each parameter were selected as reference values.

Measurements were then carried out over a full working day using a GrayWolf Gas monitoring device, which continuously recorded key environmental parameters. These included relative humidity (RH, %), temperature (°C), carbon monoxide (CO, ppm), carbon dioxide (CO_2, ppm),



	8:15	8:30	8:45	9:00	9:15	9:30	9:45	10:00	10:15	10:30	10:45	11:00	11:15	11:30	11:45	12:00	12:15	12:30	12:45	13:00	13:15	13:30	13:45	14:00	14:15
CONCENTRACIÓN MEDIA (ppm)	104,8	98,3	119,7	101,2	85,2	136,4	160,6	128,0	99,0	102,4	93,7	110,4	134,2	107,6	104,3	103,2	139,5	106,0	99,7	113,6	104,0	99,9	98,9	99,6	137,5
personas/sala	4	3	5	4	4	6	4	5	5	5	4	1	1	2	3	5	4	4	7	4	3	4	5	2	1
Estado Campana izq	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON
Estado Campana derecha	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON
ACTIVIDADES REALIZADAS	C	EHI	C	HI	EHI	CD	CHI	EHI	C	FG	FG	C	C	C	C	CE	K	CE	J	J	HI	HI	HI	J	EHI
	C	EHI	C	C	HI	CD	CHI	J	C	C	J			CD	CD	CD	CD	CD			FG	FG	FG		J
	C	HI	J	FG	CD	CD	FG	EHI	C	K	K				J	G	FG	J			C	C	C		
	HI		HI	EHI	FG	J	J	J	FG	C						J	C	J				J	K		
			EHI			C		HI	C	J							FG					J	J		
						J			A													C			

FIGURE 2
Evolution of TVOCs in the carving room of the pathology service.

total volatile organic compounds (TVOCs, ppb), ozone (O_3, ppm), formaldehyde (HCHO, ppm), and nitrogen dioxide (NO_2, ppm). Simultaneously, detailed records were kept regarding the operational status of extraction hoods, the number and position of personnel in the room, and the activities being performed.

The results were analyzed with particular attention to periods during which Threshold Limit Values (TLVs) were exceeded. The study identifies the main contributing factors to these peak exposure events, highlighting the influence of inadequate extraction performance, high occupancy, and specific tasks involving intensive chemical use (Figure 2). Based on these findings, corrective measures are proposed to mitigate exposure peaks. These include optimizing the use and maintenance of laboratory fume hoods, improving general ventilation, and adapting work practices to reduce the release and accumulation of airborne contaminants.

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Design and deployment of a low-cost sensor network for continuous indoor–outdoor air quality monitoring

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Citation

Domat, M., González-Plaza, E., Menéndez-Rubiera, A., Fernández-Aybar, A., Rodríguez-Larrad, I. Design and deployment of a low-cost sensor network for continuous indoor–outdoor air quality monitoring.

Abstract

Indoor air quality (IAQ) has become a major public health concern due to the well-established association between airborne particulate matter (PM) exposure and adverse respiratory and cardiovascular outcomes (1–3). While reference monitoring stations provide highly accurate measurements, their limited spatial coverage restricts the assessment of indoor–outdoor pollution dynamics and population exposure. Recent advances in low-cost sensing

technologies have enabled the development of dense monitoring networks capable of providing continuous, distributed, and affordable air quality information (4–6).

This work presents the design, implementation, validation, and field deployment of a modular low-cost sensor network intended for continuous indoor–outdoor air quality monitoring. The system was developed in Gijón (northern Spain), a coastal urban environment with strong industrial activity.

Each sensing node integrates a LilyGO T3 microcontroller, an SDS011 optical particle sensor for $PM_{2.5}$ and PM_{10} monitoring, and a BME280 environmental sensor for temperature, relative humidity, and atmospheric pressure measurements (Fig.1). The hardware architecture was specifically designed to minimize power consumption while maintaining reliable long-

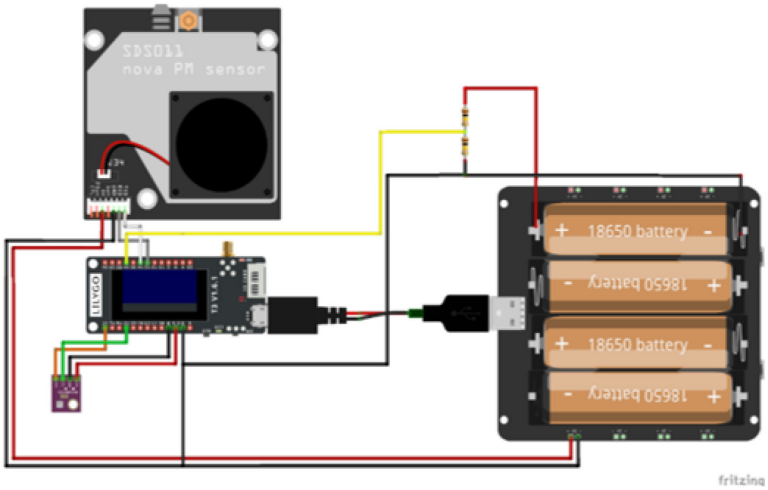


FIGURE 1
Sensors System Architecture.

term operation. Depending on the installation requirements, nodes can be powered using rechargeable batteries, power banks, photovoltaic systems, or direct grid connection. Particular attention was paid to affordability and replicability, resulting in a complete sensing node with a cost below €200, substantially lower than most commercial air quality monitoring solutions.

Communication is achieved through LoRaWAN technology, enabling long-range data transmission with very low energy consumption. Data management was initially implemented using a fully open-source architecture in which sensor nodes transmitted data through The Things Network (TTN) to a local processing pipeline based on Node-RED for data acquisition, InfluxDB for time-series storage, and Grafana for visualization and remote monitoring. In the current deployment, this infrastructure has been replaced by the SensorLabs cloud platform, which integrates data ingestion, storage, visualization, and device management within a single environment. Sensor nodes continue to communicate through TTN, while SensorLabs provides a centralized dashboard for real-time monitoring, historical data access, geolocation, and sensor fleet management.

This transition reduced infrastructure maintenance requirements and improved scalability, accessibility, and long-term management of the sensor network.

The selected sensing architecture follows the philosophy of large-scale citizen science initiatives such as Sensor.Community (7), one of the largest collaborative air quality monitoring networks in Europe, which has demonstrated the potential of low-cost technologies for distributed environmental monitoring. Building on this approach, several nodes have been deployed both indoors and outdoors, including educational facilities participating in local MediaLab activities (8), a university-led citizen science and innovation platform where students are involved in sensor assembly, deployment, and interpretation of air quality data in scholar centres. This educational dimension provides a valuable opportunity to increase environmental awareness while generating locally relevant IAQ information.

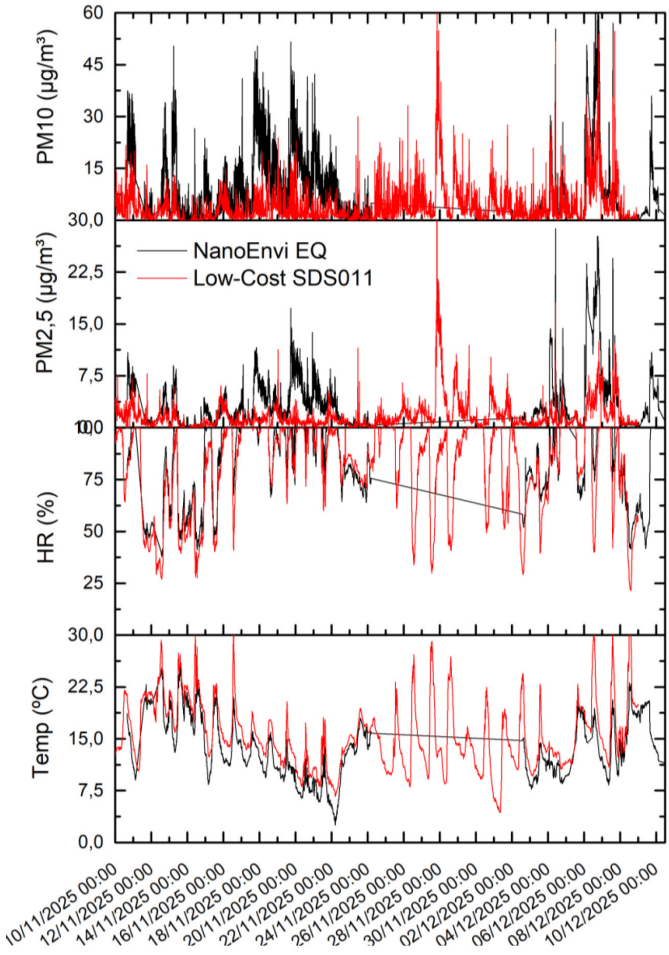


FIGURE 2
Data comparison between sensor data and commercial sensor.

Seven sensing nodes were manufactured and progressively deployed in different environments, including classrooms, university facilities, urban outdoor locations, and elevated sites, 4 of them have been working non-stop for more than a year. The deployment phase provided valuable information regarding communication reliability, power autonomy, environmental exposure, maintenance requirements, and long-term operational robustness.

Sensor performance was evaluated through laboratory calibration and field co-location experiments. In Fig. 2 the results of the comparison between one of the proposed sensors and a calibrated commercial one Nanoenvi EQ (Envira) are depicted. Results showed good correspondence between the two sensors allowing for inter-sensor repeatability and consistency under controlled conditions. Nonetheless, some concentration-dependent biases and humidity-related effects were observed in the tests, confirming previous findings reported for optical PM sensors. Individual calibration procedures significantly reduced inter-unit variability and improved agreement among devices.

Humidity was identified as one of the main factors affecting sensor performance (9). Under high-humidity conditions, particle hygroscopic growth increased optical scattering signals and introduced measurement biases that varied among instruments. This is particularly important when the relative humidity presents values over 70%. Below that level the different is not as significant in absolute terms. It is also interesting to note that for values of over 90% the discrepancies do not increase showing an average value of 7.8 $\mu g/m^3$. These findings highlight the need for environmental correction procedures when low-cost optical sensors are used in long-term IAQ applications.

The results demonstrate that reliable indoor–outdoor particulate matter monitoring can be achieved using affordable, open-source, and easily replicable technologies. Beyond hardware development, the study highlights the importance of calibration, deployment strategy, communication infrastructure, and user engagement as key elements for successful monitoring networks.

The proposed platform provides a scalable solution for IAQ assessment, exposure studies, citizen science initiatives, educational environments, and healthy building applications. Future work will focus on network expansion, advanced calibration methodologies, integration of additional environmental sensors, and the development of predictive tools capable of identifying pollution episodes and supporting air quality management strategies.

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Linking human activities to indoor air pollutant peaks: Preliminary results from a diary study in polish and Austrian households

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Citation

Mucha, D., Kristian, A., Kępa, P., Rogulski, M., Muszyński, A., Doskocz, N., Moshammer, H., Badyda, A. Linking human activities to indoor air pollutant peaks: Preliminary results from a diary study in polish and Austrian households.

Abstract

Background

Indoor air quality (IAQ) is strongly influenced by everyday household activities that can generate short-term but substantial increases in indoor pollutant concentrations. While many studies focus on background indoor pollution levels, less attention has been given to the characterization of pollution peaks associated with routine human activities in real-life residential settings (1,2,3,4). Understanding these events is essential for assessing occupant exposure and identifying effective mitigation strategies.

Objectives

This study aimed to investigate the relationships between specific household activities and short-term changes in indoor air quality parameters in occupied dwellings in Poland and Austria. Particular attention was given to identifying activity-specific pollution signatures and evaluating pollutant persistence in the absence of effective ventilation.

Methods

As part of a diary-based monitoring study, residents recorded daily household activities while indoor air quality was continuously monitored using low-cost sensors (Kaiterra). Measurements included particulate matter (PM_1, $PM_{2.5}$, PM_{10}), total volatile organic compounds (TVOCs), carbon dioxide (CO_2), relative humidity (RH), and temperature. This abstract presents three illustrative case studies: (1) birthday cake sparkler candle use, (2) indoor laundry drying, and (3) cooking involving frying and boiling on an electric cooker.

