IDEAL

INDOOR AIR QUALITY HEALTH

GUIDELINE FOR INDOOR AIR MANAGEMENT

Recommendations and Actions by the IDEAL Cluster projects

Version 1.0

2026-06-09

Co-funded by the European Union

Co-funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Health and Digital Executive Agency (HaDEA). Neither the European Union nor the granting authority can be held responsible for them.

TABLE OF CONTENTS

1. BACKGROUND

Cluster details

Cluster title	Indoor Air Quality and Health
Cluster acronym	IDEA/IDEAL
Dates and duration	September 1st 2022 – August 31st 2026 (48 months)
Horizon Europe call	HORIZON-HLTH-2021-ENVHLTH-02-02 Indoor air quality and health
Number of projects	7

IDEAL's projects

PROJECT	TITLE	GA NUMBER
K-HEALTHinAIR	Knowledge for improving indoor air quality and health	101057693
SynAir-G	Disrupting Noxious Synergies of Indoor Air Pollutants and their Impact on Childhood Health and Wellbeing	101057271
LEARN	Evaluation on indoor air quality for children around Europe	101057510
TwinAIR	Indoor air quality for healthy living	101057779
InChildHealth	Identifying determinants for indoor air quality and their health impact in environments for children: measures to improve indoor air quality and reduce disease burdens	101056883
Inquire	Identification of chemical and biological determinants, their sources, and strategies to promote healthier homes in Europe	101057499
EDIAQI	Evidence Driven Indoor Air Quality Improvement	101057497

Disclaimer

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them.

Author list

IDEAL Cluster project **K-HEALTHinAIR**:

Artur Badyda[1], Adam Muszyński1, Jose Fermoso[2]

[1] Faculty of Environmental Engineering, Warsaw University of Technology, Warsaw, Poland

[2] CARTIF Technology Center. P.T. Boecillo, Boecillo (Valladolid), Spain

IDEAL Cluster project **SynAir-G**:

Kristina Siemens[1], Nikolaos G. Papadopoulos[2], Maria Kritikou[2], Chrisitan Goroncy[3], Thanasis Charalampopoulos[4], Thanos Damialis[4]

[1] Global Allergy & Asthma European Network of Excellence, Berlin, Germany

[2] University of Athens, Athens, Greece

[3] DIN e. V., Berlin, Germany

[4] Aristotle University of Thessaloniki, Thessaloniki, Greece

IDEAL Cluster project **LEARN**:

Wai Kei Chu[1], Jeroen A.J. Vanoirbeek[1], Katie Kedwell-Simmering[2]

[1] Centre for Environment and Health, Department of Public Health and Primary Care, KU Leuven, Leuven, Belgium

[2] MANN+HUMMEL GmbH, Ludwigsburg, Germany

IDEAL Cluster project **TwinAIR**:

Vasiliki Lazari[1], Antonis Papamanolis[2], Stylianos Karatzas[3]

[1] Leiden University Medical Center, Netherlands

[2] University of Patras, Greece

[3] University of the Aegea, Greece

IDEAL Cluster project **InChildHealth**:

Robert M.W. Ferguson[1], Corinne Whitby[1], Carla Viegas[2,3] Heidi Salonen[4.5], Ulla Haverinen-Shaughnessy[6], Paula Guedes[7], Katrin Vorkamp[7]

[1] School of Life Sciences, University of Essex, Essex, United Kingdom.

[2] H&TRC—Health & Technology Research Center, ESSL—Escola Superior de Saúde de Lisboa, Instituto Politécnico de Lisboa, Lisbon, Portugal.

[3] NOVA National School of Public Health, Public Health Research Centre, Comprehensive Health Research Center (CHRC), REAL, CCAL, NOVA University Lisbon, Lisbon, Portugal.

[4] Aalto University, Department of Civil Engineering, Espoo, Finland

[5] Queensland University of Technology, International Laboratory for Air Quality and Health, Australia

[6] Civil Engineering Research Unit, Faculty of Technology, University of Oulu, Finland

[7] Aarhus University, Department of Environmental Science, Roskilde, Denmark

IDEAL Cluster project **INQUIRE**:

Marta Gabriel[1], Katie Kedwell-Simmering[2], Vasileos Salamalikis[3], Linda Schenk[4],

[1] Institute of Science and Innovation in Mechanical and Industrial Engineering (INEGI), Porto, Portugal

[2] MANN + HUMMEL GmbH, Ludwigsburg, Germany

[3] NILU, Kjeller, Norway

[4] Institute of Environmental Medicine, Karolinska Institutet, Stockholm, Sweden

IDEAL Cluster project **EDIAQI**:

Jesica Fernández-Agüera[1], Samuel Domínguez-Amarillo[1], Mario Lovric[2]

[1] Universidad de Sevilla, Sevilla, Spain

[2] Lisbon Council for Economic Competitiveness and Social Renewal, Brussels, Belgium

2. INTRODUCTION

2.1 Relevant Health Outcomes

In 2021, air pollutant concentrations in Europe considerably exceeded the levels recommended by the World Health Organization (WHO). [EEA2023a, WHO2010] Their reduction to guideline levels could have prevented a significant number of attributable deaths in countries of the European Economic Area, e.g. in 2021, 293 000 from exposure to fine particulate matter ($PM_{2.5}$) and 69 000 from exposure to nitrogen dioxide (NO_2). In children and adolescents, the number of preventable deaths associated with air pollution exceeds 1 200 and the number of disability-adjusted life years (DALYs) over 110 000 per year. [EEA2024, EEA2023a, EEA2023b] While the impact is most pronounced in low- and middle-income countries, significant health effects are still observed at lower pollutant concentrations typical of high-income countries. [Raju2020]

Even though we spend most of our time indoors, indoor air has received less attention than outdoor air. Indoor air pollution (IAP) may differ in source, composition and concentration from outdoors and therefore requires specific assessment and regulation. To date, the full range of health effects related to indoor air pollution remains largely unknown. To be able to predict and prevent health effects arising from IAP, it is essential to better understand the determinants of indoor air quality (IAQ), exposure dynamics, host susceptibility and disease mechanisms. [Vardoulakis2020; IDEAL2025]

The list of indoor air pollutants is large and growing. It encompasses gases, particulate matter (PM), volatile organic compounds (VOCs) and endocrine-disrupting chemicals (EDCs) as well as allergens and bioaerosols from plants, animals, bacteria, viruses, and fungi. [Moelling2020; Dannemiller2025; Hatem2025] While some pollutants are well known, such as PM, carbon monoxide (CO) and nitrogen dioxide (NO2), others, such as ultrafine particles or radon, are still insufficiently characterized. The WHO guideline provides recommendations on selected pollutants, including benzene, CO, formaldehyde, naphthalene, NO_2 and polycyclic aromatic hydrocarbons (PAHs). [WHO2010] For some pollutants, health effects are observed following repeated or multiple exposures over an extended period, often decades. Other pollutants affect human health more acutely following a single short-term exposure. [Coggins2021] Furthermore, synergistic interactions between biological and chemical pollutants modulate individual health effects and add to the complexity. [Papadopoulos2023]

While air pollution can affect all of us, certain populations are particularly vulnerable. Due to their smaller body height, increased hand-to-mouth contact and their respiratory physiology characterized by faster breathing rates, children potentially have a higher exposure to pollutants which can penetrate deeper into the lower respiratory tract. Children's airways are smaller and their organs and immune systems are still developing, which further increases their vulnerability. [Ahdoot2015; Bush2021; Oliveira2019] Observations from the SINPHONIE cohort demonstrated that schoolchildren in Europe are exposed to a variety of air pollutants with concentrations above the recommended thresholds while at school. These exposures were adversely associated with various health outcomes, including respiratory and allergic symptoms. This highlights the importance of improving IAQ in the school environments. [Baloch2020]

Older adults represent another group at risk. Oxidative stress plays an important role in ageing and is also an important mechanism through which air pollution affects health. Air pollution can accelerate the ageing process and related functional decline and furthermore aggravate chronic diseases with high prevalence among older adults, including heart disease, stroke, chronic obstructive pulmonary disease (COPD) and lung cancer. [Zhang2023]

Irrespective of age, individuals with hypersensitivities, such as allergies and asthma, are particularly vulnerable and tend to exhibit exaggerated and persistent inflammation, triggered by specific and non-specific stimuli, including tobacco smoke, particulate matter and other pollutants. Low socioeconomic status represents an additional risk factor due to higher exposure to air pollution, nutritional deficiencies, limited capacity to anticipate, cope with, and adapt to environmental hazards, and reduced access to healthcare. [Murray2006]

Regarding the mechanisms underlying the health effects attributable to air pollution numerous studies have reported associations with increased inflammatory biomarkers and oxidative stress. [Guo2021; Soppa2019; Soppa2017] The "epithelial barrier theory" hypothesizes that many chronic diseases, including allergic, inflammatory, and metabolic disorders, are aggravated by an ongoing epithelial inflammation triggered by exposure to a wide range of epithelial barrier–damaging insults. A compromised epithelial barrier enables the penetration of the microbiome together with allergens, toxins, and pollutants. This leads to microbial dysbiosis and local inflammation. [Kucuksezer2023] Almost every organ in the body can be affected by air pollution. Activated inflammatory cells can migrate from the organs of exposure, such as the respiratory system or skin, to distant tissues, where they can exacerbate or cause diseases. Due to their small size, some air pollutants even can penetrate directly into the bloodstream. [Akdis2021]

The profound impact of air pollution on human health is well documented, and the range of possible clinical symptoms is broad. Headaches, fatigue, shortness of breath, sinus congestion, coughing, sneezing, dizziness, nausea and irritation of the eyes, nose, throat and skin are some, typically more acute symptoms related to air pollution. Allergic symptoms, such as atopic dermatitis, rhinitis and conjunctivitis, may be exacerbated following the exposure to IAP. [Vardoulakis2020]

Chronic health effects include both cancer and non-cancer outcomes. Current evidence indicates that common indoor air pollutants such as PM, VOCs, PAHs and radon, as well as biological contaminants, can affect DNA integrity and chromosomal stability and therefore, have the potential to influence the initiation and promotion of cancer. [Kazensky2024]

Non-cancer effects include a wide range of respiratory disorders such as an increased susceptibility to respiratory infections, asthma, and COPD. [Vardoulakis2020; Hartiala2026] A large Swedish epidemiological cohort study reported that home dampness and exposure to air pollution were significantly associated with habitual snoring, which - even in the absence of sleep apnoea - is associated with daytime sleepiness and other respiratory conditions such as asthma and chronic rhinosinusitis. [Silverforsen2021] Early-life exposure to environmental stressors is a major contributor to allergic diseases and asthma and can impair lung function and development. Epidemiological as well as experimental studies confirm a link between long-term exposure to air pollution and the risk of developing asthma and asthma-like symptoms, while short-term exposures increase the risk of asthma exacerbation and hospitalisation. [Chen2015; Kanchongkittiphon2015; Lim2016; Zheng2021] Current medical guidelines on the management of asthma and allergies highlight the relevance of IAQ for prevention and satisfactory disease control. However, specific recommendations are often still sparse or vague due to a lack of robust scientific evidence. In 2025, the European Academy of Allergy and Clinical Immunology (EAACI) published specific guidance for patients and healthcare professionals (HCPs) on the impact of major indoor air pollutants on the risk of new-onset asthma, and on asthma-related outcomes. Very low to low quality of evidence was found for most indoor pollutants except for mould, for which moderate certainty of evidence for new-onset asthma is available. Thus, only conditional recommendations could be given for the assessment of IAP exposure and its reduction at an individual level. The incorporation of personalized adaptation and mitigation strategies in asthma management plans is strongly recommended. [Agache2025]

In older adults, studies have linked IAP exposure with a higher risk of cardiovascular diseases, such as heart attack and stroke, resulting in increased hospital admissions and emergency room visits. [Ndlovu2024] Furthermore, strong associations with autoimmune diseases have been reported and emerging data demonstrate the influence of respiratory exposure to air pollutants on neuropsychiatric conditions. [WHO2025] A growing body of evidence indicates that fine airborne PM is neurotoxic and affects children's neuro-behavioural development leading to reduced cognitive function. [Alter2024; Hartiala2026]

Clean, healthy air is recognized in local, national, European, and international law as a fundamental human right. In the European Union, the European Green Deal and the Zero Pollution Action Plan (ZPAP) set strategic goals for the reduction of air pollution. However, a coherent EU-wide action remains an unmet need and highlights a gap between scientific knowledge and its implementation. [EPRS2021; EU2012a; EU2012b; EU2021; EU2024; UN1948; UN1989; UN2022; UN2023]

2.2 Scope

The guideline aims to consolidate the latest insights and advancements from the IDEAL research projects into a comprehensive, practical resource for professionals and experts involved in indoor air quality assessments. This document serves as a bridge between cutting-edge research and practical implementation, ensuring that findings are accessible to those responsible for maintaining and improving indoor air quality.