Results

The use of birthday sparkler candles resulted in the most pronounced deterioration of indoor air quality. Within 5–10 minutes after ignition, PM_1, $PM_{2.5}$, PM_{10} concentrations increased by approximately 109-fold, 109-fold, and 103-fold, respectively, reaching peak values of 656 $\mu g/m^3$, 1,094 $\mu g/m^3$, and 1,500 $\mu g/m^3$. TVOC concentrations increased from 672 ppb to 2,307 ppb, while CO_2 rose by approximately 30% above baseline. Elevated $PM_{2.5}$ concentrations persisted for more than two hours, and TVOCs remained elevated for approximately three hours in the absence of ventilation.

Indoor laundry drying produced a distinct pollution pattern characterized by increased mainly TVOC concentrations and a slightly increased humidity. Relative humidity increased from approximately 34% to 37.8%, reflecting sustained moisture release from wet textiles. TVOCs showed the strongest response, increasing from baseline values of 150–200 ppb to peaks exceeding 1,300 ppb, representing a 6–8-fold increase. Elevated concentrations persisted for several hours. Particulate matter levels remained largely unchanged.

Cooking activities generated substantial increases in both particulate matter and gaseous pollutants despite continuous operation of a kitchen hood. TVOCs increased from approximately 170 ppb to 2,810 ppb (16-fold increase), while $PM_{2.5}$ and PM_{10} rose from approximately 3 $\mu g/m^3$ to 52 $\mu g/m^3$ and 76 $\mu g/m^3$, respectively. Relative humidity increased by 16 percentage points due to steam generation. Pollutant concentrations required several hours to return to pre-activity levels despite mechanical extraction.

Across all case studies, pollutant generation occurred rapidly, whereas pollutant removal was considerably slower. The observed recovery times indicate that short-term household activities can contribute substantially to cumulative indoor exposure.

Conclusions

Common household activities can generate significant short-term indoor pollution episodes, often resulting in pollutant concentrations substantially above background levels. Each activity exhibited a distinct pollution signature: sparkler candles produced extreme particulate matter peaks, cooking generated combined PM and TVOC emissions, and laundry drying primarily increased TVOCs. In all cases, pollutant concentrations remained elevated for extended periods when ventilation was insufficient. These preliminary results highlight the importance of incorporating real-world occupant activities into indoor air quality assessments and support the development of source-specific mitigation measures, particularly improved post-activity ventilation strategies.

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$PM_{2.5}$ and CO_2 in Polish schools: Two years of measurements

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Rogulski, M., Kępa, P., Kristian, A., Muszyński, A., Mucha, D., Lehmann, M., Heß, D., Badyda, A. $PM_{2.5}$ and CO_2 in Polish schools: Two years of measurements.

Abstract

Children spend a large part of their waking hours in schools, making indoor air quality in classrooms a crucial determinant of their health, well-being, and cognitive performance. In Poland, most school buildings rely on natural ventilation. Moreover, many schools have high children density in their classrooms. This leads to widespread and, to date, insufficiently studied

indoor air quality problems. Numerous studies have shown that elevated CO_2 concentrations are linked to impaired cognitive function, lower academic performance, and increased absenteeism (1-4). Exposure to elevated concentrations of particulate matter in school environments has been associated with increased prevalence of respiratory symptoms, including coughing, wheezing, and exacerbation of asthma (5-6).

The present work aimed to comprehensively characterize CO_2 and $PM_{2.5}$ concentrations in Polish schools (named SCH01-SCH08), identify diurnal and seasonal patterns of variability, assess ventilation effectiveness against international guidelines, and determine the impact of outdoor air quality on indoor $PM_{2.5}$ levels.

Continuous IAQ monitoring was conducted at 23 monitoring points located in seven schools in the Warsaw metropolitan area between January 2024 and December 2025 using commercially available low-cost sensor devices (Kaiterra). Monitoring systems incorporated sensors for carbon dioxide (CO_2), particulate matter (PM_1, $PM_{2.5}$ and PM_{10}), temperature, and relative humidity. Hourly average concentrations were analyzed, broken down by school day (6:00–15:59) and school holidays, taking into account diurnal, seasonal, and inter-facility variability.

During school days, elevated and highly variable CO_2 concentrations were observed across all monitored schools (Fig. 1). CO_2 concentrations in the school with the worst air quality were almost twice as high compared to the school with the best air quality. Mean values ranged from 642 ppm at SCH08 to 1,191 ppm at SCH07. In five of the seven schools, mean concentrations exceeded 900 ppm, while two schools exceeded 1,000 ppm, considered by the WHO to be unacceptably high. Maximum hourly CO_2 concentrations reached extremely high levels, ranging from 2,137 ppm at SCH03 to 5,306 ppm at SCH07 — values far exceeding recommended indoor air quality limits. Percentile analysis showed that 90th percentile concentrations exceeded 1,600–1,800 ppm in most schools and surpassed 2,100 ppm at SCH07, indicating that for at least 10% of school hours, children were exposed to

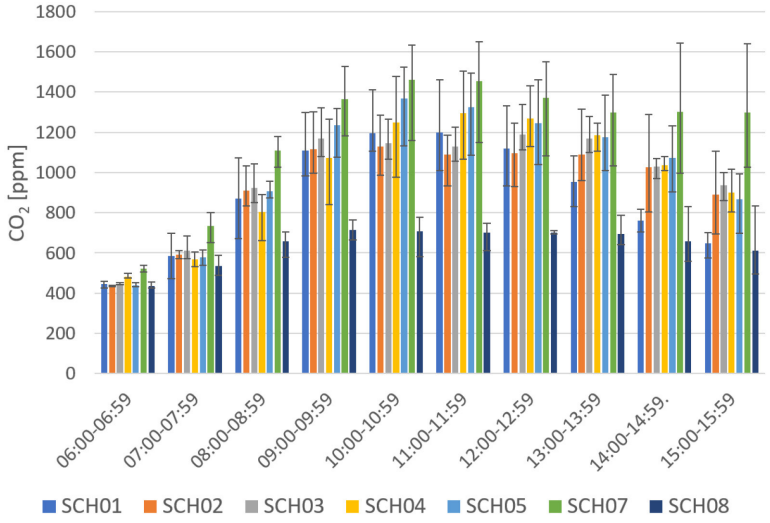


FIGURE 1
Mean hourly CO_2 concentrations on school days (06:00-15:59) by school.

very poor air quality conditions. Concentrations recorded in December were two to three times higher than in June, indicating a clear influence of the heating season. On non-school days, CO_2 levels remained low (421–470 ppm), confirming the dominant role of building occupancy.

Mean $PM_{2.5}$ concentrations during school days ranged from 11.4 μg/m^3 (SCH08) to 17.1 μg/m^3 (SCH02). Unlike CO_2, $PM_{2.5}$ distributions were strongly positively skewed, with medians substantially lower than means and large standard deviations reflecting episodic pollution events. Maximum hourly values ranged from 112.1 μg/m^3 (SCH07) to 204.0 μg/m^3 (SCH02). A critical observation is the minimal difference between school-day and non-school-day $PM_{2.5}$ concentrations. Mean values on non-school days (11.3–16.3 μg/m^3) were only marginally lower than on school days, and in some schools (SCH03, SCH04) non-school-day means were comparable to or even slightly higher than school-day values.

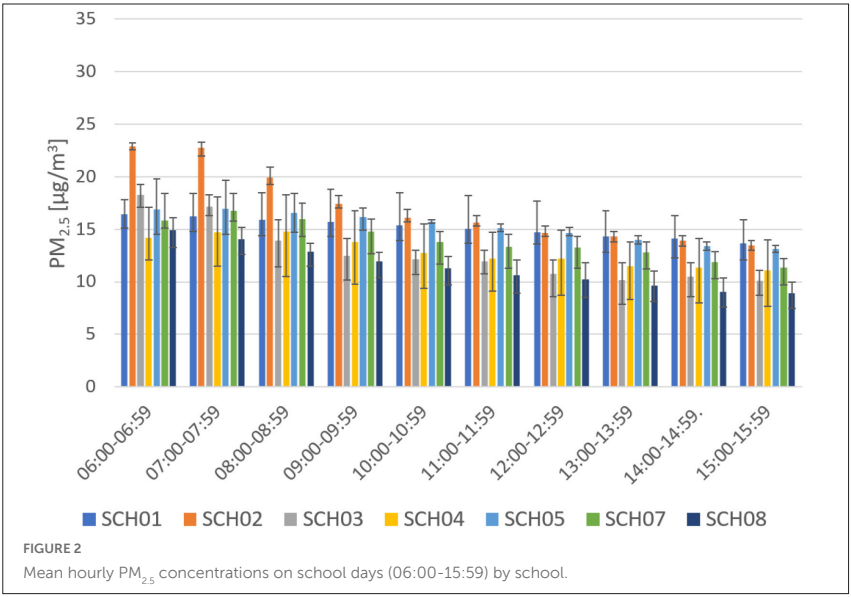


FIGURE 2
Mean hourly $PM_{2.5}$ concentrations on school days (06:00-15:59) by school.

Analysis of diurnal variability reveals a clear pattern of changes in $PM_{2.5}$ concentrations over time (Fig. 2). The highest mean values were observed in the early morning hours, particularly between 06:00 and 7:59, where mean concentrations are approximately 17.02 and 16.89 µg/m^3, respectively. As the day progresses, a gradual decrease in $PM_{2.5}$ levels was observed, with the lowest mean values recorded in the afternoon, especially between 14:00 and 15:59. Monthly, variations in concentration levels were visible between the analysed periods. Data for March and December were characterized by significantly higher values, both in terms of average and maximum values. In March were recorded the highest values in the entire dataset, reaching over 40 µg/m^3 in the morning in some schools. December also showed elevated levels, although less extreme than March, while maintaining relatively high stability of values throughout the day.

Concentration levels were significantly lower in the warmer months of June and September. June was characterized by the lowest values of all the analysed months, with many observations in the range of around 9–12 µg/m^3, and the lowest range of variability. September occupied an intermediate position – values were higher than in June but lower than in the colder months, and the data distribution remained relatively centered around the mean.

This study shows that elevated CO_2 concentrations are common in naturally ventilated school environments, frequently exceeding widely referenced indoor air quality thresholds. As a result, children are regularly exposed to suboptimal indoor air quality during school hours. Strong seasonal differences and substantial variability between classrooms indicate that adequate ventilation is not consistently achieved, particularly during the heating season. These patterns reflect both structural and operational limitations in schools that rely primarily on natural ventilation.

Indoor $PM_{2.5}$ concentrations were largely independent of occupancy and closely tracked outdoor levels, confirming ambient air as the primary source of PM's in these naturally ventilated buildings. The strong indoor–outdoor correlation, validated against concurrent data from the referential monitoring network, indicates that reducing children's $PM_{2.5}$ exposure in schools requires addressing outdoor emission sources — particularly residential solid fuel heating — in addition to building-level interventions. The opposing source profiles of CO_2 and $PM_{2.5}$ create a ventilation–filtration dilemma: increasing air exchange to reduce CO_2 may simultaneously elevate indoor $PM_{2.5}$ during outdoor pollution episodes. This dilemma cannot be resolved by natural ventilation alone and underscores the need for integrated mechanical ventilation systems incorporating heat recovery and supply air filtration, which enable simultaneous control of both indicator gases and PM's.

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Mitigating personal air pollution exposure: A 12-month trial of portable monitors

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Abstract
The study is highly relevant to the Healthy Indoors conference, as it explores the use of personal air quality monitors to better understand individual exposure and support informed mitigation strategies. Over the past few decades, ambient monitoring has evolved from costly, stationary government networks to compact, affordable Personal Air Quality Monitors (PAQMs). Driven by rapid advancements in sensor component downsizing (10), microelectronics (21), and advanced data processing capabilities (12), portable devices now allow individuals to gauge localized, real-time exposure profiles across varying environments (8). These technologies have contributed significantly to the promotion and use of personal monitoring low-cost devices among the general population (28).

The PAQMs have several advantages over conventional methods (13, 21, 28). These devices serve as crucial assets for mapping hyper-local pollution

hotspots, differentiating indoor from outdoor contributions, and revealing hidden indoor pollutant sources (18, 23, 24). Previous research indicates that individual exposure levels often vary substantially from stationary ambient monitors (19), with outdoor fine particulate matter ($PM_{2.5}$) tightly modulating indoor spaces via building infiltration mechanisms such as cracks, building pressures, effective leakage area (ELA), and Air Change per Hour (ACH) (4, 5, 6). Simultaneously, human respiration builds indoor carbon dioxide (CO_2) burdens under limited ventilation conditions (20, 22), which are strongly linked to diminished cognitive performance and an elevated risk of airborne pathogen transmission (2, 7, 15, 18, 32).

Despite the widespread commercial adoption of consumer-grade sensor technology, a detailed long-term exploration of the practical trade-offs and usability challenges of consumer-grade technology still remains less explored (16). This study addresses this gap through an intensive, one-year case study simultaneously documenting personal mitigation strategies for both $PM_{2.5}$ and CO_2 in Spain, exhibiting the inherent conflict between air filtration and ventilation.

A continuous 367-day personal monitoring protocol was implemented between July 5, 2024, and July 7, 2025. Measurements were obtained on weekdays in Granada, Spain and on weekends in Almería, Spain. Two distinct commercial PAQMs were paired simultaneously and maintained within a strict 5-meter proximity to the participant's body. The first PAQM examined was an Atmotube Pro measuring $PM_{2.5}$, temperature, humidity, and air pressure. Researchers (27) demonstrated that Atmotube Pro sensors provide $PM_{2.5}$ measurements with good precision and close match with reference monitors. The second selected PAQM was an AIRVALENT device measuring CO_2, temperature, humidity, and air pressure. Another group of researchers (33) demonstrated that its Sensirion SCD41 CO_2 sensor presents a strong correlation ($R_2 > 0.99$) with research-grade instruments. Both devices were set to a 10-minute sampling interval.

The Atmotube Pro was collocated against an equivalent reference Beta Attenuation Monitor (BAM), showing a significant linear correlation (R^2 = 0.73, $p < 2.2 \times 10^{-16}$). The unexplained 27% variance was linked to local high relative humidity, which triggers hygroscopic PM particle swelling and optical sensor over-read biases (17). Because the sensor was not exposed to harsh environments for a prolonged time, sensor drift was non-existing (29, 9). The AIRVALENT sensor was cross-validated against a gold-standard Dual Beam Nondispersive Infrared (NDIR) reference instrument, demonstrating excellent agreement (R^2 = 0.98).

Data analysis was conducted using RStudio, adopting specific packages for air quality data processing and visualization, including openair (11), Tidyverse, lubridate, and ggplot2. Exposure limit interpretations referenced guidelines from the WHO (31) and GO IAQS (14). The processed data gave an annual average exposure of 4.4 µg/m^3 for $PM_{2.5}$, which successfully fulfills the recommended threshold of 5 µg/m^3 by the WHO. Calendar visualizations (Figure 1) confirmed complete compliance with daily thresholds, never

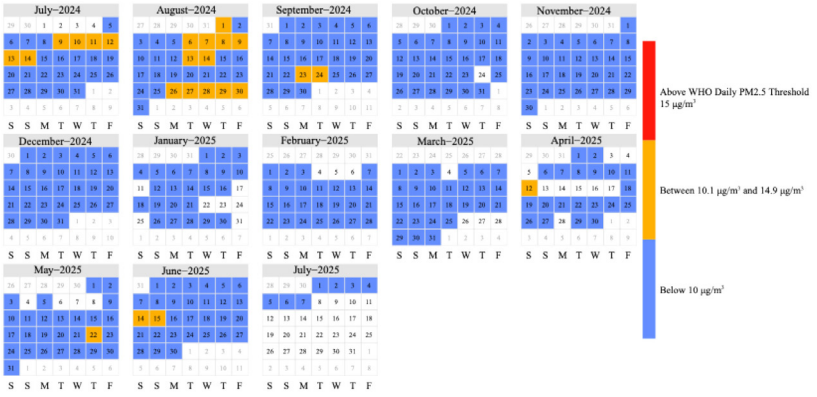


FIGURE 1

Calendar visualization for $PM_{2.5}$ concentrations: (**a**) Days with blue colour indicated concentrations below 10 µg/m^3; (**b**) days with orange colour represent concentration levels between 10.1 µg/m^3 and 14.9 µg/m^3, and days with red colour signifying concentrations above the WHO daily threshold.

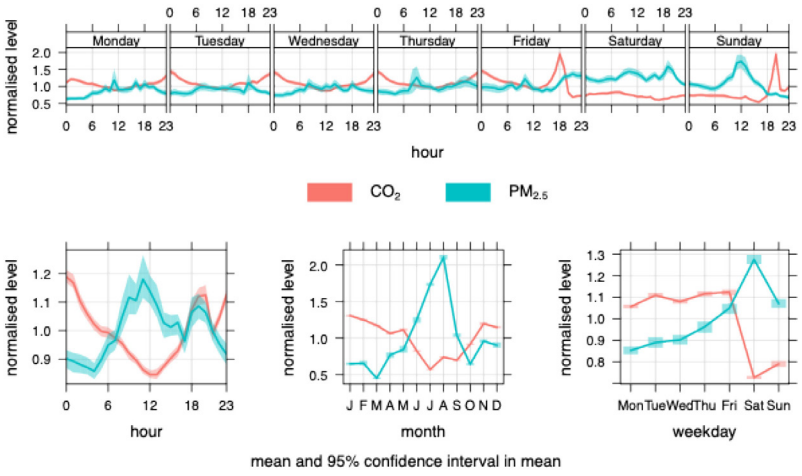


FIGURE 2
Normalized variation of $PM_{2.5}$ and CO_2 concentrations for different days, hour and months.

exceeding the WHO daily limit of 15 μg/m^3. Conversely, the annual average CO_2 concentration was 1077 ppm, indicating that ventilation was frequently suboptimal.

A profound seasonal mitigation trade-off emerged (Figure 2). During the winter, the participant prioritized thermal comfort and sealed the indoor environment to avoid outdoor pollution from residential wood burning. Under limited natural ventilation, CO_2 remained elevated, whereas summer window ventilation dropped CO_2 but increased outdoor $PM_{2.5}$ infiltration.

This aligns with studies finding an inverse correlation between low $PM_{2.5}$ and high indoor CO_2 based on ventilation and activity patterns (30). Peak CO_2 concentrations were obtained during night hours in bedrooms due to human exhalation (26), and in enclosed vehicle spaces. For $PM_{2.5}$, weekend spikes correlated well with human activity like meal preparation (3).

Furthermore, the study exposed prominent technical limitations. The Atmotube Pro dataset suffered a final data loss of 20.9% due to application file export failures and cloud data gaps. Such missing data can significantly underestimate the impact of air pollution exposure, emphasizing the importance of daily data completeness for accurate time-series analysis (25). While others claim that the primary challenge remains the inherent inaccuracy of low-cost sensors themselves rather than the absence of data (1), both factors present risks to proper exposure estimation. The AIRVALENT device was more reliable, presenting only 7.3% of CO_2 data missing.

The study demonstrates the potential of personal air quality monitors as practical tools for assessing individual exposure across different indoor environments encountered during daily life. If space permits, consider reinforcing this broader message in the conclusions, highlighting how personal monitoring can support an initial assessment of exposure and help identify situations where more detailed investigations may be warranted.

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AuNP@8-MOA-based electrochemical immunosensor for passive screening of airborne aflatoxin B1-associated contamination

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Citation

Iriarte-Cela, M., Pérez-Setién, C., Figols, M., Fermoso, J., Diéguez-Uribeondo, J. AuNP@8-MOA-based electrochemical immunosensor for passive screening of airborne aflatoxin B1-associated contamination.

Abstract

Background

Airborne mycotoxins are an emerging concern in fungal-contaminated indoor environments, where the development of Aspergillus species can promote aflatoxin B1 (AFB1) production and potential inhalation exposure (1–4). Although AFB1 is routinely monitored in food, feed and liquid extracts, direct approaches for the preliminary screening of airborne AFB1-associated contamination remain limited. This is particularly relevant in indoor or occupational environments affected by fungal growth, where mycotoxins may be associated with spores, dust particles or fungal fragments.

Objective

This work aimed to develop a disposable electrochemical immunosensor for passive screening of airborne AFB1-associated contamination using a nanostructured gold-nanoparticle interface on thick-film carbon electrodes.

Methodology

The sensing platform was prepared by modifying disposable carbon electrodes with 8-mercaptooctanoic-acid-functionalized gold nanoparticles (AuNP@8-MOA), which provided a suitable nanostructured interface for anti-AFB1 antibody immobilization (5–8). The stepwise construction of the biosensor was assessed through physicochemical and electrochemical characterization (Figure 1). AFB1 recognition was monitored by cyclic voltammetry using the ferri/ferrocyanide redox probe, where antigen binding produced a decrease in the anodic peak current due to partial interfacial blocking (9–12). The analytical response was evaluated using AFB1 standard solutions, and proof-of-concept passive exposure assays were performed by placing the biosensors in the headspace of fungal culture environments.

Key Results

The AuNP@8-MOA layer improved the electrochemical accessibility of the electrode surface and enabled anti-AFB1 immobilization. The

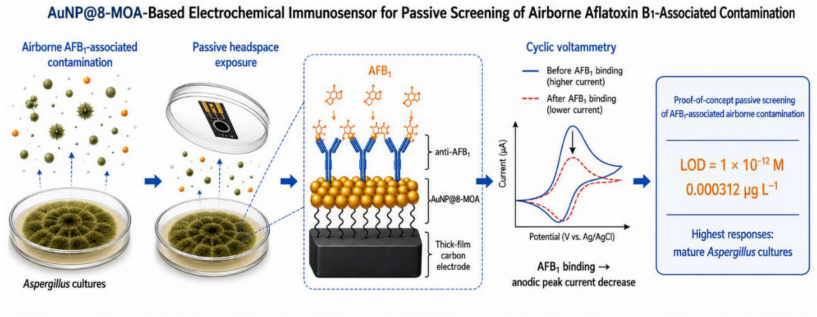


FIGURE 1
Schematic representation of the AuNP@8-MOA-based electrochemical immunosensor for passive screening of airborne AFB_1-associated contamination.

immunosensor showed a concentration-dependent response to AFB1, with an experimentally estimated detection limit of 1×10^{-12} M, equivalent to 0.000312 μg L^{-1}. In passive exposure assays, the highest AFB1-equivalent responses were obtained from mature Aspergillus cultures, whereas lower responses were observed in mixed microbial environments and less developed fungal cultures. The uninoculated culture-medium control remained below the estimated detection limit.

Conclusions

These results support the potential of AuNP@8-MOA-based electrochemical immunosensors as simple disposable tools for preliminary passive screening of airborne AFB1-associated contamination. The approach is intended as a proof-of-concept screening platform rather than a fully quantitative air-monitoring method. Future work should incorporate controlled airflow sampling and independent analytical validation to enable quantitative determination of airborne mycotoxins in real indoor environments.

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Precision of MICA devices: Experimental validation under realistic indoor conditions

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Citation
Irisarri, A., Figols, M. Precision of MICA devices: Experimental validation under realistic indoor conditions.

Abstract

Introduction and Objective

Continuous indoor air quality (IAQ) monitoring is increasingly used as an operational input for ventilation control, building management systems (BMS) and certification schemes. The value of that input depends on data quality: unreliable measurements propagate into mistimed control actions and inefficient energy use.

Two properties are frequently conflated. Accuracy describes how close a measurement is to the true value; precision, also referred to as intra-model variability, describes the consistency of measurements between identical devices exposed to the same conditions. Their relative relevance is application-dependent: HVAC regulation, BMS integration and trend detection rely primarily on precision, whereas performance testing and compliance verification rely primarily on accuracy. Low precision produces incoherent fluctuations between units and unnecessary control adjustments [1].

MICA is an intelligent monitor for continuous IAQ measurement; the parameters assessed in this study are listed in Table 1. MICA devices hold RESET Air Accredited Monitor Grade B certification and are aligned with the technical requirements of the WELL Performance Verification Guidebook.

The Objective
is to experimentally validate the precision of MICA devices under realistic indoor conditions, by evaluating the consistency of the trends measured for each parameter, and to assess the effect of the MICA enclosure on the measurements once the sensors are integrated into the final device. This approach is consistent with the RESET Air Accredited Monitor Process [2], which prioritises coherence between monitors of the same model over absolute accuracy against a reference instrument, and with the AIRLAB Microsensor Challenge [3] and co-location literature [4].