The target audience is:

1. Indoor air quality professionals: Experts – such as exposure assessors, including IAQ professionals, public health officers, environmental engineers – conducting assessments and implementing indoor air quality improvements, including environmental engineers, indoor air quality consultants, and building managers.
2. Academics: Researchers and educators who incorporate IAQ topics in their curricula and are engaged in advancing this field.
3. Students and future professionals: Individuals pursuing careers in environmental health sciences, public health, exposure science, building science, and related areas, equipped with the knowledge to become leaders in IAQ management.

By providing a unified guideline informed by the IDEAL cluster projects, this document aims to elevate the practice of IAQ management across Europe, fostering healthier indoor environments and informed policymaking.

2.3 IDEAL Cluster

The Indoor Air and Health Cluster (IDEAL) is an EU-funded research initiative established in 2022. Its purpose is to enhance scientific understanding of indoor air quality (IAQ) and its effects on human health, influence policymaking, and promote healthier indoor environments throughout Europe. The cluster includes seven research projects: K-HEALTHinAIR, SynAir-G, LEARN, TwinAIR, InChildHealth, INQUIRE, and EDIAQI. Collectively, these projects aim to optimize collaboration, prevent redundancies, and increase their collective impact. Supported by a €50 million grant under Horizon Europe's "Indoor Air Quality and Health" topic, the IDEAL cluster brings together more than 120 European organizations and partners.

2.4 Structure of the document

The document is structured as follows: After an introductory section that outlines the objectives and identifies the target audience, Chapter 3 examines the assessment of indoor air quality, a critical step in pinpointing areas that require improvement and analysing the effectiveness of implemented strategies. This chapter also provides important contextual information for evaluating indoor air quality.

Chapter 4 explores the primary factors influencing indoor air quality (IAQ), encompassing physical parameters as well as a diverse range of chemical and biological agents, including gaseous pollutants, particulate matter, microorganisms, and allergens. The chapter is divided into two distinct sections: the first provides essential background information on the various agents and parameters that affect IAQ and their significance in indoor environments, while the second outlines general recommendations and actionable strategies for improving IAQ.

Chapter 5 introduces a comprehensive set of practical, actionable recommendations designed to increase indoor air quality. Importantly, these recommendations do not focus on the selection or use of specific chemicals or compounds. Instead, they emphasize practical measures and behaviours that have a significant impact on IAQ. Key focus areas include promoting improved construction methods, incorporating supportive equipment, and adopting appropriate hygiene practices.

3. CONTEXTUAL INFORMATION TO ASSESS INDOOR AIR QUALITY

3.1 Background

Several key considerations should be addressed before conducting an IAQ assessment. Contextual information about the indoor environment and the objectives of the sampling campaign or measurements are essential for determining an appropriate sampling and analysis strategy. Indeed, the objectives of an IAQ assessment can vary significantly – ranging from rapid screening during an outbreak or pandemic to risk assessment, evaluation of the effectiveness of exposure-control measures, or scientific research.

The collection of contextual data supports not only the chosen sampling strategy but also the interpretation of the data collected and the identification of exposure determinants and sources of contamination [Dias2024]. In fact, effective interventions to reduce health risks associated with indoor air quality (IAQ) must begin with the establishment of robust methods for assessing and identifying critical substances, their sources, and any relevant factors influencing their emission, dispersion, or dilution. This constitutes the foundation for developing policies and preventive measures grounded in source-control strategies.

Building- and occupant-specific questionnaires have therefore become fundamental tools in IAQ assessments. Basic guidance on the type of contextual information to be collected during indoor air monitoring and sampling is provided in established international standards, such as ISO 16000-1 [ISO16000-1] and ASTM D7297 [ASTM-D7297-21].

Nevertheless, over recent decades, major European research initiatives investigating IAQ across different building typologies – particularly offices [Bluyssen1996; Mandin2017], homes [Gabriel2020], and schools [Csobod2014; Gabriel2021] – have developed and implemented comprehensive questionnaires and checklists to document building characteristics, surrounding environments, and occupant behaviours, carefully tailored to the specific objectives of each study.

Findings from several well-structured national and international research projects have demonstrated that many pollutant emissions can be anticipated by identifying known sources, such as emissions from construction materials, consumer products, and indoor activities. Based on this evidence, the WHO developed a screening tool designed to support the identification of educational buildings that may be at higher risk of elevated levels of chemical pollution [WHO2021]. This tool relies exclusively on contextual data related to building characteristics, location, and use, providing a scientific rationale for prioritising facilities that require more comprehensive IAQ assessments and targeted mitigation measures.

The questionnaire can be completed during the on-site audit, based on a walkthrough inspection, and may require additional input from building managers or occupants to ensure that the collected information accurately reflects the building’s usual operating conditions.

3.2 General Building Characteristics

This section collects basic descriptive information about the building, including its type, function, year of construction or most recent refurbishment, total floor area, number of storeys, occupancy rate, and usage schedule. These data provide essential context for interpreting IAQ measurements and help identify factors that may influence pollutant concentrations, such as the age and composition of construction materials, material selection policies concerning chemical content, and intensity of use.

The diversity of room types within the building should also be recorded, for example, the presence of canteens, indoor swimming pools, laboratories, gyms, or other specialized areas, as these spaces often have distinct emission sources and ventilation requirements that can significantly affect indoor pollutant levels.

The configuration of the indoor space is an important factor in the fluid dynamics within a room and, consequently, the movement of pollutants. In each location where measurements are conducted, the layout of the room relative to the placement of the sensors should be known, including the dimensions of the room and presence of furniture, walls, and partitions.

3.3 Building Construction Materials

Questions in this section address the materials and products used in the construction or refurbishment of the building. Particular attention should be given to surface finishes (paints, flooring, wall coverings), insulation materials, sealants, adhesives, and furnishings, as these can constitute significant sources of volatile organic compounds (VOCs), formaldehyde, and other emissions. Where available, product labelling (e.g. low-emission certifications) should be recorded.

3.4 Consumer Products and Electronics

This part of the questionnaire identifies consumer, cleaning, and electronic products present or used indoors, as these are recognized sources of VOCs, semi-volatile organic compounds (SVOCs), and other pollutants relevant to IAQ. Information should include the types of products used, their chemical composition, where available (e.g. whether products are fragranced, solvent-based, or containing additives), frequency and duration of use, storage conditions, and any ventilation practices applied during and after use.

Electronic equipment such as computers, printers, photocopiers, televisions, and similar devices should also be documented, as they can emit specific substances, including aldehydes, plasticizers, and brominated flame retardants, some of which may act as endocrine-disrupting chemicals (EDCs).

3.5 Climatization, Ventilation and Fenestration

Information regarding the building's heating, ventilation, and air conditioning (HVAC) systems is essential for understanding air-exchange rates and pollutant dispersion patterns. The questionnaire should record the type of ventilation in use (mechanical, natural, or hybrid), as well as the design and operational characteristics of the HVAC system. Relevant aspects include the percentage of fresh air flow, system maintenance practices, filter types and replacement frequency, and the location of air intakes and exhaust outlets.

In addition, envelope features that influence air movement and thermal behaviour should be documented. These include the presence, extent, and orientation of glazed façades, as well as the number and distribution of openable windows. Particular attention should be given to how these elements affect daylight exposure, solar gains, and the potential for natural ventilation.

The questionnaire should also explore occupant practices related to window opening and the seasonal variation in the operation of both ventilation systems and windows, as these behaviours strongly affect indoor air renewal, humidity levels, and pollutant accumulation dynamics.

It is also important to document any systems for air purification, humidity control, or temperature regulation, as these may significantly influence both pollutant concentrations and thermal comfort.

3.6 Occupants and Behaviours

Occupant density, activities, and behaviours significantly influence IAQ. The questionnaire should therefore collect data on the number of regular occupants, their age, time spent indoors, and specific activities that may generate pollutants, such as cooking, smoking, use of printers or photocopiers, and cleaning routines. Behavioural factors such as window-opening frequency, use of air fresheners, and temperature and humidity preferences can also provide valuable insights into pollutant variability and exposure patterns. This ensures comparability of the results and better interpretation of the data.

3.7 Location and Outdoor Sources

This subsection aims to characterize the building's external environment and its potential influence on IAQ. The questionnaire should note the building's geographical location, surrounding land use, and proximity to possible outdoor pollution sources, including high-traffic roads, industrial facilities, commercial areas, or agricultural operations. The presence of green areas such as parks with trees, gardens, or tree-lined streets should also be noted, as vegetation can influence local air pollutant levels and microclimatic conditions. Prevailing wind direction may also be relevant for understanding the dispersion of outdoor pollutants.

Documenting these factors is critical for assessing the extent to which outdoor contaminants contribute to indoor pollutant levels and for identifying opportunities to mitigate infiltration through improved ventilation management or building design.

4. RELEVANT INDOOR AIR QUALITY PARAMETERS

4.1 Overview

The following section describes a range of parameters that influence indoor air quality. For each parameter, background information is provided, along with information on how to measure or sample it and what actions can be taken to prevent these parameters from reducing indoor air quality.