Methodology
Five MICA devices were subjected to evaluation. Two factory-calibrated sensor modules mounted on PCB without enclosure were used to build the operational reference, defined as the mean of the two modules. Two exceptions apply. For PM, the reference modules were used with enclosure, since the PM module is designed to operate in its final configuration. For temperature and relative humidity, a Testo 440 with high-precision probe and ENAC-accredited calibration certificate was used as reference; these two parameters are therefore reported as accuracy rather than precision.

- Measurement protocol: seven days of continuous monitoring per parameter, with a 1-minute logging frequency and data aggregated in 15-minute intervals for subsequent analysis.

- Conditions: co-location test in a controlled test room under normal conditions of use, with the devices mounted symmetrically on a panel; approximately 25 °C and 50 %RH, representative of typical occupied indoor environments. Only three sensors were used for temperature and relative humidity, to reduce the influence of spatial gradients. During the PM test a particle peak (80 µg/m^3) was generated with a candle, extending the dynamic range beyond baseline indoor concentrations.

- Analysis: time series and scatter plots of each sensor against the reference, with the precision band (reference ± sensor specification). RMSE, Pearson correlation, R^2, MAPE and SMAPE were computed per sensor and parameter; SMAPE was applied to PM because the reference series contains zeros, for which MAPE is undefined.

Results

All parameters met inBiot specifications for indoor monitoring and control applications under the conditions of this test (precision, and accuracy for temperature and relative humidity). Absolute errors remained below the specification limits in every individual case: RMSE < 0.21 °C for temperature, < 1 %RH for relative humidity, < 14 ppm for CO_2, < 5 index points for TVOC, < 10 ppb for formaldehyde and < 1 µg/m^3 for all four PM fractions. Relative errors were below 1 % for temperature, 2% for relative humidity, 3 % for CO_2 and TVOC, and 11 % for all PM fractions. Pearson correlation exceeded 0.92 for every individual sensor and parameter, and 0.99 for CO_2, TVOC and all PM fractions, indicating that the devices reproduce events, peaks and trends consistently across units.

TABLE 1: Mean performance metrics per parameter (5 MICA devices; 3 for temperature and relative humidity)

Parameter	Specification (±)	RMSE	Pearson	R^2	MAPE / SMAPE (%)
Temperature (n=3)	0.5 ºC	0.156 ºC	0.996	0.966	0.61
Relative humidity (n=3)	2 %RH	0.82 %RH	0.939	0.788	1.22
CO_2	(30+3% m.v.) ppm	10.2 ppm	0.997	0.990	1.55
TVOC	15 pts or 15% m.v.	2.55 pts	0.999	0.999	1.78
Formaldehyde	20 ppb or 20% m.v.	4.25 ppb	0.962	n.a.§	16.26
$PM_{1.0}$	(5 µg/m^3+5% m.v.)	0.33 µg/m^3	0.999	0.995	7.96
$PM_{2.5}$	(5 µg/m^3+5% m.v.)	0.36 µg/m^3	0.999	0.995	8.96
$PM_{4.0}$	25 µg/m^3	0.35 µg/m^3	0.998	0.996	8.91
PM_{10}	25 µg/m^3	0.36 µg/m^3	0.998	0.995	8.62

Discussion and limitations

Formaldehyde required a differentiated interpretation. Individual MAPE ranged from 8.2 % to 34.6 %, and R^2 was excluded: the metric is penalised by small systematic offsets that remain within the sensor precision limits, combined with the low relative variance of the series. Pearson above 0.95 in all cases and RMSE below 10 ppb confirm that peaks and trends are correctly reproduced. The same applies to relative humidity (R^2 = 0.79, RMSE < 1 %RH). Metric selection must therefore be adapted to the dynamic range and variance of each parameter.

Three limitations apply. The study quantifies intra-model precision against an operational reference and does not establish metrological accuracy traceable to calibration standards, except for temperature and relative humidity. The conditions tested are representative of typical occupied indoor environments and do not characterise behaviour outside that range. The seven-day duration per parameter does not address long-term sensor drift.

Conclusions

Under the conditions tested, MICA devices showed a high degree of consistency and reproducibility between units: absolute errors remained within the specified limits for every parameter, and trends, peaks and events were reproduced coherently across devices. This intra-model consistency supports the use of MICA for continuous IAQ monitoring, trend detection and integration into Building Management Systems, applications in which coherence between units is the governing requirement. The negligible deviation between integrated devices and bare reference modules confirms the correct integration of the sensor hardware. Complementary studies against traceable references and over extended periods would be required to characterise absolute accuracy and long-term stability.

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Session 4 – Data Analytics, Artificial Intelligence and Standardised Methodologies for IAQ Assessment

Assessment of indoor environmental quality under real operating conditions in nearly zero-energy university classrooms using the TAIL method

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Citation
Rey-Martínez, F.J., Arroyo-Gómez, Y., Rey-Hernández, J.M., San José Gallego, L.J., San José-Alonso, J.F. Assessment of indoor environmental quality under real operating conditions in nearly zero-energy university classrooms using the tail method.

Abstract

The transition toward Nearly Zero Energy Buildings (NZEBs) is significantly influencing the design and operation of HVAC systems in educational facilities (1,2). However, limited field-based evidence is available on their actual performance in terms of Indoor Environmental Quality (IEQ) under real operating conditions (3-8). This study applies the TAIL methodology—an integrative framework covering Thermal (T), Acoustic (A), Indoor Air (I), and Luminous (L) domains (9,10)—to assess IEQ in university classrooms within an NZEB certified under the VERDE scheme (11) and aligned with LEED criteria.

The study was conducted in two university classrooms in the IndUVa building at the University of Valladolid (Spain), with 29–40 occupants. The six-story building (ground floor + five floors) is dedicated to academic activities, with technical installations located in the basement.

The HVAC system operates with 100% outside air, without recirculation, and comprises two integrated subsystems: (a) a centralized air handling unit (AHU) that conditions and distributes outside air, providing thermal preconditioning; and (b) independent local low-profile AHUs with four-pipe dual-coil heating and cooling systems in each classroom, with three operating modes according to occupancy (Table 1). The supply airflow is regulated by classroom CO_2 sensors.

The TAIL framework combines quantitative performance indicators derived from EN 16798-1 (12) and the WHO air quality guidelines (13,14) to establish standardized IEQ thresholds (10,11) (Table 2). The methodology included: (i) selection and characterization of representative classrooms based on mechanical ventilation and control strategies, as well as occupancy profiles

TABLE 1: Operating schedule and control models of the HVAC system

Period	Time Slot	Teaching Period	Central System — Common Areas	Central System— Classrooms	Local System — Common Areas	Local System — Classrooms
Open without teaching	07:00–09:00 14:00–16:00 21:00–22:00	Yes	100% (a)	30% (a)	ON	OFF
Open with teaching	09:00–14:00 16:00–21:00	Yes	100% (a)	100% (a)	ON	ON
Closed (night time)	22:00–07:00	No	30% (b)	30% (b)	OFF	OFF
Closed (weekends/holidays)	00:00–24:00	No	30% (b)	30% (b)	OFF	OFF

(*) Notes: (a) Air is pre-conditioned: heated to 21°C in winter and cooled to 26 °C in summer. (b) Air is heated to 18 °C in winter; no thermal treatment is applied in summer.

TABLE 2: Environmental factors included in the TAIL-rating scheme

Parameter/escala		Level I	Level II	Level III	Level IV
FACTOR THERMAL (T)					
PPD (%)[a]		< 6	< 10	< 15	< 25
FACTOR ACOUSTIC ENVIRONMENT (A)					
Backgroung sound pressure (dBA)[b]		≤ 30	≤ 34	≤ 38	Unacceptable
FACTOR INDOOR AIR QUALITY (I)					
Ventilation rate	Outdoor air supply (l/s·person)[c]	≥ 10	≥ 7	≥ 4	≥ 2.5
	Outdoor air supply (l/s·m²) – LPB-1[d]	≥ 0.5	≥ 0.35	≥ 0.2	≥ 0.15
	Overpressure (Pa)	≥ 15	≥ 10	≥ 6	≥ 2.5
Polluted	$PM_{2.5}$ (µg/m³)[e]	< 5	≥ 5	No criteria	≥ 15
	TVOC (µg/m³)[f]	≤ 200	≤ 3000	≤ 25,000	≥ 25,000
	CO_2 (ppm)[b]	≤ 550	≤ 800	≤ 1,350	Unacceptable
	Formaldehyde (µg/m³)	< 30	≥ 30	No criteria	≥ 100
	NO_2 (µg/m³)[e]	< 10	< 20	No criteria	≥ 20
	O_3 (ppm)[f]	< 4.7	> 4.7	No criteria	Unacceptable
FACTOR QUALITY LUMINOUS (L)					
Total iluminance horizontal (lx)[g]		≥ 500	≥ 300	≥ 200	Unacceptable
Daylight Factor (%)[h]		≥ 5.0	≥ 3.3	≥ 2.0	Unacceptable

[a] Standard ISO 7730:2025, Ergonomics of the thermal environment — Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria.
[b] Standard EN 16798-1, 2019, Energy performance of buildings - Ventilation for buildings - Part 1: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics - Module M1-6.
[c] Assuming: CO_2 emission rate of 20 l/h per person.
[d] Assuming: Very Low Pollution Building (LPB).
[e] WHO Air Quality Guidelines 2021.
[f] WHO Guidelines for Indoor Air Quality 2010.
[g] Standard EN 17037+A1 Daylight in buildings 2021.
[h] Standard EN 12464-1 Light and lighting. Lighting of work places. Part 1: Indoor work places.2021.

(Figure 1); and (ii) in situ monitoring during several morning sessions, starting from unoccupied baseline conditions and extending throughout occupied periods. The measured variables included outdoor air supply rates, CO_2 concentration as an indicator of ventilation effectiveness, particulate matter ($PM_{2.5}$, PM_{10}), gaseous pollutants, and thermal, acoustic, and lighting parameters.

Results indicate an overall IEQ classification of level III (moderate quality) in both classrooms (Figure 2). The main limiting factor was insufficient outdoor air ventilation under steady-state occupied conditions, leading to suboptimal CO_2 levels. In contrast, the HVAC system showed adequate dynamic response to peak occupancy events, effectively reducing CO_2 concentrations. Additionally, limited daylight availability contributed to suboptimal luminous conditions.

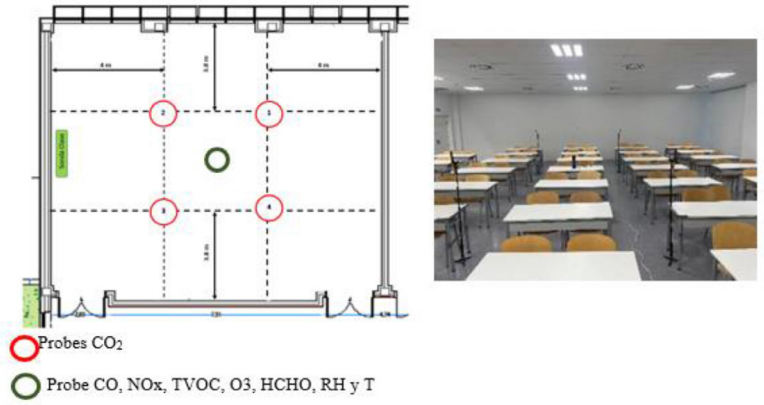


FIGURE 1
Location of the monitoring probes for chemical compounds in classrooms 1.1 and 1.4.

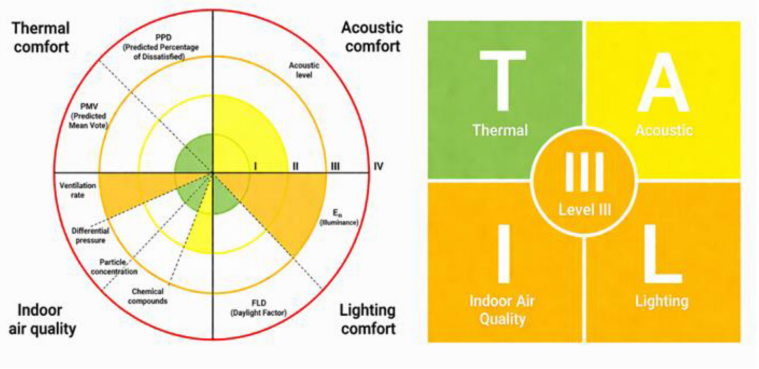


FIGURE 2
TAIL results in classroom 1.1 of the IndUVa building.