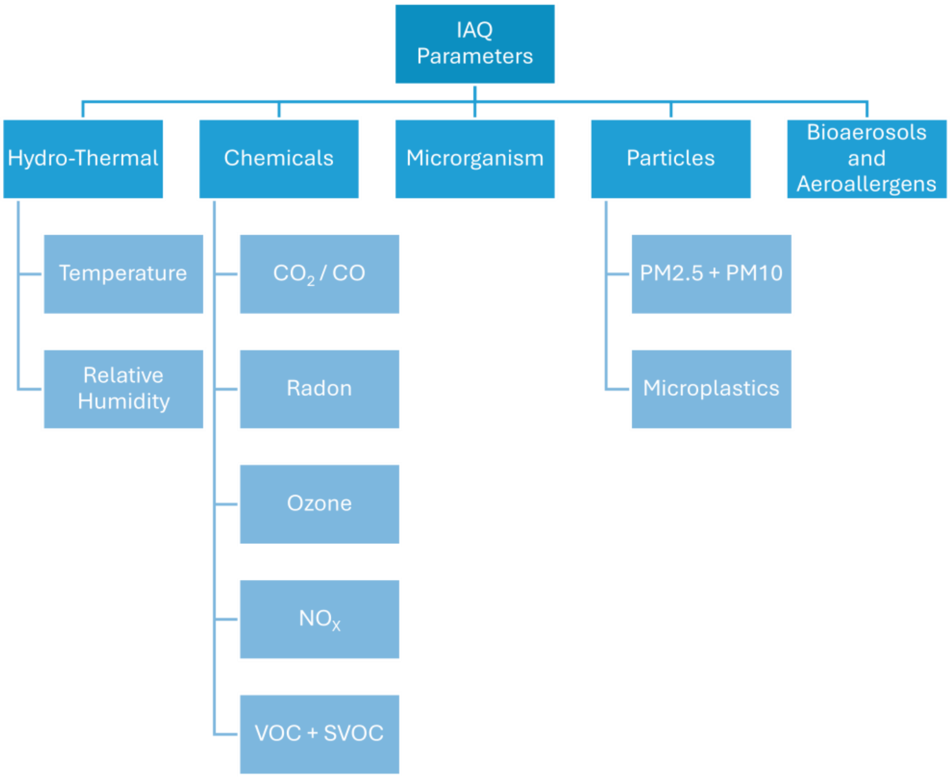

Fig. 1: Overview of parameters described in the guideline

4.2 Hydro-thermal parameters for temperature and humidity

Temperature and relative humidity are fundamental parameters for comfort and IAQ that affect occupant health, indoor pollutant dynamics, and the performance of ventilation systems. Studies of residential, educational, and workplace environments have shown that elevated temperatures and poor humidity control can exacerbate occupant discomfort, worsen respiratory symptoms, impair cognitive function, and increase the risk of heatstroke. [Lan2021; Wang2019; Bell2026]

4.2.1 Temperature

Background

Indoor air temperature directly affects comfort, perceived air quality, ventilation efficiency, and the emission rate of volatile and semi-volatile pollutants. Studies consistently show that excessively high indoor temperatures (typically above 27–30 °C) can lead to increased fatigue, decreased work efficiency, increased thermal discomfort, and a higher risk of heat-related symptoms such as heatstroke. There is also evidence that high indoor temperatures affect respiratory health, diabetes management, and symptoms of schizophrenia and dementia. Some instruments for measuring air pollution can be affected by temperature.

Buildings should maintain temperatures within a defined comfort range (typically 18–24 °C, as recommended by WHO) and refer to international (e.g. ISO 7730 and ASHRAE 55) and national guidelines, considering building type, occupancy patterns, activity levels, and outdoor conditions. [Dimitroulopoulou2023, Olesen2002]

Measurement & Assessment Guidance

Temperature is recorded using a calibrated temperature sensor. Place the sensor at breathing height (approximately 1–2 metres) and away from heat sources, cold surfaces, direct sunlight, ventilation outlets, or drafts. Continuous or high-frequency recording (e.g. every 1–5 minutes) is recommended to capture daily variations.

Actions for IAQ Improvement

1. **Adjust Indoor Temperature:**
   - Ensure that the indoor temperature remains within the defined comfort range (e.g. 18-22°C for most residential environments) to maximize comfort and energy efficiency.
   - Regularly monitor temperature levels using a thermostat to ensure consistent conditions.
2. **Investigate Temperature Deviations:**
   - If strong deviations from the comfort range are observed, assess potential causes such as:
     - Inadequate Ventilation: Inspect ventilation systems for blockages, irregular airflow, or malfunctions. Replace or clean filters regularly and ensure there is adequate air circulation.
     - Overheating Issues: Check for sources of excessive heat, such as sunlight through windows, energy-intensive appliances, or heating systems operating beyond the required setpoint.
     - Poor Building Envelope Performance: Inspect insulation, doors, and windows for leaks, cracks, or inadequate sealing that could lead to heat loss or gain. Consider improvements such as weather-stripping, insulating walls/roof, or upgrading windows to double/triple glazing.
3. **Improve Occupant Awareness:**
   - Educate occupants about appropriate ventilation and heating practices, highlighting their impact on financial savings, environmental sustainability, and health benefits.
4. **Develop Actionable Steps for Occupants:**
   - Develop a practical guide for occupants that includes:
     - Best times and methods for ventilating (e.g. brief, strategic airing instead of leaving windows open all day).
     - Proper thermostat settings for day/night and occupied/unoccupied periods.
     - Tips on maintaining heating systems (e.g. boiler servicing or radiator bleeding).
5. **Schedule Regular Maintenance:**
   - Ensure that HVAC systems are checked and maintained at least annually to address potential inefficiencies that may affect indoor temperature regulation or energy demand.

4.2.2 Relative Humidity

Background

Indoor air humidity has both negative and positive effects, and it is usually expressed as relative humidity (RH), which depends on both absolute humidity (AH) and temperature (T). For humans, dry air (15 %) can cause discomfort (dry skin and eyes leading to irritation). More seriously, dry air may reduce the effectiveness of the self-clearing mechanism of the respiratory tract. Moist air is not always preferable as condensation on surfaces promotes microbial growth, for example, moulds and bacteria, which can be harmful to susceptible occupants and trigger allergic reactions. Relative humidity (RH) strongly influences comfort, pollutant emissions, microbial growth, and the survival of airborne allergens and pathogens. Low humidity is common during the cold season and has been associated with an increased risk of respiratory symptoms and infections. [Guarnieri2023] From a technical point of view, RH is an important parameter to monitor, as some pollutant measurement devices are sensitive to either low or high humidity. Indoor RH is generally recommended to be maintained between 30 % and 60 %. RH consistently above 60 % can lead to condensation and promote microbial activity, while RH below 30 % can lead to dry and irritated eyes, throat, and skin. [Dimitroulopoulou2023]

Measurement & Assessment Guidance

Indoor RH is recorded using a calibrated hygrometer. The instrument is placed in the same location as the temperature sensor. RH should be continuously recorded to identify daily and periodic trends. Fluctuations in RH should be interpreted in conjunction with building occupancy, seasonal changes, ventilation conditions, and external weather conditions

Actions for IAQ Improvement

1. **Monitor Humidity Levels:**
   - Routinely track levels throughout the home or building.
2. **Address Low Humidity:**
   - Use **humidifiers** in dry seasons or climates (e.g. winter). Select devices suitable for the space size (e.g. room humidifiers vs. whole-house humidifiers).
   - Add indoor plants as a natural way to increase humidity.
   - Place water basins near heat sources to increase evaporation.
3. **Address High Humidity:**
   - Use **dehumidifiers** to remove excess moisture, especially in areas prone to humidity, such as basements, bathrooms, or kitchens.
   - Ventilate areas with high moisture generation, such as bathrooms (via exhaust fans or open windows).
   - Ensure proper sealing of doors and windows to minimize outdoor humidity entry.
   - Dry clothes outside when possible or in well-ventilated areas and use range hoods and exhaust fans during cooking.
4. **Ventilation System Adjustments:**
   - Maintain adequate airflow using mechanical ventilation systems (e.g. HRVs or ERVs) or through natural ventilation by briefly opening windows.
   - Ensure balanced airflow to prevent areas of stagnant air where moisture can accumulate.
5. **Insulate and Repair Building Envelope:**
   - Upgrade insulation, seal cracks, and repair leaks where moisture could enter from outside.

- In warm climates, use air conditioning systems to help control both temperature and RH.

6. **Improve Occupant Awareness:**
   - Educate occupants about the importance of proper humidity management, highlighting its impact on financial savings, environmental sustainability, and health benefits.

4.3 Chemicals

4.3.1 CO_2

Background

CO_2 is a commonly used indicator of IAQ, particularly for assessing ventilation effectiveness. While CO_2 itself is not highly toxic, elevated concentrations often reflect insufficient air exchange, which can lead to the accumulation of other indoor pollutants such as VOCs, particulate matter, or bioaerosols. High CO_2 concentrations are also associated with decreased cognitive function, drowsiness, and discomfort in indoor environments. Indoor CO_2 primarily originates from human respiration, but combustion processes such as gas heating or cooking can also locally increase indoor CO_2 levels. [Canada2021]

An indoor CO_2 level <800 ppm indicates good ventilation; 800-1000 ppm indicates moderate ventilation, and >1000 ppm indicates insufficient ventilation requiring corrective measures. Outdoor CO_2 concentrations are typically between 300 and 500 ppm, which can be used as a baseline for indoor measurements. [ASHRAE2016]

During the pandemic, CO2 has been used as an indicator of ventilation adequacy, to decrease the likelihood of disease and virus transmission.

Measurement & Assessment Guidance

Preferably use a continuous real-time monitoring device with data logging. Place the device at breathing height (1-2 metres), away from direct airflow from vents, windows, or local CO_2 sources. [SINPHONIE2015]

Continuous measurements are recommended, especially during the occupied periods. Typically, CO_2 concentrations increase during occupancy until equilibrium is reached, depending on both occupancy (CO_2 generation) and air exchange. Monitoring the patterns over 5-10 days provides a general indication of ventilation adequacy, and CO_2 levels should not exceed the recommended values. Exceeding the recommended values regularly is an indication of overcrowding or inadequate ventilation.

The CO_2 device should be calibrated regularly according to the manufacturer's instructions. While many devices have auto-calibration functionalities, on-site checks using outdoor air (approximately 400 ppm) as a reference help ensure device accuracy. An accuracy of ±50 ppm and a measurement range of 400 – 5000 ppm are adequate for most indoor settings. During measurements, record occupancy, ventilation patterns, and outdoor conditions to ensure proper interpretation of CO_2 data.

Actions for IAQ Improvement

Maintain proper indoor air quality by minimizing CO_2 sources and ensuring adequate ventilation. Cover topics such as [Canada2021]:

1. **Monitor CO_2 Levels:**
   - Routinely monitor levels throughout the home or building.

2. **Ventilation Practices:**
   - Open windows regularly to allow fresh air to circulate, provided outdoor air quality permits.
   - Use mechanical ventilation systems, such as heat recovery ventilators (HRVs), to ensure consistent air exchange, especially in spaces with limited access to outdoor air.
3. **Reducing Indoor CO_2 Sources:**
   - Avoid smoking indoors, as it significantly contributes to indoor CO_2 and other harmful pollutants.
   - Prevent overcrowding in small spaces, as more occupants can lead to faster CO_2 accumulation.
4. **Appliance Maintenance:**
   - Ensure all fuel-powered appliances, such as stoves, fireplaces, and heaters, are well-maintained, regularly inspected, and properly ventilated to reduce CO_2 emissions and ensure safe operation.
5. **Improve Occupant Awareness:**
   - Educate occupants about CO_2 and its effects, including the effects of prolonged exposure to elevated indoor CO_2 concentrations. Provide guidance on how to respond when CO_2 levels exceed defined thresholds.

4.3.2 CO

Background

Carbon monoxide (CO) is a colourless, odourless, and tasteless gas produced by the incomplete combustion of carbon-based fuels. While the European Environment Agency (EEA) primarily focuses on ambient air, CO is a critical indoor pollutant as it can accumulate from faulty boilers, wood-burning stoves, tobacco smoke, or vehicle exhaust from attached garages. Its toxicity stems from its ability to bind to haemoglobin, forming carboxyhaemoglobin, which inhibits oxygen transport in the blood. Even at low concentrations, prolonged exposure can lead to headaches and fatigue, while high levels are life-threatening.

The WHO has developed guidelines for both acute and chronic exposures (i.e. 30 mg/m^3 for 1 hour; 10 mg/m^3 as a maximum daily 8-hour mean; 10 mg/m^3 for 1 day). All fuel-powered appliances should be kept in good condition and well-ventilated. [Canada2021]

Measurement & Assessment Guidance

Accurate monitoring is essential to detect CO before it reaches toxic thresholds. According to EEA technical standards:

- Reference method: The standard method for CO measurement is non-dispersive infrared (NDIR) spectroscopy, which ensures high specificity and sensitivity.
- Metric: Compliance is measured against the maximum daily 8-hour mean.
- Limit values: The EEA (Directive 2008/50/CE) monitors a strict limit value of 10 mg/m^3 to protect public health. For indoor environments, high-resolution sensors are recommended to detect transient peaks that may indicate malfunctioning appliances, even if the 8-hour average remains below the legal limit. Data can be cross-referenced with the EEA Air Quality Statistics to distinguish between indoor sources and external infiltration.