The findings highlight the need for improved ventilation control strategies, including optimization of airflow rates and operational practices such as maintaining doors closed to ensure system balance. Enhancing daylight utilization is also recommended to improve visual comfort and reduce energy demand. The study identifies key performance gaps relative to design targets and demonstrates the applicability of the TAIL methodology as a practical tool for HVAC performance assessment and IEQ optimization in NZEB educational buildings.

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Continuous multi-parameter indoor air quality monitoring for operational IAQ management in hospital environments

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Abstract

Healthcare environments represent highly dynamic indoor microenvironments where indoor air quality (IAQ) is influenced by occupancy patterns, ventilation

conditions, cleaning and disinfection activities, medical procedures, and building-related emission sources (1–3). Conventional IAQ assessment approaches based on punctual measurements or averaged concentrations may therefore fail to capture transient pollutant accumulation events and short-term exposure scenarios potentially relevant for patients and healthcare workers. In recent years, the development of low-cost sensor (LCS) technologies and smart monitoring systems has enabled new approaches for continuous and operational IAQ assessment in complex indoor environments (1,4).

The present work aimed to evaluate the temporal behaviour of key IAQ parameters across different hospital environments using continuous multi-parameter monitoring combined with targeted chemical characterization. The study additionally explored how continuous IAQ monitoring can support more adaptive and operationally oriented ventilation management strategies compatible with future Building Management System (BMS) integration. Monitoring was conducted in different hospital microenvironments between June 2023 and December 2025 using commercially available low-cost sensor devices (MICA Plus, inBiot, Spain). Monitoring systems incorporated sensors for carbon dioxide (CO_2), particulate matter (PM_1, $PM_{2.5}$ and PM_{10}), formaldehyde (CH_2O), temperature, relative humidity, and total volatile organic compounds (tVOCs). Twelve monthly targeted sampling campaigns complemented continuous monitoring, with VOCs analysed by TD-GC/MS and aldehydes by HPLC. Outdoor environmental data, including temperature, relative humidity and selected air pollutants, were additionally used to contextualize indoor conditions. A total of 1.79 million raw records were processed using a reproducible Python-based workflow including timestamp harmonization, quality control procedures, duplicate removal, temporal aggregation, and sensor coverage evaluation. The final dataset included 1.42 million indoor measurements and 264,311 hourly aggregated observations. The study included multiple hospital typologies, including

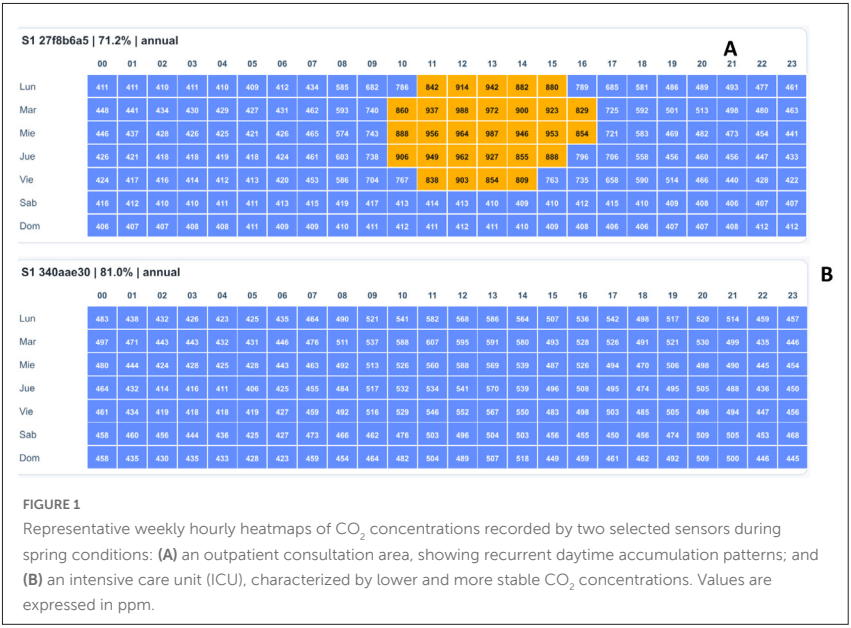


FIGURE 1

Representative weekly hourly heatmaps of CO_2 concentrations recorded by two selected sensors during spring conditions: **(A)** an outpatient consultation area, showing recurrent daytime accumulation patterns; and **(B)** an intensive care unit (ICU), characterized by lower and more stable CO_2 concentrations. Values are expressed in ppm.

hospitalization wards, consultation and waiting areas, intensive care units (ICUs), pathological anatomy laboratories, and common spaces.

The results revealed strongly differentiated IAQ dynamics across the monitored hospital environments. CO_2 concentrations showed clear temporal signatures consistent with occupancy-related ventilation demand, particularly in waiting and consultation areas, where recurrent daytime accumulation periods were observed. Representative examples of these contrasted temporal patterns between outpatient consultation areas and ICUs are shown in Figure 1. In contrast, formaldehyde exhibited more persistent accumulation patterns in selected hospitalization rooms and laboratory-associated spaces, suggesting contributions from persistent

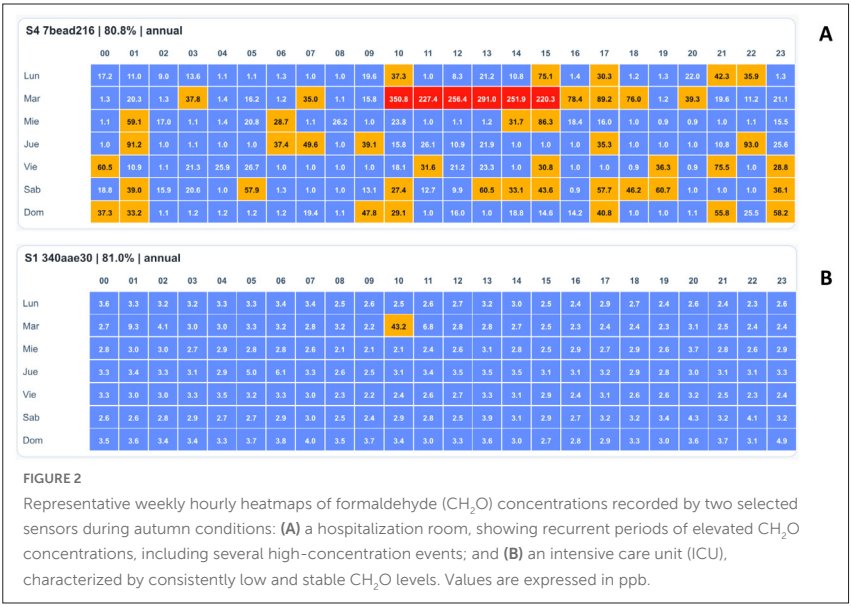


FIGURE 2

Representative weekly hourly heatmaps of formaldehyde (CH_2O) concentrations recorded by two selected sensors during autumn conditions: **(A)** a hospitalization room, showing recurrent periods of elevated CH_2O concentrations, including several high-concentration events; and **(B)** an intensive care unit (ICU), characterized by consistently low and stable CH_2O levels. Values are expressed in ppb.

indoor emission sources and heterogeneous ventilation conditions, consistent with previous studies performed in healthcare facilities (2). Figure 2 illustrates this contrast using two representative sensors, with recurrent high-concentration events observed in a hospitalization room during autumn, whereas the ICU maintained consistently low and stable CH_2O levels. Several areas showed recurrent periods with acceptable CO_2 concentrations while simultaneously presenting elevated formaldehyde levels, highlighting the limitations of occupancy-based IAQ assessment approaches. This decoupling was particularly evident in outpatient consultation facilities during summer, where CO_2 remained within the "Good" category for >95% of hours, while CH_2O was outside the corresponding "Good" category for 59.6% of

hours and reached an hourly P90 of 106.5 ppb at 07:00. $PM_{2.5}$ concentrations generally remained low and stable throughout the monitoring period, although localized short-term peaks were identified in selected operational and laboratory areas. Targeted chemical characterization confirmed strongly differentiated pollutant signatures across hospital typologies. Pathological anatomy showed a marked process-related profile, with mean acetone and formaldehyde concentrations of 2043 and 181 $\mu g/m^3$, respectively, whereas hospitalization areas showed a different chemical profile, including mean acetaldehyde and α-limonene concentrations of 65 and 30 $\mu g/m^3$, respectively. These findings supported the interpretation of the temporal volatile accumulation patterns identified by continuous monitoring. The integration of continuous monitoring with targeted chemical characterization substantially improved the interpretation of recurrent pollutant accumulation scenarios and pollutant-specific operational behaviours across the hospital environments. Importantly, these differentiated temporal signatures provide operational information beyond pollutant concentrations alone, allowing occupancy-related ventilation demand to be distinguished from persistent or recurrent chemical accumulation scenarios.

The study demonstrates that continuous multi-parameter IAQ monitoring can provide valuable operational information for understanding pollutant dynamics in complex healthcare environments, particularly where occupancy-related indicators such as CO_2 do not capture persistent chemical accumulation. The identification of pollutant-specific operational signatures suggests that different IAQ conditions may require differentiated management responses: CO_2 can inform occupancy-related ventilation demand, whereas persistent CH_2O and tVOC signals may indicate chemical accumulation that could warrant extended or pre-occupancy ventilation, source investigation, or localized corrective actions. These findings provide an observational basis for developing multi-parameter BMS control strategies, whose effectiveness and energy implications should be validated in future intervention studies (1,3,4).

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Architectural guardrails for AI-assisted IAQ assessment: An agent reasoning across WELL, GO IAQS, EPBD and beyond

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Citation
Escribano Hierro M. Architectural guardrails for AI-assisted IAQ assessment: An agent reasoning across WELL, GO IAQS, EPBD and beyond.

Abstract

Background

Continuous indoor air quality (IAQ) monitoring is spreading rapidly across buildings worldwide as sensors become cheaper, outdoor pollution and wildfire episodes push attention indoors, and certification schemes raise expectations for evidence-based interpretation. In Europe, the 2024 recast of the Energy Performance of Buildings Directive (EPBD) further accelerates this shift by turning IAQ monitoring and control from a voluntary add-on into a regulatory expectation phased in from 2026 (1). Yet the frameworks that govern how monitoring data should be interpreted - the WELL Building Standard v2 (2), the Global Open IAQ Standards (GO IAQS) (3), ASHRAE 62.1 and 55 (4) and the WHO indoor air quality guidelines (5) - remain fragmented in scope, parameters, averaging periods and limit values. A single reading of 900 ppm CO_2 or 18 µg/m^3 PM2.5 means different things under each. Continuous sensing is widely available; continuous, standard-referenced

interpretation is not. Streaming and historical sensor archives now grow faster than traditional consultancy can review building by building, while dumping those exports into general chatbots exposes wrong calculations, hallucinations, opaque cost and weak audit trails. Organisations are also shifting to hybrid human-agent work in which agentic tools augment consultant capacity under human accountability, amid rising expectations for ethical AI use, cost transparency and regulatory oversight. Anne targets that intersection: scaled IAQ data, fragmented standards, limits of manual interpretation, and governed generative assistance rather than ad hoc chatbot use.

Objectives

We developed Anne, an agentic IAQ consulting system, and examined it in a shared hosted web laboratory and in operational use. Anne ingests real-time data from certified sensors, reasons across multiple harmonised IAQ standards, flags health and exposure risks against peer-reviewed evidence, and produces consultant-grade outputs - findings, recommendations and audit-ready dashboards - under human-in-the-loop control. A purpose-built software harness around the model keeps numerical correctness and auditability in tools and curated knowledge, not in the language model alone.

Methodology

Anne is built in two layers (Figure 1). A *knowledge layer* - a portable plugin used from developer assistants (Claude Code, Cursor, Codex) and from an optional Chainlit chat web app - carries Anne's persona, an observe-orient-decide-act (OODA) reasoning sequence with an explicit human gate, eight task "skills" (assess, GO IAQS, WELL, EPBD, benchmark, trend, ventilate, help) and threshold/reference files for each standard, cross-checked against ASHRAE and WHO. The Chainlit app is operated as a shared hosted laboratory: a password-gated web workspace for the inBiot team and invited partners, with live sensor connections, chat history and the observability used in evaluation. Knowledge is plain Markdown that IAQ experts can edit without coding, and only the material a task needs is loaded into the model. A *data layer* of two Model Context Protocol (MCP) servers (6) - standard tool

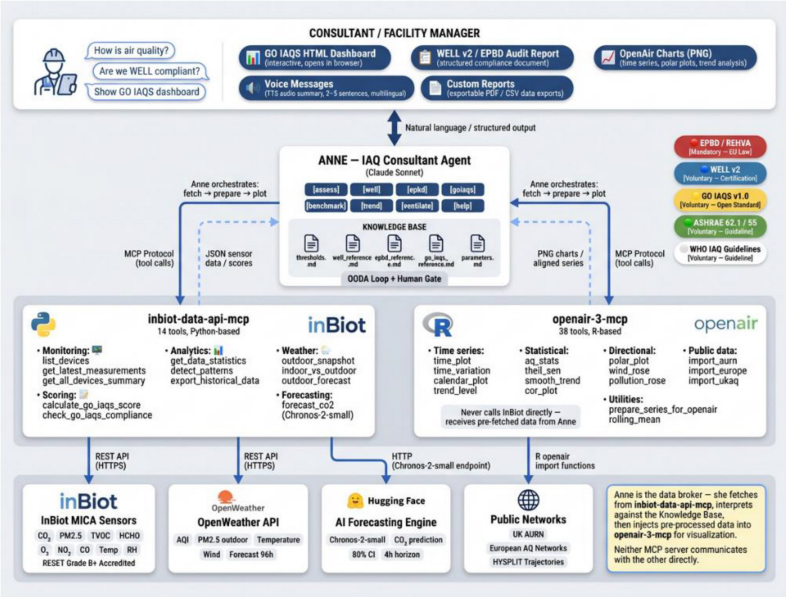


FIGURE 1
Anne's three-layer architecture: platform entry point (Claude Code / Cursor / Codex / Chainlit), an agent and knowledge layer (persona, OODA loop with human gate, eight skills, Markdown standards knowledge), and two MCP servers exposing 52 deterministic functions (inBiot sensors, OpenWeather, Chronos-2 CO_2 forecasting, GO IAQS scoring engine, openair analysis). All numerical computation runs outside the language model. Provided as a separate file.

interfaces the agent can call - exposes 52 functions: one server (14) handles inBiot sensor ingestion, outdoor weather, Chronos-2 CO_2 forecasting (7) and a deterministic GO IAQS scoring engine; a second (38) wraps openair, the established R package for air-quality analysis (8), for temporal, statistical and directional plots. All numerical computation runs outside the language model, so identical inputs yield identical outputs. Findings are always presented before recommendations to limit AI-anchoring of the human expert (9); WARN or FAIL parameters carry a cited health-impact

statement, and any empathetic narrative is flagged as inference rather than measurement. Comparable sensor chatbots can still invent or shift numbers even when given pre-computed statistics (10); Anne keeps calculation in deterministic tools.

The openair case shows the design claim: trusted analysis tools join as MCP servers without rewriting the knowledge layer, so capability grows by adding tools to the harness rather than retraining a model.

Key Results

Evaluation today covers inspectability, tested numerical consistency and early real-world use; a formal multi-assessor agreement study has not been run. In the shared laboratory, each turn shows a TaskList of tool phases, optional Step panels (arguments, summarised results, timing) and a provenance footer built only from tool outputs, so a consultant can see which analyses ran and which data backed the answer. Calls are routed through OpenRouter (a multi-model gateway with cost, token and error accounting) and recorded in Langfuse Cloud, an operations dashboard that stores latency and prompt/response traces for later review; shared login history supports peer review of prior threads. Consistency of the numerical core is architectural and tested: scoring, statistics and plotting stay in MCP tools (GO IAQS white-paper parity tests; 35-case openair smoke suite with zero failures). Anne's use is growing across public engagements - a Budapest primary-school classroom study, a live event wall at the IDEAL Cluster Summit in Brussels (Figure 2), and assisted wildfire-smoke and local fire-impact assessments - and, with greater day-to-day intensity, across private work by inBiot staff and partners in the laboratory (proposals, content and data analysis). Across WELL, EPBD-aligned checks and GO IAQS, eight task modules produce audit-oriented outputs. Core laboratory observability is in place; a formal multi-assessor agreement study remains future work.



FIGURE 2
Live public dashboard generated by Anne from real-time inBiot sensors at the IDEAL Cluster Summit (Residence Palace, Brussels, 9 June 2026): GO IAQS score, live CO_2 trajectory for the plenary hall, outdoor context, evidence-based health-impact assessment and empathetic-focus narrative. Provided as a separate file.

Conclusions

Separating deterministic scoring and plots from the language model, organising standards knowledge by procedural task rather than document similarity, and presenting findings before recommendations make harmonised IAQ assessment workable under human oversight without relying on model-level safety alone. The architecture is extensible: tools such as openair join as MCP servers without rewriting the knowledge layer, and a planned regulatory-vigilance pipeline will keep curated standards current. With Langfuse tracing plus on-screen tool Steps and provenance, Anne is

observable in routine laboratory and engagement use; the next priority is a continuous-improvement process in which those traces and operational lessons update the product and knowledge roadmap. Human-in-the-loop control and automatic logging also align with the transparency and oversight direction of the EU AI Act (11), without claiming a completed high-risk conformity assessment. Stable elements as models and MCP evolve are certified sensor APIs, deterministic scoring, curated standards and human oversight. The approach extends to further standards, local regulations and exposome-related indices, and is advanced within the IDEAL cluster of European IAQ projects, of which K-HealthInAir is part.

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Impact of occupancy dynamics on indoor CO_2 forecasting across real-world scenarios

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Citation

Garcia-Pinilla, P., Jurio, A., Figols, M., Paternain, D. Impact of occupancy dynamics on indoor CO2 forecasting across real-world scenarios.

Abstract

Accurate forecasting of indoor CO_2 concentrations supports proactive indoor air quality (IAQ) management and data-driven ventilation control. This work is based on the article published in the journal Forecasting (MDPI), DOI: https://doi.org/10.3390/forecast8020026 (1). Because CO_2 is widely used as a proxy for ventilation and occupancy (2,3), anticipating its evolution makes it possible to mitigate high-CO_2 episodes before they occur and to balance air quality, occupant comfort, and energy use. However, the performance of forecasting models is strongly influenced by occupancy dynamics, which vary considerably across indoor environments. Although machine-learning (ML) models have shown strong performance in controlled settings such as

school classrooms (4), their generalization to spaces with diverse occupancy patterns remains poorly characterized. This work addresses that gap by benchmarking forecasting models across six heterogeneous real-world use cases.

The study evaluates whether forecasting findings previously obtained in schools generalize to other use cases with different spaces, occupancy patterns, and CO_2 dynamics. Three hypotheses are tested: (H1) the best-performing model family depends jointly on the forecasting horizon and the use-case context; (H2) findings derived from a single scenario, such as classrooms, are not necessarily robust in other indoor contexts; and (H3) modern time-series foundation models can be competitive for indoor CO_2 forecasting under real operating conditions.

CO_2 was monitored at 10-minute resolution over 18 consecutive weeks using low-cost IoT sensors (MICA devices, inBiot), based on non-dispersive infrared (NDIR) technology and certified under the RESET standard (5). Sixteen devices were deployed across six representative indoor environments in Europe — conference rooms, dining halls, hospitals, food markets, offices, and student residences — yielding 290,304 CO_2 observations, with two to three devices per use case located in southern Norway (conference rooms, dining halls, student residences) and Barcelona, Spain (hospital, food market, offices). The study was conducted within the framework of the European K-HEALTHinAIR project (6). The selected environments span markedly different occupancy regimes, from sporadic and unstructured use (conference rooms, student residences) to recurrent cyclic patterns (offices, dining halls, food markets) and continuous occupancy (hospital). These differences are reflected in the descriptive statistics: in most use cases the mean CO_2 concentration remained close to the baseline of an unoccupied space, between 428 and 441 ppm, whereas the continuously occupied hospital averaged 927 ppm. Figure 1 shows the weekly CO_2 patterns of each use case, revealing characteristic occupancy driven signatures — sharp daytime bands in cyclic spaces and persistently elevated levels in the hospital.

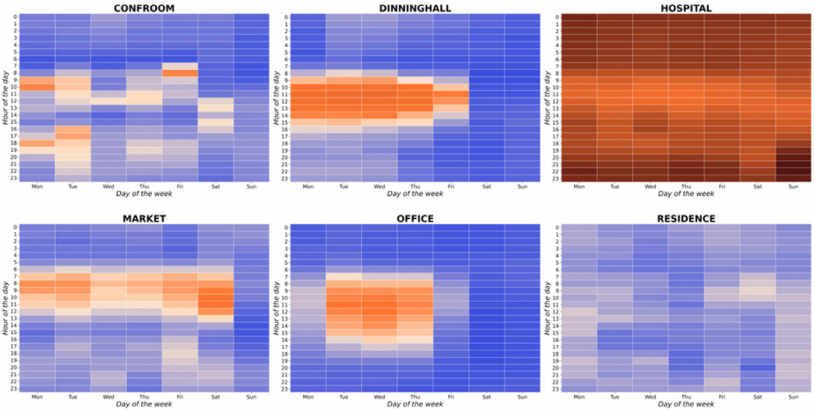


FIGURE 1
Weekly CO_2 concentration patterns across the six use cases. Each heatmap shows the mean CO_2 concentration by hour of the day (vertical axis) and day of the week (horizontal axis) aggregated over the 18-week period; the colour scale ranges from approximately 400 ppm (blue) to 1400 ppm (dark red). Reproduced from (1).

Eleven forecasting models were benchmarked under a shared, univariate protocol covering three methodological families: simple baselines (Shifted and Moving Average), a statistical model (auto-ARIMA), and ML-based approaches comprising classical ML (Random Forest, XGBoost), deep learning (N-HiTS, Temporal Convolutional Network, Transformer), an ensemble (ENS, the arithmetic mean of Random Forest, N-HiTS and TCN), and two Chronos-T5 (Tiny) time series foundation models (7,8) integrated via AutoGluon and evaluated in zero-shot (LLM-ZS, no local training) and fine-tuned (LLM-FT, adapted to each building's historical data) settings. All models shared a fixed 24-hour look-back window of 144 observations — which for the foundation models also defines the input context length — and a direct forecasting strategy, predicting four decision-relevant horizons: 10 minutes, 1, 2, and 4 hours. A common training configuration was applied without

per-model hyperparameter tuning (200 epochs, batch size 256, Adam optimizer, learning rate 10^{-3}, dropout 0.1, and inputs normalized to [0, 1] for the classical ML and deep learning models), with the remaining settings left at library defaults (DARTS). Models were evaluated independently per device with 14-fold rolling cross-validation, using scale independent metrics — MAPE and a MAE ratio relative to the Shifted baseline — complemented by a hierarchical non-parametric statistical analysis.

No single model consistently outperformed the others across all environments and horizons. At the shortest horizon (10 minutes), simple baselines — particularly the Shifted model — and ARIMA were statistically superior, consistent with the strong short-term autocorrelation of indoor CO_2. As the horizon extended to 2 and 4 hours, learning-based approaches, especially the ensemble and the fine-tuned foundation model, became the most robust, capturing weekly and hourly patterns that simple heuristics miss. Performance also depended strongly on the structure of occupancy: in spaces with sporadic occupancy the Shifted baseline remained competitive across horizons, whereas in cyclic scenarios ML models clearly outperformed the baselines in the long term, confirming for offices and dining halls the trend previously reported in schools. The continuously occupied, mechanically ventilated hospital was the most challenging case, with errors exceeding 28% for all models — including foundation models — indicating that the historical CO_2 series alone is insufficient to capture its dynamics. This univariate design was deliberate — it isolates the effect of occupancy dynamics by benchmarking every model on a common protocol — but it also marks the study's scope boundary: continuously occupied, HVAC-driven spaces such as hospitals will likely require multivariate inputs to be forecast accurately. Remarkably, the zero-shot foundation model achieved competitive accuracy without any local training, surpassing trained models such as N-HiTS and XGBoost in several use cases. Figure 2 summarizes the relative performance of each model, expressed as the MAE ratio with respect to the Shifted baseline, across use cases and horizons.