Actions for IAQ Improvement

Implement practices based on EEA pollution reduction frameworks to minimize CO exposure and promote a safe indoor environment. Cover topics such as:

1. **Source Control:**
   - Schedule annual professional inspections of all combustion-based heating systems, cookers, and other fuel-burning appliances. This ensures proper functioning, complete combustion, and reduces CO production.
2. **Enhanced Ventilation:**
   - Ensure sufficient air exchange rates in all indoor spaces, particularly in modern "airtight" energy-efficient buildings where air circulation is often restricted.
   - Use the European Air Quality Index to plan ventilation times during periods of low outdoor pollution to avoid introducing contaminants from outside.
3. **Detector Installation:**
   - Install certified CO alarms in critical areas, such as near bedrooms and rooms with combustion appliances, to provide an added layer of safety should CO levels rise unexpectedly. These alarms act as a secondary safety feature to regular appliance maintenance.
4. **No-Smoking Policy:**
   - Strictly prohibit indoor smoking since it is a significant source of CO and fine particulate matter, both of which compromise indoor air quality and health.
5. **Improve Occupant Awareness:**
   - Raise awareness among occupants about the dangers of CO and how to prevent indoor CO formation.

4.3.3 Radon

Background

Radon (^{222}Rn) is a naturally occurring radioactive noble gas that poses significant public health risks when accumulated in poorly ventilated indoor environments. It is classified as a human lung carcinogen by the International Agency for Research on Cancer. [WHO1988, Salonen2025] Radon is the second leading cause of lung cancer after smoking among the general population, and the primary cause among never-smokers. [Bulut2024, Gordon2018] The health risks associated with radon are particularly concerning for children in educational facilities due to prolonged exposure during a biologically vulnerable period. [Gordon2018]

Measurement & Assessment Guidance

Measurement methodologies broadly fall into active and passive sampling categories. Active sampling methods, such as using the Lucas cell, are suitable for short-term radon concentration monitoring and provide real-time data fluctuations. Passive sampling methods, typically involving track detectors or electrets, are used for long-term monitoring and offer less variable data across extended periods. [Salonen2025]

Actions for IAQ Improvement

Effective mitigation requires identifying dominant radon entry routes, which most often include:

1. **Identify dominant radon entry routes**
   - Cracks and joints in foundations and floors,
   - Installation penetrations,
   - Basements, crawl spaces, and utility rooms,

- Pressure differences caused by ventilation or heating systems,
- Active radon monitors are recommended for diagnostic surveys.

2. **Mitigation Measures – Hierarchical Approach**
   - Low-impact measures (typically effective at moderately elevated levels):
     - Sealing visible cracks and penetrations,
     - Improving controlled ventilation,
     - Limiting radon transfer from basements to living areas.
   - Technical measures (for concentrations above the reference level):
     - Mechanical ventilation systems,
     - Ventilation of sub-floor or basement spaces,
     - Air pressure balancing.
   - System solutions (for high radon concentrations):
     - Sub-slab depressurization,
     - Soil gas extraction systems,
     - Dedicated radon mitigation installations.
3. **New Buildings – Prevention by Design**
   - The radon potential of the site should be considered at the design stage,
   - Preventive measures (radon barriers, sub-slab piping) should be installed upfront,
   - Post-construction radon testing is strongly recommended,
   - Preventive construction is significantly more effective and cost-efficient than remediation.
4. **Risk Communication with occupants is essential**
   - Emphasize that radon risk is manageable and reducible,
   - Explain the difference between concentration and actual exposure,
   - Avoid alarmist messaging; instead highlight the effectiveness of mitigation.
5. **Follow-up and Continuous Improvement**
   - Mitigation must always be verified by control measurements,
   - Long-term monitoring may be advisable in high-radon areas,
   - If mitigation is ineffective, reassessment and redesign of measures are required.

4.3.4 Ozone

Background

Ozone is a trace atmospheric gas with significant oxidizing properties. While beneficial in the stratosphere, its presence in the troposphere is problematic due to its high reactivity with various compounds, resulting in oxygenated organic species and particles. Human exposure to ozone predominantly occurs through inhalation, although skin reactions may also occur. Ozone's acute and chronic health effects, its contribution to morbidity and mortality, and potential DNA damage over prolonged exposure are well-documented. Children are particularly vulnerable due to their higher air intake relative to their body weight and narrower airways, potentially leading to lasting lung damage. Ozone exposure in this group is associated with respiratory illnesses, increased asthma-related symptoms, and school absenteeism. In urban areas, ozone is formed through sunlight-induced reactions between nitrogen oxides and volatile organic compounds. Outdoor sources primarily contribute to indoor ozone levels, reaching approximately 30 %-70 % of outdoor concentrations, unless specific ozone-producing devices are used indoors. [Salonen2018]

There are significant correlations between indoor and outdoor ozone concentrations in school and office buildings. The absence of major indoor sources, gas-phase reactions, and deposition can lead to lower indoor ozone levels. Seasonal differences are evident, with both indoor and outdoor ozone concentrations typically higher in the summer. However, these trends at the European level do not always match observations at the country level. Factors such as ventilation types, filter types, open windows, and the presence of specific materials and decorative elements significantly affect indoor ozone levels. Additionally, indoor chemistry, particularly terpene reactions with ozone, may reduce indoor ozone concentrations. Devices such as printers, photocopiers, and various indoor appliances, including air cleaners, can release ozone either intentionally or unintentionally. [Salonen et al. 2018]

Thresholds and Limit Values:

- EEA/EU target value: 120 µg/m³, not to be exceeded more than 25 days per calendar year.
- WHO recommendation (strict): The WHO Global Air Quality Guidelines recommend a more stringent level of 100 µg/m³ (8-hour mean) to minimize respiratory health risks.
- Information threshold: 180 µg/m³, the level at which the public must be informed of potential risks to sensitive groups.

Measurement & Assessment Guidance

Monitoring ozone levels is critical due to its high reactivity and its role as a powerful oxidizing agent. Unlike other pollutants, indoor ozone levels are primarily driven by outdoor-to-indoor infiltration, although certain office equipment (e.g. laser printers) and specific air purifiers may serve as internal sources.

In accordance with EEA standards and the EU Air Quality Directive, the official reference method for measuring ozone is ultraviolet (UV) photometry (European Standard EN 14625:2012: The technical protocol for UV photometry measurement). This technique quantifies O_3 concentrations by measuring the absorption of UV light at a wavelength of 254 nm. The primary metric for health assessment is the maximum daily 8-hour mean.

Indoor monitoring strategy: For indoor air quality guidelines, it is recommended to use calibrated electrochemical sensors or metal-oxide semiconductor sensors to monitor the indoor/outdoor (I/O) ratio. This helps evaluate the effectiveness of building envelopes and the performance of activated carbon filters in HVAC systems, which are essential for neutralizing ozone.

Actions for IAQ Improvement

Implement effective strategies to minimize indoor ozone levels and associated reaction products. Cover topics such as [Salonen2018]:

1. **Outdoor Ozone Filtration:**
   - Reduce the penetration of outdoor ozone into indoor spaces by installing high-efficiency filters (e.g. activated carbon filters) within the ventilation system to filter ozone from the incoming air supply.
2. **Limiting Indoor Ozone Sources:**
   - Minimize the use of devices and appliances that emit ozone indoors, including printers, photocopiers, and other electronic equipment, particularly in poorly ventilated areas or near frequently occupied zones.
   - Use devices labelled as "low-emission" or "ozone-free" to reduce indoor ozone concentrations.
3. **Reducing Gas-Phase Reactions:**
   - Limit the use of materials and products, such as certain cleaning chemicals and air fresheners, that release emissions which can react with ozone to form secondary pollutants.
4. **Improve Occupant Awareness:**
   - Raise awareness among occupants about the risks associated with ozone and how to reduce indoor ozone concentrations.

4.3.5 NO_x

Background

Nitric oxide (NO) and nitrogen dioxide (NO_2) are the principal nitrogen oxides associated with combustion sources, including vehicle emissions, industrial activities, and residential heating systems. [Demirel2014] In indoor environments, NO_2 can infiltrate from outdoor sources or be produced by indoor combustion appliances that use wood, oil, kerosene, or coal, such as stoves, heaters, and fireplaces. [Seinfeld2016] Exposure to NO_2 at levels exceeding the ambient air limit (200 µg/m³ for 1 hour) may affect pulmonary function, particularly in individuals with asthma. Additionally, NO_2 is a precursor to tropospheric ozone, contributing to indoor gas-phase chemistry reacting with ozone to form the nitrate radical. This connection highlights the importance of considering NO_2 concentrations when discussing air quality standards. [Salonen2019]

Measurement & Assessment Guidance

Measurement strategies, as outlined in ISO 16000-15, involve both short-term and long-term monitoring using methods such as continuous chemiluminescence, which can capture peak exposure levels. [ISO16000-15] It is essential to assess both indoor and outdoor NO_2 levels, given the considerable variation across different regions and building types. Factors such as ventilation type, air-exchange rates, and building airtightness significantly affect indoor NO_2 levels and personal exposure. [Weschler1994; Kornartit2010] Monitoring methods should prioritize real-time data capture to better evaluate exposures linked to health effects in school and office environments. [Salonen2019]

Actions for IAQ Improvement

When assessing individual exposure, ambient NO_2 concentrations alone are insufficient. Other factors affecting personal exposure, such as activity patterns (e.g. opening windows and using NO_2-emitting devices) and outdoor activities, should be considered. It is also important to account for short-term peak exposure levels, as these are relevant to adverse respiratory effects associated with NO_2 exposure. [Salonen2019]

Implement measures to maintain NO_2 levels below the WHO guideline values and to mitigate both long-term and peak exposure risks. Cover topics such as:

1. **Strategic Location Planning**
   - Be aware that traffic is a major source of NO_x and consider this in construction planning.
   - Plan window and air-intake locations carefully, ensuring they are positioned away from outdoor sources of NO_2, such as busy streets or industrial areas.
2. **Indoor Environment and Appliance Planning:**
   - Minimize or eliminate the use of NO_2-emitting appliances, such as unvented heaters or gas stoves, in indoor environments. Use safe alternatives, like electric heaters, to reduce indoor emissions.
3. **Ventilation and Air Purification:**
   - Improve ventilation system efficiency to maintain sufficient air exchange without compromising indoor air quality.
   - Advise closing windows during periods of high ambient NO_2 levels.
   - For new buildings, consider mechanical ventilation systems equipped with air purification technologies, such as HEPA filters or activated carbon filters, to reduce NO_2 concentrations.
4. **Enhancing the Building Envelope:**
   - Increase building airtightness by improving insulation, sealing gaps, and using advanced materials to reduce the infiltration of outdoor pollutants, including NO_2.
5. **Improve Occupant Awareness:**
   - Raise awareness among occupants about the risks associated with NO_x and measures to reduce indoor NO_x concentrations.