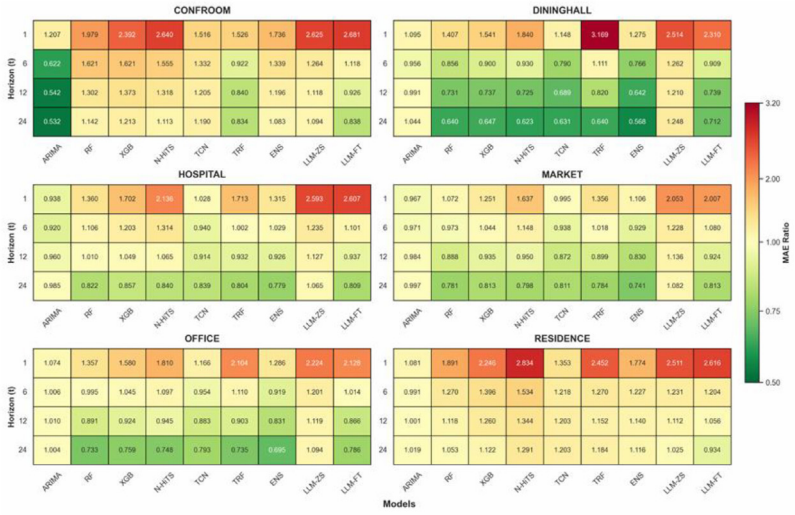


FIGURE 2
MAE ratio of each model relative to the Shifted baseline (SH) across use cases and forecasting horizons (t). Green shades indicate improvement over the baseline, while red shades indicate lower performance. Reproduced from (1).

The statistical significance of these differences was assessed through a hierarchical procedure that grouped the models into five families: baselines, statistical methods, classical ML, deep learning, and foundation models. Group comparisons relied on the Aligned-Friedman test (9) with Holm post-hoc correction (10), and pairwise comparisons on the Wilcoxon signed-rank test (11), using adjusted p-values at a significance level of 0.05. The tests confirmed the horizon dependent transition observed in the error metrics: at the shortest horizon the Shifted baseline was statistically superior, whereas at the 2- and 4-hour horizons the learning-based branch prevailed and the ensemble emerged as the global winner. The ensemble significantly outperformed most individual architectures, but no significant difference was found between the ensemble and the fine-tuned foundation model,

indicating that LLM-FT statistically matches top-tier ensemble performance in the most challenging long-term scenarios. These results reflect average robustness and do not rule out that specific environments may favour particular architectures.

The optimal CO_2 forecasting strategy is therefore context- and horizon-dependent, which challenges the assumption of a universal solution for IAQ applications. Simple and statistical models suffice for immediate next-step prediction, while ensembles and fine-tuned foundation models are preferable at longer horizons in spaces with structured occupancy. Foundation models, particularly in zero-shot mode, enable scalable deployment for predictive IAQ control in data-scarce buildings, reducing the need for extensive historical data before obtaining useful forecasts. By clarifying which conclusions from educational settings replicate in other indoor domains and which do not, this work supports the transition from reactive monitoring toward predictive and adaptive IAQ management. Future work will therefore explore multivariate extensions for such complex, mechanically ventilated environments — incorporating exogenous variables such as HVAC operation, occupancy counts, or outdoor conditions — together with operational deployment aspects, such as inference and retraining costs, and the transferability of models across environments with shared behavioural characteristics.

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“Focus 1%” approach to indoor air quality: Translational application of targeted air purification technologies

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Citation
García-Gallardo Sanz, P., García-Gallardo Sanz, M.V., Gayubo Ausín, S. “Focus 1%” approach to indoor air quality: Translational application of targeted air purification technologies.

Background

Indoor air quality (IAQ) is a major determinant of human health, as people spend most of their time in enclosed environments (1–3). Indoor spaces may accumulate pollutants originating from outdoor air, building materials, human activities, cleaning products, and biological sources (2,4). Chronic exposure has been associated with respiratory, cardiovascular and neurological diseases, allergic disorders, and premature mortality (1,2).

Conventional IAQ management is primarily based on dilution ventilation, whereby outdoor air is introduced and indoor air is exhausted to reduce contaminant concentrations (4,10). Mechanical filtration is commonly incorporated, mainly targeting particulate matter. Consequently, ventilation

rates, filtration efficiency and carbon dioxide (CO_2) levels are frequently used as indicators of indoor environmental quality.

This approach presents important limitations. Increasing air renewal requires moving, heating, cooling and conditioning large air volumes, resulting in significant energy consumption (5,10). Furthermore, outdoor air may introduce gases, volatile organic compounds (VOCs), odours, ultrafine particles and other pollutants.These challenges are particularly relevant in existing buildings where ventilation systems are insufficient and space constraints limit the installation of new ductwork.

Conventional filtration alone does not fully address IAQ challenges. MERV-rated filters are often preferred because of their compatibility with existing systems; however, they remain limited in their ability to control ultrafine particles and are not specifically designed to remove gases, VOCs or odours (6–8). In HVAC systems, filtration is typically located at central air-handling units. Although bypass and uncontrolled air mixing have been progressively reduced in modern installations, mixing between zones remains a concern because filtration cannot guarantee complete removal of ultrafine particles, gaseous pollutants, odours or biological contaminants.

Within this context, Focus 1%® is proposed as a conceptual framework for selective IAQ management. The approach is based on the hypothesis that a relatively small fraction of indoor air may contain a significant proportion of the contaminants responsible for human exposure and health risks. If this fraction can be identified and continuously treated, conventional ventilation strategies may be complemented through targeted interventions focused on priority pollutants.

Objectives

To present Focus 1%® as a methodological framework for targeted indoor air quality management, describe its technological implementation, and discuss its potential implications for pollutant control, building operation and energy efficiency.

Methodology

Focus 1%® was developed through the analysis of the limitations of dilution-based ventilation and its comparison with alternative strategies combining recirculation, environmental sensing and selective contaminant treatment.

Rather than focusing exclusively on the total air volume, the methodology addresses the critical contaminated fraction that disproportionately influences overall indoor air quality. The approach combines controlled outdoor air renewal, mechanical filtration, indoor recirculation, environmental monitoring and complementary treatment technologies.

Ventilation remains essential, but outdoor air introduction should be managed carefully because it may also transport contaminants indoors. Mechanical filtration effectively reduces particulate matter but does not independently eliminate gases, VOCs, odours, the entire ultrafine particle fraction or biological contamination. Environmental sensing enables system responses to be adapted to real operating conditions.

Within this framework, photolysis and photocatalysis are incorporated as complementary technologies to mechanical filtration. These processes have been widely investigated for the degradation of gaseous pollutants and VOCs in indoor environments (9). Although these processes are widely applied in industrial environments with high contaminant loads, indoor applications require different approaches because pollutant concentrations are generally lower and treatment must occur in occupied spaces. As these technologies may involve UVC radiation and the potential generation of secondary products, their implementation requires confined, controlled and validated designs.

The approach considers it preferable to achieve more complete treatment of a controlled fraction of contaminated air than to apply a lower treatment intensity across the entire indoor volume. Within the Focus 1%® framework, localized recirculation near the occupied zone is prioritized over strategies based exclusively on centralized recirculation. This configuration promotes

repeated treatment of the air fraction with the highest contaminant burden while reducing unnecessary mixing between areas with different environmental quality. In this context, thermal conditioning and ventilation are considered complementary but distinct functions: the former is primarily intended to ensure thermal comfort, whereas the latter aims to manage contaminant exposure.

Key Results

Current outcomes can be grouped into three areas: intellectual property development, technological implementation and partial experimental validation.

The Focus 1%® framework has generated several patent applications and industrial property registrations associated with different technological solutions, reflecting the translation of the concept into practical IAQ applications.

These developments include UVGHIT®, AIREFICIENT® and AIRESPEJO®. UVGHIT® is intended to enable the safe use of UVC-based photolysis and photocatalysis in occupied environments. AIREFICIENT® is designed for terminal points within ventilation systems, placing recirculation and active treatment close to the occupied space as a complement to central filtration. AIRESPEJO® is aimed at public sanitary facilities and other locations where odours and aerosol generation are relevant concerns.

Several technologies associated with the framework have been evaluated under controlled laboratory conditions, including aerosol-based studies and representative contaminant testing. Some developments have also been implemented in real environments, providing preliminary evidence of operational feasibility.

The analysis suggests an intervention architecture based on the combination of central filtration and localized recirculation with active treatment close to the occupied zone. Such a configuration may reduce cross-contamination

between areas and facilitate interventions closer to pollutant sources or exposure locations, addressing limitations previously identified in ventilation-based approaches (4,10).

The framework also supports separating thermal load management from ventilation requirements. Although air can contribute to heating and cooling, its thermal capacity is limited. Except in spaces with very high occupancy or specific operational requirements, ventilation systems should primarily be sized according to air quality needs, while thermal loads may be addressed through more suitable conditioning systems.

Finally, the approach shows particular potential for existing buildings with limited or non-existent ventilation infrastructure, where the installation of new duct networks may be constrained by space, cost, construction requirements or operational disruption. The methodology enables rapid, localized and progressive interventions in areas presenting specific IAQ challenges.

Main Conclusions

Focus 1%® proposes an evolution from conventional dilution-based strategies relying on the movement of large air volumes towards targeted management of the critical contaminated fraction. The framework integrates controlled ventilation, central filtration, localized recirculation, environmental sensing and photolysis/photocatalysis as complementary active treatment technologies.

Although experimental validation remains partial, the technological developments, intellectual property activity and laboratory testing performed to date support the feasibility of the approach and justify further research aimed at quantifying its effects on human exposure, indoor air quality and energy efficiency.

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Session 5 – Policy, Roadmap and Stakeholder Perspectives for IAQ

From awareness to action: K-HEALTHinAIR's strategic approach to stakeholder engagement and policy translation for indoor air quality

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Citation
Pérez Saiz, L., Ferri, M., Ferrando, M. From awareness to action: K-HEALTHinAIR's strategic approach to stakeholder engagement and policy translation for indoor air quality.

Abstract
Despite growing recognition of indoor air quality (IAQ) as a critical public health determinant, significant gaps persist in stakeholder awareness, engagement infrastructure, and evidence-based policy frameworks across

Europe. The K-HEALTHinAIR (K-HIA) project addresses these challenges by combining an extensive IAQ monitoring campaign across representative EU indoor environments with a systematic participatory strategy to foster knowledge uptake, behavioural change, and policy action.

Within K-HIA, a dedicated social engagement [1] and educational strategy [2] was designed and implemented as an integrated component of the project, systematically embedding participatory approaches across all pilot sites and throughout the full project lifecycle. This work describes the strategy's implementation across five European pilot settings: Barcelona (Spain), Rotterdam (The Netherlands), Grimstad (Norway), Baden-Württemberg (Germany), and Poland/Austria, with the aim of fostering stakeholder participation across all quadruple helix profiles — academia, industry, public authorities, and civil society — with particular attention to vulnerable populations including respiratory outpatients, older people, children, and occupationally exposed workers.

The strategy, encompassing two complementary tasks - social engagement and educational activities - was grounded in the IAP2 Core Values for Public Participation [3] and the Quadruple Helix model, and implemented across two phases through a four-step process: (1) **ecosystem analysis** mapping stakeholder networks and existing engagement infrastructures in each pilot scenario; (2) **diagnosis** through an IAQ awareness survey, training needs assessments across all pilot sites, impact mapping workshops, platform consultations with consortium partners and external IDEAL Cluster stakeholders, and SWOT analysis; (3) an **action plan** structured across five progressive participation levels — inform, consult, involve, collaborate, empower; and (4) coordinated **dissemination and communication**. Moreover, educational activities were developed iteratively in close coordination with pilot partners, grounded in pilot-specific training needs assessments and continuously validated with end users. All outputs were integrated into the Knowledge Sharing Module (KSM) of the project's Open Access Platform, organised by target audience profile aligned with the quadruple helix.