4.3.6 Volatile and semi-volatile organic compounds

Scope and definitions

Volatile organic compounds (VOCs) and semi-volatile organic compounds (SVOCs) are important classes of organic compounds commonly present in indoor air. Indoor environments are often the dominant contributor to personal VOC exposure, while SVOCs often have multiple exposure pathways including inhalation, dust ingestion, and dermal contact. [Wallace1989] VOCs and SVOCs primarily originate from building and construction materials, furnishings, electric equipment, consumer and personal care products, as well as heating and combustion activities. Outdoor sources such as industrial processes and traffic exhaust also contribute to indoor VOC and SVOC levels. [Halios2022] Short-term exposure to VOCs can cause irritation, headaches, fatigue, and respiratory symptoms, while long-term exposure is associated with allergies, asthma, and the carcinogenicity of certain compounds. [Csobod2014]

Organic compounds are commonly classified according to their volatility based on their boiling points measured at standard atmospheric pressure (101.3 kPa) (Table 1). SVOCs may also be operationally defined by their chromatographic retention range: when using a capillary column, they elute within a retention range between *n*-pentadecane ($C_{15}H_{32}$) and *n*-docosane ($C_{22}H_{46}$) for non-polar systems, and between ethyl adipate ($C_{10}H_{18}O_4$) and methyl palmitate ($C_{17}H_{34}O_2$) for polar systems.

Table 1: Definition of very volatile and semi-volatile organic compounds, adapted from [EPA2025]

DESCRIPTION	ABBREVIATION	BOILING POINT RANGE (°C)	EXAMPLES
Very-volatile organic compounds	VVOC	<0 to ≤100	Propane, butane, methyl chloride
Volatile organic compounds	VOC	<100 to ≤250	Formaldehyde, d-Limonene, toluene, acetone, ethanol, 2-propanol (isopropyl alcohol), hexanal
Semi-volatile organic compounds	SVOC	<250 to ≤400	Pesticides (DDT, chlordane), plasticizers (phthalates), polychlorinated biphenyls (PCBs), certain flame retardants (e.g. polybrominated biphenyls), polycyclic aromatic hydrocarbons (PAHs)

Polycyclic aromatic hydrocarbons (PAHs) are a large group of SVOCs containing two or more aromatic rings and are widespread in the environment. PAHs with two or three aromatic rings are more volatile and typically present in the gaseous phase, while those with four or more rings are found mostly bound to particles. [Keyte2013, Lohmann2004] They are formed during incomplete combustion or pyrolysis processes of organic matter and can originate from both natural and anthropogenic sources, including industrial activities, traffic emissions and biomass burning. In indoor air, sources include smoking, cooking, candle burning, heating and gas-fired appliances, in addition to infiltration from outdoors. [Howsam1988, VanDrooge2013]

Several PAHs have carcinogenic classifications according to the International Agency for Research on Cancer (IARC) ranging from Group 1 (e.g. benzo[a]pyrene) to Groups 2A/2B (e.g. dibenzo[a,h]anthracene; benzo[a]anthracene; chrysene; benzo[j]/[b]/[k]fluoranthene; indeno[1,2,3-cd]pyrene), while others (e.g. benzo[ghi]perylene, fluoranthene, pyrene) are classified in Group 3. Among PAHs, benzo[a]pyrene is currently used as the main marker compound for regulatory assessment in ambient air. Under Directive (EU) 2024/2881, the annual average target value of 1 ng/m^3 for benzo[a]pyrene in ambient air will become a binding limit value from 2030. Beyond their carcinogenicity, several compounds from the PAH group also have toxic and mutagenic effects, while epidemiological studies have further documented adverse effects on cognitive function, developmental processes, and respiratory health, particularly in children. [Mortamais2017, Alemany2018, Zhen2023]

Common principles

Sampling of VOCs and SVOCs in indoor environments can be conducted using passive or active techniques, each with distinct advantages and limitations. It should be noted that for both techniques, post-sampling desorption of VOCs is a risk that must be controlled.

1. Passive sampling

Passive sampling is cost-effective, silent and independent of power supply, with sampling durations ranging from hours to days (VOCs) or weeks (SVOCs). Passive samplers capture compounds solely through concentration-gradient-driven diffusion. Their uptake rate depends on the sampler geometry, pollutant diffusion coefficients, and temperature, which should be recorded for accurate concentration calculations. The uptake proceeds in a linear uptake phase, followed by a curvilinear phase before equilibrium is reached between sampler and air (Figure 2).

For deployment, place the passive sampler at breathing height (1–2 m above the floor) and at least 1 m away from doors, windows, ventilation outlets or other strong airflows, and protected from direct sunlight exposure. Remove the sampler cap or seal immediately before deployment without touching the sorbent surface. Position the opening according to instructions to minimize deposition of dust and droplets. Expose the sampler for the planned period and, at the end of the exposure, close and store it sealed (typically at ≤4 °C or frozen for some SVOCs), with field blanks handled identically.

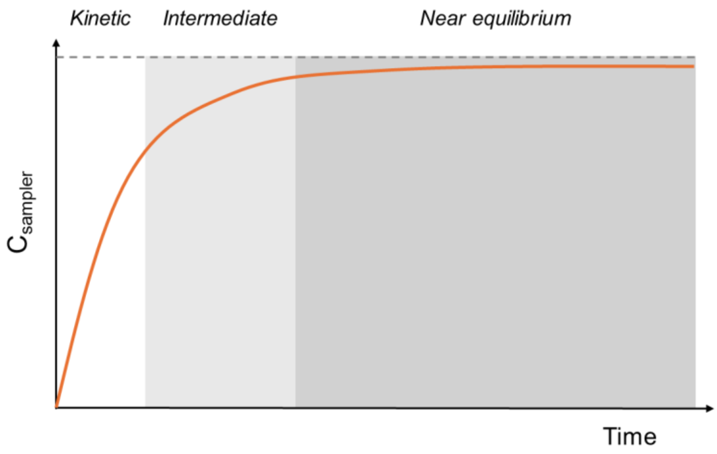

Fig. 2: Generalized uptake profile for a passive sampling device [Mayer2003]

For passive air sampling, the following equation is used to calculate the concentration of a given organic compound:

$$\text{Eq. 1:} \quad C\ (\mu g\ L^{-1}) = \frac{m\ (\mu g)}{Q\ (L\ min^{-1}) \times t\ (min)}$$

Where *m* is the mass of the pollutant, *t* is the sampling time, *Q* is the sampling rate (known as diffusive uptake rate), which depends on the diffusion coefficient of the target pollutant and is directly associated with the cross-sectional area of the sampler opening and the length of the diffusion zone. Sampling rates are compound-specific and temperature-dependent.

2. Active sampling

Active sampling uses a pump to draw a defined volume of air through a collection device, allowing both continuous (online automated) and discontinuous (offline) measurements. Active sampling enables precise control of sample volumes and is recommended for applications requiring accurate concentration measurements.

If sampling is carried out during occupancy hours, it is important to minimize pump noise, for example by placing the pump in a sound insulated enclosure while leaving the sampling inlets outside. For deployment, mount the sampling inlet at breathing height (1–2 m above the floor) and at least 1 m away from windows, doors, and ventilation outlets. Set the pump to the required flow rate (e.g. 2 L/min) and verify the flow using a calibrated flow meter before starting the sampling. Connect the sampling pump to the sorbent tube or filter holder, ensuring correct flow direction and using leak-tight fittings, and start the pump. Sampling should ideally occur during occupancy hours to reflect real exposure conditions. Check the pump flow at least at the beginning and end of the sampling period (and intermittently for longer runs) to ensure that the flow rate remains within the acceptable range.

At the end of sampling, disconnect the sorbent tube or filter, immediately cap both ends and wrap it in aluminium foil (or place the filter in a clean Petri dish or cassette). Direct contact of the tube with plastic material should be avoided, as it may cause contamination. Store samples according to the planned SVOC analysis (e.g. sealed, refrigerated or frozen, and protected from light) and transport them to the analytical laboratory together with field blanks and pump calibration records for subsequent analysis.

For active air sampling the sampling rate *Q* in Eq. 1 is substituted by the defined pump flow rate *F* (L min^{-1}) giving the following equation:

$$Eq.\ 2 \quad C\ (\mu g\ L^{-1}) = \frac{m\ (\mu g)}{F\ (L\ min^{-1}) \times t\ (min)}$$

Where C is the air concentration, m is the collected mass of the target compound, F is the calibrated pump flow rate, and t is the sampling duration.

Table 2: Recommended duration of sampling for VOC assessments in school environments

SAMPLING DURATION	ADVANTAGES	DISADVANTAGES
24 h / 5 days (entire school week)	Higher air volume sampled, decreases detection limit	Can lead to overestimation of exposure to certain pollutants (overnight accumulation).
5-8 h / 5 days (during occupancy periods, entire school week)	More accurate exposure assessment for certain pollutants	Lower air volume sampled, increases detection limit (compared with 24 h / 5 days). Requires samplers to be capped after the sampling period, resulting in additional time required for sampling by technical staff.

Volatile Organic Compounds (VOCs)

1. Sampling of VOCs

As described in the previous section, sampling of VOCs can be conducted using passive diffusion tubes and similar samplers, which are suitable for long-term averaged measurements and routine monitoring. Active sampling uses calibrated pumps to draw air through sorbent tubes and allows more precise control of the sampled volume.

ISO 16000-5 describes sampling strategies for VOCs; ISO 16000-6 specifies active VOC sampling on adsorbent tubes followed by thermal desorption (TD) and analysis by gas chromatography with mass spectrometry (GC–MS) or flame ionisation detection (GC–FID). Solvent desorption using activated carbon and carbon disulfide [EN14662-5] is a cost-effective alternative.

Carbonyl compounds such as formaldehyde, acetaldehyde, and other low-molecular-weight aldehydes are commonly analysed using derivatization with 2,4-dinitrophenylhydrazine (DNPH). In this approach, air is actively sampled through DNPH-coated cartridges, where carbonyl compounds react to form stable hydrazone derivatives. These derivatives are subsequently extracted with an organic solvent and analysed by high-performance liquid chromatography (HPLC), typically coupled with UV detection.

This method is described in ISO 16000-3 and is widely regarded as the reference technique for the quantitative determination of formaldehyde and other carbonyl compounds in indoor air. Recent experimental studies have further demonstrated the robustness of DNPH-based sampling for gaseous formaldehyde, while also highlighting the influence of sampling parameters and calibration strategies on quantitative performance, particularly under low-concentration indoor conditions

[Souza2020]. DNPH-based methods provide high sensitivity and selectivity for aldehydes and are therefore well suited for regulatory assessments and health-oriented exposure studies.

2. Analysis of VOCs

After collection, VOCs are pretreated for analysis using thermal desorption (TD) or solvent desorption (SD). In the TD method, VOCs are thermally released from the adsorbent, concentrated in a cold trap, and then injected into a gas chromatography equipped with either a mass spectrometer (GC-MS), a flame ionisation detector (GC-FID), or a photoionization detector (PID) for analysis. In the SD method, VOCs are extracted from the sorbent using a solvent, typically carbon disulfide (CS_2), and then analysed by GC-MS or GC-FID. Internal standards are used to correct for variations in sample preparation and injection. Both the TD and SD methods comply with ISO 16000-6 and ISO 16017-2 and enable sensitive and selective quantification of a broad range of VOCs.

Semi-Volatile Organic Compounds (SVOCs)

1. Sampling of SVOCs

As described in the common principles section, sampling of SVOCs can be performed using passive methods (based on diffusion of a compound into a sorbing matrix) or active methods (based on a defined volume of air). However, due to their semi-volatile nature, SVOCs partition between the gas phase and particles. The more volatile an SVOC, the higher its partitioning into air. Since passive samplers only take up chemicals from the gas phase (unless specifically designed and deployed to allow gravimetric particle deposition), the total concentration in air obtained from passive sampling is likely to be underestimated, with larger differences for less volatile compounds.

Active sampling for SVOCs is mostly conducted using discontinuous (offline) measurements. In this approach, pollutants are usually collected on filters or sorbent tubes for laboratory analysis. However, even in active sampling, the partitioning of SVOCs between gaseous and particulate phases should be considered. For accurate measurement of air concentrations, both phases should be collected, for example by combining particle filters with downstream gas-phase sorbents.

PAHs with two to three aromatic rings (e.g. naphthalene), predominantly present in the gas phase, are typically sampled using active sorbent tubes or passive polyurethane foam (PUF) disk samplers. In contrast particle-bound PAHs (≥4 rings; e.g. benzo[a]pyrene), are typically collected by drawing air through quartz or polytetrafluoroethylene (PTFE) filters, often positioned upstream of a sorbent to capture both phases. Active sampling using sorbent tubes enables the collection of both gas-phase and particle-bound PAHs and this approach does not allow for differentiation between these two phases. [Aretaki2024] To provide a more comprehensive characterization of PAH profiles in air, gas-phase, particle-phase, and combined total concentrations should be reported.

2. Analysis of SVOCs

After collection, samplers (filters, sorbent tubes, or disks) are extracted (e.g. Soxhlet, ultrasonic, or pressurized liquid extraction) using an appropriate solvent. A clean-up step may be necessary to remove matrix interferences (e.g. using silica gel or Florisil), followed by concentration of the extracts. Depending on the compounds of interest, analysis is carried out by GC–MS(/MS) for hydrophobic and thermally stable compounds (e.g. phthalates, organophosphate esters, brominated flame retardants, PAHs) or by LC–MS(/MS) for more polar or thermally labile SVOCs. Quantification is performed using calibration curves, ideally with isotope-labelled internal standards to correct for recovery losses and matrix effects.

Quality assurance / quality control

Stringent QA/QC procedures must be implemented during sampling and analysis. Key elements include calibration of passive samplers (e.g. to account for different sampler geometries, temperature effects, etc.), verification of pump flow rates before and after sampling for all active sampling campaigns, breakthrough testing for active sorbent methods, and the use of field and laboratory blanks. Instrument calibration using certified reference standards and routine performance checks for

GC–MS, GC–FID, and LC–MS systems are required. Internal standards should be used, environmental conditions (particularly temperature) should be documented, and relevant ISO standards (e.g. for VOCs: ISO 16000-1, -4, -5, -6; ISO 16017-2; ISO 16000-3 for DNPH/HPLC) should be followed to ensure reproducibility and comparability across monitoring programmes.

For the specific case of DNPH-coated cartridges, quantitative performance depends strongly on sampling conditions, especially flow rate and sampling duration. Intermediate flow rates generally provide the optimal derivatization; very low rates may cause mass-transfer artefacts, while high flow rates can lead to incomplete reaction. Calibration procedures also influence accuracy, and liquid-phase DNPH standards are widely used but may introduce biases compared with gas-phase sampling, especially when absolute concentrations are reported. These effects are less critical for comparative assessments and exposure screening, for which DNPH methods are particularly well suited, provided that sampling parameters are carefully controlled and results are interpreted in context.

Recommendations

For VOCs, passive sampling is recommended for long-term averaged screening, whereas active sampling should be used when accurate concentration data are required. For SVOCs (including PAHs), collect both gas and particle phases to determine accurate air concentrations. Indoor SVOC concentrations should always be interpreted in the context of the applied sampling strategy, as factors such as sampling duration, flow rate, sorbent or filter type, and storage conditions influence the effectiveness with which particle-bound SVOCs are captured.

Reported concentrations should therefore be accompanied by clear information on sampling and analytical protocols and should only be compared with guideline or reference values derived using comparable methods. All procedures must meet agreed QA/QC requirements, including flow checks, field blanks, and defined quantification limits.

To support reliable and comparable indoor air assessments, the following recommendations apply:

- Define the measurement objective before choosing sampling parameters; DNPH-based carbonyl methods are better suited for exposure assessment and comparative studies than for determination of absolute concentrations.
- Select appropriate flow rates to ensure adequate residence time for gas–solid interaction and derivatization in the case of DNPH-based carbonyl methods (intermediate flow rates are generally preferable).
- Adjust sampling duration according to expected concentration levels without exceeding validated operational limits.
- Consider SVOC partitioning between the gas and particle phase, choose an appropriate sampling strategy and interpret results accordingly.
- Account for calibration procedures and matrix effects when interpreting results.
- Prioritize consistency in sampling and analytical conditions when comparing different spaces.
- Report key methodological parameters (flow rate, duration, sampler type, storage, analytical method) alongside concentration results.

Actions for IAQ Improvement

By implementing the following measures, indoor exposure to volatile and semi-volatile organic compounds (VOCs and SVOCs) can be effectively reduced, supporting healthier indoor environments and lowering both acute and chronic health risks for occupants.

1. **Exposure Assessment:**
   - Conduct a systematic walkthrough survey to identify potential sources of VOCs and SVOCs, including building materials, furnishings, flooring, paints, adhesives, sealants, cleaning

products, air fresheners, personal care products, pesticides, electronics, and combustion-related activities.

- Measure VOCs using integrated or real-time sampling techniques (e.g. sorbent tubes, passive samplers, PID sensors) to capture both background levels and short-term peaks.
- Assess SVOCs using combined air and dust sampling, as well as surface wipe sampling, as SVOCs tend to partition to indoor surfaces and settled dust.
- Account for temporal variability (e.g. newly renovated spaces, seasonal ventilation patterns) and spatial gradients (e.g. proximity to sources such as treated furniture or electronic equipment).
- Collect contextual data by recording ventilation rates, temperature, relative humidity, occupancy patterns, cleaning practices, product usage, and building age, as these factors strongly influence VOC and SVOC emissions and persistence.

2. **Source Control:**
   - Use low-emission or certified products (e.g. low-VOC paints, adhesives, furnishings, and floor finishes).
   - Use ready-to-burn wood when using indoor combustion appliances (e.g. fireplaces) for heating purposes to promote more complete combustion and reduce the formation of toxic by-products (e.g. PAHs).
   - Avoid materials known to contain SVOCs of concern, such as certain plasticizers, flame retardants, and biocides, particularly in frequently occupied spaces.
   - Minimize the use of fragranced products, air fresheners, solvents, and pesticides indoors.
   - Store chemicals, cleaning agents, and maintenance products in sealed containers away from occupied areas.
   - Schedule refurbishment activities during periods of low occupancy.
   - Allow sufficient off-gassing time for new materials before occupancy, supported by increased ventilation.
   - Avoid window ventilation in buildings close to major roads or other outdoor combustion sources during traffic peaks or when outdoor pollutant levels are high. Where possible, ventilate during periods of lower outdoor pollution or use filtered mechanical ventilation.
   - Avoid indoor smoking and uncontrolled combustion sources, which can significantly increase VOC levels.
   - Avoid wearing outdoor footwear indoors to reduce the transfer of particle-bound pollutants into indoor environments.
3. **Ventilation and Air Exchange:**
   - Provide ventilation rates in compliance with national regulations to dilute internally emitted VOCs.
   - Increase ventilation during periods of elevated emissions, such as following renovation activities, installation of new furnishings, or intensive cleaning.
   - Use mechanical ventilation systems with controlled air exchange to ensure consistent dilution of gaseous pollutants.
   - In areas with outdoor VOC pollution, use filtration or air treatment systems and manage air-intake timing to limit pollutant ingress.

- Maintain moderate indoor temperatures and humidity levels, as elevated temperatures can increase VOC and SVOC emission rates from materials.

4. **Cleaning, Surface Management, and Dust Control:**
   - Implement regular cleaning routines using vacuum cleaners equipped with HEPA filters to reduce SVOC-contaminated dust reservoirs.
   - Damp wiping of surfaces is preferred over dry dusting to limit resuspension.
   - Use low-emission, fragrance-free cleaning products to avoid introducing additional VOCs.
   - Maintain and clean surfaces that can act as SVOC sinks (floors, upholstered furniture, textiles), as these materials influence long-term exposure.
5. **Awareness, Communication, and Risk Management:**
   - Inform occupants about common indoor sources of VOCs and SVOCs and practical actions to reduce emissions.
   - Apply stricter precautionary measures in environments occupied by sensitive groups (e.g. children, pregnant individuals, older populations).
   - Recognize that SVOCs contribute to chronic exposure through accumulation and re-emission from indoor reservoirs, requiring sustained management rather than short-term interventions alone.

4.4 Microorganisms

Background

Airborne microorganisms (microbial bioaerosols) are fundamental to both ecological balance and human health, playing a significant role in immune system regulation and development particularly during childhood [Rook2023; Cervantes2025]. However, indoor microorganisms can have severe effects on human health, for example by exacerbating asthma symptoms or acting as allergens or infectious agents [Hartiala2026]. In particular, when aerosolized and inhaled, they can trigger reactions in susceptible individuals [Kumar2021]. Approximately 30 % of the global population suffers from some type of allergy related to fungi [Crameri2013]. Even though the microbiome may account for up to one-third of airborne pollutants, it is rarely considered in IAQ standards [Viegas2019a; Carrazana2023; Cervantes2025].

The indoor air microbiome is usually less diverse than that of outdoor air and contains taxa that are absent or rare outdoors [Kembel2012; Carrazana2023]. The bacterial microbiome is composed of species derived from occupants, indoor microenvironments, and outdoor air, with Gram-positive genera, such as *Micrococcus*, *Staphylococcus*, *Streptococcus*, *Kocuria*, *Corynebacterium*, *Actinobacteria*, *Arthrobacter,* and *Bacillus* dominating. Less numerous Gram-negative bacteria, including *Enterobacter, Pseudomonas, Alcaligenes, Acinetobacter*, *Moraxella,* and *Pantoea,* are of increasing concern due to the release of endotoxins that cause adverse health effects. The fungal microbiome in buildings without dampness problems is largely derived from the outdoors and is shaped by geographic conditions, with common genera including *Cladosporium, Alternaria, Aspergillus, Trichoderma, Fusarium*, *Penicillium, Rhizopus* and *Stachybotrys.* Microbial species closely related to human pathogens are often present indoors at higher concentrations than outdoors [Kembel2012; Chawla2023; Hartiala2026]. Opportunistic pathogens occur at lower abundance in residential environments compared with higher-risk settings such as hospitals [Madsen2023; Atalay2023; Hartiala2026]. Schools have been reported as buildings with the highest bioaerosol levels due to the high occupancy and insufficient ventilation [Wargocki2020; Vornanen-Winqvist2020; Hartiala2026].

Sampling & Assessment Guidance

As with all exposure assessments, it is essential to align the choice of sampling methods and assays carefully with the study objectives [Ferguson2019; Cox2020; Whitby2022]. Collecting contextual data in the investigated rooms not only informs the choice of sampling strategies but also supports the interpretation of the results and the identification of key exposure determinants and potential sources of contamination [Dias2024; Vorkamp2024]. Information on environmental variables is particularly valuable when assessing microorganisms, as it enables observed variations in microbial diversity to be linked to specific conditions present during sample collection. [Vorkamp2024] This relationship provides insight into how environmental factors influence bioaerosol composition [Cox2020] and supports the development of more targeted and appropriate recommendations.

1. Sampling

Sampling campaigns targeting microbial contamination should be conducted using multiple sampling methods (passive and active), as well as a combination of culture- based and culture-independent (molecular) methods [Whitby2022; Carrazana2023; Dias2024; Cervantes2025; Hartiala2026]. This multi-method approach overcomes the limitations of individual techniques and provides a more reliable characterization of microbial contamination for exposure and risk assessment [Dias2024; Cervantes2025; Šunić2026].