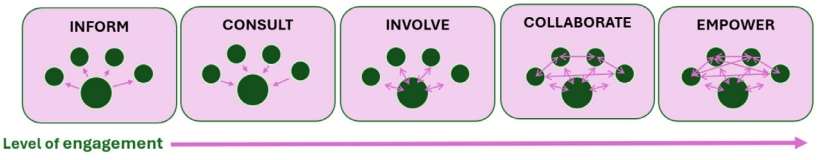


FIGURE 1
Levels of participation.

The strategy progressively transitioned from awareness-raising toward collaborative co-creation, empowerment, and policy translation across all participation levels (Figure 1). **At the inform level,** knowledge dissemination produced knowledge pills (k-pills) — including four based on preliminary project monitoring data — and accessible versions of technical deliverables, expanding reach beyond research communities. Pilot-specific educational materials were developed in response to identified training needs across all sites, including infographics on device usage and ventilation recommendations, health impact guides for respiratory outpatients, cooking environment guidance, IAQ pollutant overviews, and ventilation guidance for school administrators. Awareness activities at pilot level — such as information stands, infoscreens, and lectures — further extended reach to local communities and industry stakeholders. All materials are openly accessible through the KSM (https://k-healthinair.eu/knowledge/). **At the consult level,** two consultative processes were implemented as part of the action plan: an iterative platform consultation process — initially with internal consortium partners and subsequently expanded to external IDEAL Cluster stakeholders, achieving a 4.6/5.0 usability rating — and a nine-country regulatory survey revealing significant gaps in EU IAQ frameworks and strong consensus on prioritising residential settings and vulnerable populations as immediate regulatory targets. **At the involve level,** a series of three open webinars was organised, each with a distinct focus: the first introduced the project and its scientific foundations, featuring the European Federation of Allergy and Airways Diseases Patients' Associations (EFA) as external speaker on the policy landscape of respiratory health;

the second disseminated preliminary findings from over 205 monitored homes and featured a patient testimonial, actively positioning patients as co-communicators of IAQ evidence; and the third was focused on IAQ in schools settings. Beyond the webinar series, primary care engagement activities — including a World COPD Day community screening event in Barcelona featuring oscillometry testing with K-HIA portable monitoring equipment — demonstrated real-world application of project tools and fostered direct involvement of healthcare professionals and patients. At the **collaborate level,** K-HIA advanced on several fronts. Within the EU research ecosystem, the project contributed actively to the first two IDEAL Cluster policy briefs, exchanged educational materials with EDIAQI to strengthen school-focused resources, and participated as speakers in the IDEAL Cluster Colloquium and in the EDIAQI webinar on the economic dimensions of IAQ. At the pilot level, co-design workshops and engagement with existing expert panels ensured that K-HIA evidence was co-developed with and reached out to relevant decision-making communities across different national contexts. Finally, policy translation continued advancing through the development of a third IDEAL Cluster policy brief, currently underway. Finally, **at the empower level,** the strategy enabled to interpret IAQ data and take informed decisions. Capacity-building workshops implemented across the pilot sites supported the communities involved in identifying problematic patterns, and implementing improvements independently, helping them become active advocates for healthier indoor environments.

Effective IAQ policy translation requires adaptive strategies responsive to local contexts, results-driven communication, and sustained collaboration bridging research and practice. The K-HIA framework shows how progressive level participation — from foundational awareness-raising to collaborative co-creation and community empowerment — can help translate monitoring evidence into policy and regulatory actions. This is reflected in the multi-country consultation, which identified shared regulatory gaps and in the development of a third IDEAL Cluster policy brief. The integration of social engagement and educational activities within a single coherent strategy, continuously adjusted through iterative coordination with pilot partners, offers a replicable and adaptive model for embedding participatory approaches in

environmental health research. Critically, by positioning diverse stakeholder profiles as active agents rather than passive recipients, the strategy lays the groundwork for sustained IAQ improvement and knowledge uptake beyond the project's lifetime — ensuring that K-HIA's contributions to public health and policy endure well beyond the end of the project.

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The $PM_{2.5}$ exposure in 14 schools in the Lodz area in Poland

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Citation

Hanke, W., Brzeznicki, S., Kristian, A., Moshammer, H., Hess, D., Ziomek-Świątkiewicz, M., Gansiniec, A. The PM2.5 exposure in 14 schools in the Lodz area in Poland.

Abstract

Background

The study aimed to assess the impact of indoor air pollution on children's particulate matter (PM) exposure and to identify factors influencing indoor air quality (IAQ) in schools in the Lodz metropolitan area. The primary sources of $PM_{2.5}$ emissions in the region include household combustion of hard coal and biomass, as well as heavy urban traffic. Elevated outdoor PM concentrations may significantly contribute to indoor air pollution in schools and adversely affect children's health. (1,2,3) Recently the question was raised if the closing the windows during breaks stop the air pollution penetration to the classroom (4).

Methods

PM2.5 concentrations were continuously monitored in 14 schools that agreed to collaborate in the KHEALTHinAir project tLodz area using Mann+Hummel sensors installed in classrooms and teachers' rooms. Three periods of the school day were analyzed: before lessons, during morning classes, and during the first long break. Mean PM2.5 concentrations were calculated for autumn 2023, winter 2023/2024, and spring 2024. The measurements were done in all school days in these periods. Differences between the beginning and the end of each analysed period, as well as exceedances of the World Health Organization (WHO)-recommended daily $PM_{2.5}$ limit value (15 μg/m^3), were assessed. For selected schools located near monitoring stations of the Chief Inspectorate for Environmental Protection, indoor measurements were compared with outdoor air quality data.

Results

During the heating season (autumn–winter 2023/2024), $PM_{2.5}$ concentrations exceeded the WHO daily limit value during 21–78% of school operating time, whereas in spring 2024 exceedances ranged from 2% to 35%. Indoor $PM_{2.5}$ concentrations measured before lessons were comparable to those recorded during classes and breaks. Only minor fluctuations in $PM_{2.5}$ levels were observed throughout the school day, indicating relatively constant exposure conditions. Similar concentration ranges were found across all analyzed time periods. Comparison with outdoor monitoring data demonstrated a clear correlation between outdoor and indoor particulate matter concentrations.

Conclusions

Elevated $PM_{2.5}$ concentrations in schools were observed, particularly during the heating season, with frequent exceedances of WHO guideline values. The findings indicate that outdoor air pollution is a major determinant of indoor air quality in schools in the Lodz area. The similarity of $PM_{2.5}$ levels before lessons, during classes, and during breaks suggests that natural ventilation through window opening does not substantially affect indoor $PM_{2.5}$ concentrations.

The Policy Implications of the Findings

Since our results suggest that outdoor pollution is a major driver of indoor exposure, we strongly support the idea that improving IAQ in schools requires not only actions inside the buildings (e.g., Heating, ventilation, and air conditioning systems, filtration, or ventilation strategies), but also broader measures led by public authorities to improve outdoor air quality. For example, this could include the faster implementation of cleaner heating systems, the reduction of traffic-related emissions, fleet-renovation policies, or other urban air quality interventions.

We would like to underline the importance of involving society and stakeholders in the discussion and prioritization of actions, acknowledging that some measures may have temporary social or economic impacts but could provide important long-term health benefits.

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Net4CleanAir: A COST Action for indoor air cleaning technologies

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Abstract

Background

Indoor air quality (IAQ) is a growing public health and governance priority because most exposure occurs indoors and IAQ measures must be balanced with energy and climate objectives. WHO guidance (ventilation roadmap; global air quality guidelines) and ventilation standards such as ANSI/ASHRAE 62.1 provide the policy and technical framework for ventilation and complementary air-cleaning interventions (1–3). However, translating IAQ science into procurement, guidance, and regulation remains challenging because evidence is dispersed, terminology is inconsistent, and performance reporting is often incomplete or not comparable across studies and technologies.

This gap is particularly relevant as portable/in-room air cleaners are increasingly deployed when ventilation upgrades are constrained or outdoor air is polluted, as highlighted in the Net4CleanAir project framing (4). CADR (ANSI/AHAM AC-1) enables repeatable comparison for particle removal, but gas-phase performance is frequently compound-specific and time-dependent, limiting the interpretability of generic "VOC removal" claims without clear test conditions (5,6). Policy frameworks must also address trade-offs: indoor chemistry evidence and chamber testing show that some air-cleaning technologies can generate secondary pollutants, supporting the need to evaluate both removal and emissions in guidance and standards (7–9).

COST Action Net4CleanAir (CA23139) addresses these challenges by establishing an evidence-to-policy pipeline in which Working Group (WG) 1 harmonizes taxonomy, compiles structured literature and market datasets, and integrates them into a Knowledge Hub to support stakeholder access, comparability, and literature-derived recommendations for guidance and roadmap priorities (4). Net4CleanAir started in October 2024 as a four-year COST Action and is currently in its second year of implementation. The results presented here correspond to ongoing WG1 activities, with the taxonomy and core databases already established and the Knowledge Hub continuing to expand through additional data integration and validation.

Objectives

This contribution presents the methodological backbone of WG1 of Net4CleanAir (CA23139) and its relevance for policy and stakeholder decision-making (4). We aim to: (i) harmonize terminology and taxonomy for indoor air cleaning; (ii) build structured, interoperable datasets from scientific literature and the commercial market; and (iii) enable stakeholder access to these outputs through digital tools, supporting evidence exploration and comparison and providing structured inputs for guidance and roadmap development in later WGs (including WG6).

Methodology

WG1 implemented a multi-layer workflow that links evidence generation, knowledge organization, and stakeholder access.

- Task 1.1 established controlled terminology and taxonomy for pollutants, air-cleaner types, mechanisms (e.g., filtration, sorption, oxidation/photocatalysis, ionization/plasma, ultraviolet disinfection), and key descriptors (e.g., CADR/airflow/ACH), enabling consistent classification across studies and products.

- Task 1.2 compiled scientific evidence into a standardized literature dataset capturing pollutant typology, indoor environments, technologies/materials, performance descriptors (efficiency, CADR/flow when reported), ventilation context, device features (sensors/remote control; commercial vs. custom-built), maturity level, and stakeholder-relevant fields (energy/maintenance, secondary products, and recommendations for users/policymakers).

- Task 1.3 created a harmonized market database of 413 verified products based on manufacturer documentation, including technology stages, pollutant coverage, declared performance, operational parameters, and standards/certification claims, aligned with the literature dataset for cross-domain comparison.

- Task 1.4 developed a Knowledge Hub (currently being expanded) combining an AI chatbot for natural-language querying of the literature database and a PostgreSQL-based market platform supporting filtering, comparison, dashboards, and controlled updates.

Key Results

The WG1 approach produces a decision-ready evidence structure rather than a single technology assessment. First, the datasets enable cross-cutting views of pollutants, technologies, and indoor contexts (e.g., residential, educational, healthcare, offices, and transport) and make reporting gaps visible for standardization and procurement. Reported performance and airflow/CADR metrics vary widely across pollutants and operating conditions, underlining the need for standardized, context-aware reporting and guidance linked to room size, ventilation, and operational use. Second, a distinctive feature of the literature dataset is a dedicated field for recommendations for users and/or policymakers. Examples extracted from the literature include operational guidance (placement and runtime strategies; coordination with window/door use), maintenance considerations (filter replacement and degradation), ventilation–air-cleaning coordination, and attention to potential secondary emissions for some technologies. These outputs provide structured inputs for guidelines, roadmap development, and stakeholder-facing recommendations derived from a standardized evidence model. Third, the market review indicates a technologically mature but uneven landscape: filtration-based solutions dominate and reporting is frequently incomplete for pollutant specificity, test conditions, standards reference, and by-product disclosure, motivating harmonized minimum disclosure expectations for comparability and consumer/procurement confidence (4). Finally, the Knowledge Hub improves accessibility by allowing non-specialists to retrieve and compare evidence through natural-language queries and interactive filtering and will progressively strengthen decision support as coverage and validation expand.

Conclusions

Net4CleanAir WG1 provides an evidence-to-policy pipeline by combining harmonized terminology, structured evidence synthesis, market intelligence, and digital access. This infrastructure supports stakeholder decision-making today (evidence exploration and comparison) and provides a scalable foundation for future guidance, reporting frameworks, and roadmap activities in subsequent WGs, ultimately contributing to more transparent, comparable, and implementable indoor air-cleaning strategies. Although several WG1 deliverables are already operational, further expansion and validation of the databases and Knowledge Hub will continue throughout the remaining years of the Action.

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