Passive methods collect particles through gravitational settling and/or electrostatic attraction. These methods have the advantage of allowing extended sampling periods and provide data over a broad temporal scale (weeks to months), but they are not aligned with specific events (e.g. cleaning or ventilation activities). In contrast, active sampling can provide data integrated over hours or minutes, which can be aligned with specific events; however, due to high variability in bioaerosol concentrations, it may underrepresent the microorganisms present. [Dias2025; Ferguson2019; Viegas2024]

For passive sampling, electrostatic dust collectors (EDCs) are recommended for monitoring a broad spectrum of microorganisms – including fungi, bacteria, and viruses [Viegas2019b; Viegas2022; Furst2024; Furst2025; Sequeira2024] – as well as microbial by-products such as endotoxins and mycotoxins [Viegas2023; Viegas2024; Kristono2019]. The adaptability of passive methods and their ease of use, make them valuable tools for environmental monitoring in both indoor and occupational settings. EDCs are recommended as a complementary approach alongside traditional air sampling, as indoor dust is the main reservoir of microbial taxa in domestic environments.[1]

Active sampling (air sampling devices) should be selected to effectively capture microorganisms and allow for both quantification and diversity analyses, while minimizing sampling bias [Lemieux2019; Whitby2022; Ferguson2019]. The three most common methods for bioaerosol sampling are air filtration, impaction and liquid impingement.

Filtration has the highest collection efficiency and the greatest DNA recovery. [Ferguson2019] There are three main classes of filters: fibrous (which trap particles within a fibre matrix), membrane (with a complex structure of pores in which particles are deposited) and flat filters (air passes through the membrane pores and particles collect on the filter surface). With filtration, desiccation can affect cell integrity and reduce bacterial viability, resulting in a preferential recovery of more resilient spore forming taxa (e.g. *Bacillus*), depending on filtration time, pore size, and filter type [Whitby, 2022]. However, if molecular methods are applied (e.g. metagenomics), maintaining cell viability may not be essential [Whitby, 2022]. Furthermore, the use of filters for molecular analyses allows for the nucleic acids to be extracted directly; however, elution from filters can cause sample losses, and optimisation of sample recovery is required [Ferguson2019]. For example, air filtration using polycarbonate filters

[1] Reference: InChildHealth paper, to be published

with a phenol-chloroform DNA extraction method resulted in the highest bacterial DNA yield recovery [Ferguson2019].

Impactors collect microbial cells by depositing them directly onto the surface of a suitable agar culture medium perpendicular to the airflow. Their efficiency depends on particle inertia during collection, and this feature allows impactors to classify all particles into different size fractions. [Grydaki2024; Ferguson2021] However, cell viability may be reduced due to impact stress, and some microorganisms may therefore be preferentially recovered over others. Moreover, not all microorganisms can be cultured under laboratory conditions, so this method underestimates the total number of cells in the air. [Whitby2022]

Impingers collect particles in a liquid collection medium, which can be cultured to enumerate viable microorganisms or analysed by culture-independent molecular methods. Current impingers include cyclone-based samplers with high airflow rates, allowing for shorter sampling periods than filtration-based samplers. Such devices with high flow rates and/or high collection efficiency are essential when collecting samples for molecular assays, as low concentrations of bioaerosols in indoor environments, make it challenging to obtain sufficient genetic material [Ferguson2019]. Furthermore, the type of matrix used to collect the air samples is important to consider, as this may affect yield and introduce inherent biases [Ferguson2019]. Another potential issue with liquid samplers is sample matrix loss through evaporation, which should be replenished, particularly during extended sampling periods [Ferguson2019].

2. Assays

Following the same rationale as for sampling methods, the combined use of both culture-based and culture-independent (molecular) assays helps to overcome the limitations inherent in each individual approach [Whitby2022; Viegas2023; Viegas2024; Cervantes 2025]. While molecular tools provide highly refined capabilities for exposure assessment, certain aspects of microbial contamination cannot be addressed by molecular methods alone. For example, evaluating fungal azole resistance, bacterial antimicrobial resistance, and determining minimum inhibitory concentrations (MICs) is critical for environmental isolates from specific indoor environments, such as hospitals, schools, and care homes, and can only be accomplished using culture-based methods [Cervantes2025]. Therefore, applying culturomics using multiple culture media to enable broader characterization of microbial diversity – including adjusting incubation temperatures to identify thermotolerant species – is essential in IAQ assessments. [Cervantes2025]

Microscopic analysis of airborne biological particles using a variety of stains (e.g. FISH, CARD-FISH) can also be applied and has the advantage of quantifying both culturable and non-culturable microorganisms. For example, impaction or liquid impingement onto glass slides has been used to quantify airborne bacteria and fungal spores by microscopy. [Whitby2022] However, this approach can be time-consuming and requires specialized knowledge and expertise during sample processing, staining, and visualisation.

Regarding molecular tools, different approaches can be applied depending not only on the study aim, as mentioned earlier, but also on the type of indoor environment being assessed. In the case of an outbreak caused by a specific agent, targeted methods such as qPCR, LAMP or ddPCR are suitable, since the targets are already identified (e.g. Legionella or influenza virus). [Bani2024]

However, when assessing an indoor environment without specific complaints or reported illnesses among the occupants, broader, untargeted approaches should be considered to capture the full microbial diversity. A major consideration with molecular methods is nucleic acid yield and maintenance of nucleic acid integrity, and therefore the microbial diversity recovered. This depends on both the nucleic acid extraction protocol used and the sampling method, which may introduce biases, and is particularly important for low-biomass bioaerosol samples, where the DNA extraction method needs to achieve high recovery efficiencies. [Ferguson2019; Šunić2026]

Furthermore, molecular methods such as DNA-based methods (via PCR) do not discriminate between intact cells and cell debris, as both types of material can be amplified by PCR, and it can be difficult to determine whether a microbial DNA signature originates from a viable organism. As most health effects are caused by exposure to microbial products (e.g. endotoxins, mycotoxins) rather than viable microorganisms themselves, methods to measure these compounds in relation to human exposure are also important. [Whitby2022]

The most important implications for sampling and evaluation are:

- Sampling: Avoid using a single overarching standardized method; instead, bespoke methods should be designed for each environment and target microorganism(s) to ensure a representative sample of the specific environment is collected and sample integrity is maintained. Combine active sampling (air/ bioaerosol samples) with passive sampling methods (e.g. EDCs, settled dust).
- Assays: Employ a combination of culture-based methods (e.g. screening for fungal azole resistance and thermotolerance) and molecular tools (for more accurate characterization), either targeted (qPCR/LAMP) for specific agents, or broad (e.g. sequencing).
- More long-term integrated analyses of bioaerosols are needed including the use of real-time analysis methods. This will provide a more comprehensive picture of the microbial components and their activities.

Actions for IAQ Improvement

Implement effective strategies to reduce the impact of microorganisms on indoor air quality. Cover topics such as:

1. **Exposure Assessment:**
   - Use a standardized walkthrough survey checklist to collect contextual information specific to the indoor environment, such as moisture sources, ventilation patterns, and occupant activity levels that may influence microbial exposure.
2. **Ventilation:**
   - Optimize ventilation to reduce bioaerosol concentrations and control indoor humidity, thereby preventing bacterial accumulation and mould growth. Adjust ventilation strategies seasonally to balance effective air exchange with minimized thermal losses or gains.
   - Open windows fully for short intervals several times a day to ensure effective air exchange; use cross-ventilation techniques where feasible.
   - Before opening windows, evaluate outdoor air quality to avoid introducing external contaminants.
   - Use intelligent ventilation systems in smart buildings that adjust airflow based on real-time sensor data, such as occupancy levels, pollutant concentrations, and CO_2 levels.
3. **Hygiene Practices:**
   - Maintain indoor humidity within the 30–60 % range to inhibit mould growth, and encourage the use of mechanical ventilation, dehumidifiers, or extractors in damp or high-risk areas.
   - Avoid overuse of antibacterial cleaning products; excessive sterilization may disrupt beneficial microbial communities that are crucial for immune health and increase the likelihood of antimicrobial or fungal resistance.

4. **Thresholds:**
   - Establish a robust evidence base to develop health-relevant targets for microbial exposure that are specific to the building type, purpose (e.g. schools, homes, workplaces), and the population assessed (e.g. children, immunocompromised individuals). These thresholds should guide acceptability standards for microbial presence and be adaptable based on environmental factors and evolving scientific knowledge.
5. **Improve Occupant Awareness:**
   - Raise occupants' awareness of the influence of microorganism on indoor air quality and the measures that can be implemented to reduce their impact.

4.5 Particulate Matter and particle-related pollutants

4.5.1 $PM_{2.5}$ and PM_{10}

Particulate matter (PM) consists of a heterogeneous mixture of solid and/or liquid particles suspended in air, composed of organic and inorganic substances of widely varying size and chemical composition. Outdoor PM originates from both natural sources (e.g. dust, sea spray, pollen, spores) and anthropogenic activities (e.g. combustion, road traffic, industrial emissions, heating, biomass burning). In indoor environments, particles may originate from outdoor infiltration, indoor combustion, cooking, cleaning, resuspension of settled dust, occupant activities, building materials, textiles, furnishings, and consumer products. Particle exposure is commonly assessed using mass-based metrics, such as $PM_{2.5}$ and PM_{10}, but other metrics, including particle number concentration, size distribution, black carbon, chemical composition, and microplastic content, are also considered depending on the assessment objective. Concentrations are expressed in $\mu g \cdot m^{-3}$

Particles are commonly classified according to their aerodynamic diameter:

- PM_{10}: particles with a diameter ≤10 µm.
- $PM_{2.5}$: particles with a diameter ≤2.5 µm.
- PM_1 (subset of $PM_{2.5}$): ultrafine fraction with a particularly high capacity for deep lung penetration.

PM_{10} mainly deposits in the upper respiratory tract, whereas $PM_{2.5}$ (and especially PM_1) can penetrate deep into the bronchial tree and reach the pulmonary alveoli. A fraction of ultrafine particles may even translocate into the bloodstream and reach cerebral vessels. Numerous epidemiological studies have demonstrated associations between short- and long-term exposure to $PM_{2.5}$ and PM_{10} and increased risks of respiratory diseases (e.g. exacerbation of asthma and COPD, reduced lung function, respiratory infections), cardiovascular morbidity and mortality, adverse pregnancy outcomes, and premature death [WHO2021; HEI2020].

PM can be:

- Primary, i. e. directly emitted (e.g. cooking aerosols, coal- and wood-burning stoves, candles, tobacco smoke, resuspended dust).
- Secondary, formed in the atmosphere from precursor gases (SO_2, NOx, NH_3, VOCs).

Indoors, major sources include cooking (especially frying), solid-fuel heating, gas appliances, candles, incense, tobacco and e-cigarettes, printers, and the resuspension of settled dust due to occupant activity. Outdoor PM infiltration is also a significant contributor to indoor concentrations, particularly in urban and industrial areas.

$PM_{2.5}$ and PM_{10} are widely regulated in outdoor air and serve as key indicators in public health and environmental policies.

According to the WHO Global Air Quality Guidelines (2021), the recommended outdoor air guideline values for particulate matter are 5 µg/m³ as the annual mean and 15 µg/m³ as the 24-hour mean for $PM_{2.5}$, and 15 µg/m³ as the annual mean and 45 µg/m³ as the 24-hour mean for PM_{10}. These values are health-based benchmarks intended to reduce adverse health effects associated with both long-term exposure and short-term pollution episodes [WHO2021]. In the absence of indoor limit values for $PM_{2.5}$ and PM_{10}, these outdoor air guideline values may be used as reference points for the interpretation of indoor measurements.

Measurement & Assessment Guidance

PM is typically measured using:

- Gravimetric reference methods: Air is drawn through size-selective inlets (PM10 or PM2.5 impactors or cyclones) and collected on pre-weighed filters. After conditioning, filters are re-weighed to determine mass concentration ($\mu g \cdot m^{-3}$). This is the reference method for regulatory compliance.
- Optical particle counters (OPCs) and laser photometers: Provide real-time monitoring by estimating particle mass concentration based on light scattering. While highly useful for IAQ diagnostics and event-based analysis (e.g. cooking episodes), they require calibration and may be influenced by particle composition and humidity.
- Condensation particle counters (CPCs): Used to measure ultrafine particles (number concentration), particularly in research contexts.

For indoor air quality (IAQ) assessments, measurement strategies should consider:

- Duration (short-term event-based measurements vs. 24-hour or longer averages).
- Occupancy patterns and activities.
- Outdoor PM levels and ventilation strategies.
- Seasonal variability.

Continuous monitoring over several days is recommended to capture variability and identify peak exposure events (e.g. cooking, cleaning, heating periods).

Results should be interpreted in relation to:

- WHO guideline values.
- National or European regulatory limits (mainly defined for outdoor air).
- Building use type (e.g. schools, dwellings, healthcare facilities).
- Presence of sensitive populations (e.g. children, older adults, patients).

Short-term peaks are particularly relevant indoors, even when daily average concentrations comply with guideline values.

Actions for IAQ Improvement

By employing the following measures, indoor PM exposure can be effectively minimized, contributing to improved indoor air quality and reduced health risks for occupants.

1. **Exposure Assessment:**
   - Source Identification: Conduct a walkthrough survey of the indoor environment to identify potential PM sources, including cooking practices, combustion appliances, smoking, candles, and cleaning activities.
   - Real-Time and Integrated Monitoring: Combine continuous monitoring using optical sensors to assess real-time PM variability with integrated gravimetric sampling when regulatory-grade accuracy or long-term measurements are required.
   - Outdoor Infiltration Analysis: Assess the contribution of outdoor PM by comparing indoor and outdoor concentrations, considering infiltration, ventilation mode, and proximity to outdoor sources such as traffic, industry, ports, airports, construction sites, and biomass burning.
   - Contextual Data Recording: Collect additional contextual parameters such as occupancy patterns, ventilation rates, window-opening behaviour, outdoor air quality conditions (e.g. identification of major emission sources), and meteorological data to support accurate exposure assessments.
2. **Source Control (Priority Measure):**
   - Use extraction hoods during cooking, ensuring that they are vented outdoors and regularly maintained to reduce PM concentrations from cooking activities.
   - Avoid smoking indoors and limit the use of combustion-based heating systems to control direct PM emissions indoors. If this is not possible, consider replacing older heating systems with more efficient alternatives, even if solid fuels continue to be used for heating purposes.
   - Avoid the routine use of air fresheners, scented candles, incense, fragranced cleaning and personal-care products in shared indoor environments, as they can emit VOCs directly and may react with ozone to form secondary pollutants.
   - Regularly maintain and service combustion appliances to ensure clean and efficient operation.
   - Request emission or safety data sheets for building materials, furnishings, paints, adhesives, and flooring products, particularly in schools, healthcare settings, and other environments occupied by sensitive groups.
3. **Ventilation and Filtration:**
   - Ensure adequate ventilation in compliance with national regulations (e.g. RITE/CTE in Spain) to maintain acceptable indoor air quality.
   - Consider mechanical ventilation systems with heat recovery (MVHR) equipped with high-efficiency filters (e.g. ePM1 or HEPA filters) to effectively reduce indoor PM concentrations.
   - In areas with high outdoor PM levels, avoid opening windows during peak pollution periods and rely on filtered mechanical ventilation where available. If adequate mechanical ventilation with filtration is not available, portable air cleaners equipped with high-efficiency particle filters may be used as a supplementary measure.
4. **Cleaning and Maintenance:**
   - Use vacuum cleaners equipped with HEPA filters to minimize PM resuspension during cleaning activities.

- Implement a regular cleaning schedule, focusing on reducing settled dust and preventing its resuspension into the air.
- Maintain indoor relative humidity between 40–60 %, as this range reduces particle resuspension and limits secondary particle formation processes.

4.5.2 Microplastics

Background

Microplastics, defined as plastic particles typically smaller than 5 mm in diameter, are generated through the degradation of larger plastic items or deliberate manufacturing at a reduced scale. The increasing presence of microplastics as contaminants in indoor air has raised concerns due to their widespread occurrence in household goods, furnishings, and consumer products. Microplastics in indoor air can originate from the deterioration of plastics used in construction materials, furniture, and common household objects, leading to the dispersion of particles within indoor spaces. Inhalation of airborne microplastics is an emerging exposure pathway of concern. Potential health risks depend on particle size, shape, polymer type, additives, sorbed chemicals, and associated biological material [Dong2020]. However, evidence on long-term health effects and dose–response relationships remain limited, and standardized exposure thresholds have not yet been established. This underscores the need for research to evaluate risks and establish safe exposure thresholds.

Measurement & Assessment Guidance

The omnipresence of plastics results in a high risk of contamination in all determinations of microplastics. Contact with plastic materials must be avoided, including all components of the sampling equipment as well as synthetic fibres in clothing. Field blanks are essential and should be complemented by procedural laboratory blanks for the analytical determination.

Active air sampling is recommended as the primary approach for estimating airborne microplastic concentrations in defined volumes of indoor air, while dust sampling can be used as a complementary method to indicate longer-term accumulation on indoor surfaces.

Active air sampling may be performed using low- or medium-volume pumps equipped with pre-weighed, low-background filters such as quartz fibre, typically in the PM_{10}, inhalable particle, or total suspended particulate (TSP) size range. Sampling flow rate and duration should be selected to obtain sufficient particle loading for analysis without overloading the filter; existing studies on airborne microplastics often use flow rates of a few litres per minute and sampling durations ranging from several hours to 24–48 hours. [Geiss2024, Solórzano2025, Torres-Agullo2021, Torres-Agullo2025]. For deployment, mount the sampling inlet at breathing height (1–2 m above the floor) and at least 1 m away from windows, doors, and ventilation outlets.

Settled dust sampling, for example by vacuuming defined floor or textile areas using clean, inert equipment and collecting dust into pre-cleaned containers, can be used to estimate indoor microplastic deposition rates and to differentiate indoor from outdoor contributions. Dust samples often contain larger fibres and fragments and may require pre-sieving or pre-filtration to remove coarse material before microplastic isolation and analysis [Solórzano2025, Torres-Agullo2021].

Analysis

Analytical methods should be selected according to the particle size range, polymer type, and study objective. Visual observation alone is insufficient for polymer identification and should be combined with spectroscopic or mass chromatography techniques where possible. Common approaches include µ-FTIR, Raman spectroscopy and pyrolysis-GC-MS. Results should report particle number, size range, morphology, polymer type and mass concentration when the analytical technique used allows it. [Torres-Agullo2022, Zuri2026]

Samples should be processed in a clean laboratory suitable for microplastic analysis. Negative and positive controls should be included during sample processing. Procedural blanks serve as negative controls to monitor potential contamination during sample processing and analysis. Samples spiked with microplastics in a relevant size range serve as positive controls to monitor recovery and losses during the sample preparation steps.

Common steps in sample preparation include wet peroxide or enzymatic digestion to remove organic matter, density separation using high-density salt solutions to isolate plastics, and filtration onto analytical filters with pore sizes suitable for capturing particles down to at least tens of micrometres [Solórzano2025]. Procedures should avoid aggressive conditions that may degrade polymers or alter particle morphology.

Initial screening can be performed by stereomicroscopy or optical microscopy to classify suspected particles by size, shape (e.g. fibre, fragment, film, bead), and colour, followed by polymer identification using micro-Fourier transform infrared spectroscopy (μ-FTIR) or Raman spectroscopy on a representative or exhaustive subset of particles [Wright2019; Din2023]. Using these spectrometric methods, microplastics are commonly quantified as the number of plastic particles within a given size fraction and polymer type. The lower size range is typically 10-20 μm, pose challenges for alignment with health-relevant particulate matter size ranges. [Levermore2020]

Pyrolysis-GC/MS methods commonly quantify microplastics as the mass of a given polymer. The size fraction is defined by filtration steps in the sample processing rather than by instrumental limitations, thus enabling the detection of particles in the nano-size range. Combining $PM_{2.5}$ and PM_1 sampling with pyrolysis-GC/MS can extend coverage, but it requires sufficient collected mass to exceed method detection limits [Geiss2024] and stringent QA/QC measures.

Depending on the instrumental technique, results can be reported using different units, such as particle number or polymer mass per cubic metre of air for active sampling. For settled dust, results can be expressed as particle surface deposition per square metre and time unit. Reporting should include size ranges, shapes, polymer types, and key QA/QC information (e.g. field and procedural blank levels, detection limits, and recovery estimates). Given the lack of standardized parameters for reporting, as many details as possible should be provided to enable comparison between studies.

Recommendation

- Implement stringent QA/QC measures, including field blanks, as well as negative and positive controls in the laboratory. Avoid plastic materials during sampling and sample processing and prepare the samples for analysis in a dedicated clean laboratory.
- Sample airborne microplastics using active air sampling campaigns with size-selective inlets (e.g. PM10) at breathing-zone height in representative occupied rooms, with sampling durations sufficient to capture typical occupancy and activity patterns.
- Supplement air sampling with settled dust sampling in selected locations (e.g. floors, soft furnishings, ventilation outlets) when longer-term accumulation or source identification is required.
- Apply harmonized and documented protocols for sampling, sample preparation, and analysis, including defined procedures for filter selection, handling, digestion, density separation, and instrumental analysis.
- Report microplastic metrics according to instrumental outputs, i.e. in number-based and/or mass-based terms, with stratification by size class (e.g. 10–100 μm, 100–300 μm), morphology, and polymer composition, with clear reference to sampling and sample processing protocols. Provide as many details as possible to enable comparisons with other studies in the absence of more standardized reporting.

Actions for IAQ Improvement

1. **Exposure Assessment**
   - Identify likely indoor sources of microplastics, including synthetic textiles, carpets, upholstered furniture, plastic-containing furnishings, packaging, and household dust.
   - Assess exposure using indoor dust sampling and, where feasible, airborne particle monitoring focused on fine and fibrous particles.
   - Record occupant activities (e.g. vacuuming, laundry handling, textile movement), ventilation patterns, and cleaning practices.
2. **Source Control (Priority Measure)**
   - Prefer natural or low-shedding materials for textiles, furnishings, and floor coverings wherever feasible.
   - Minimize unnecessary plastic-based decorative items and soft furnishings in occupied spaces.
   - Manage textile wear by limiting excessive abrasion (e.g. through aggressive cleaning or movement of synthetic fabrics).
3. **Ventilation and Air Treatment**
   - Ensure adequate ventilation to reduce airborne particle accumulation, in compliance with national IAQ regulations.
   - Use mechanical ventilation or standalone air cleaners equipped with high-efficiency particle filters (e.g. HEPA) to reduce airborne microplastics.
   - Avoid high indoor air turbulence that may resuspend settled microplastic-containing dust.
4. **Cleaning and Dust Management**
   - Implement regular cleaning focused on dust removal using HEPA-filtered vacuum cleaners.
   - Prefer damp cleaning methods over dry dusting to limit resuspension.
   - Maintain surfaces and textiles to reduce fibre release and dust accumulation.
5. **Awareness and Precautionary Approach**
   - Raise awareness among occupants about common indoor sources of microplastics and practical reduction measures.
   - Apply precautionary strategies, particularly in environments occupied by sensitive groups (e.g. children, pregnant individuals, older populations).
   - Address microplastics as a long-term IAQ issue linked to material choices and dust management, rather than short-term peak exposures.

4.6 Bioaerosols and Aeroallergens

Background

The IPCC has characterized bioaerosols (particularly pollen and fungal spores) as bio-indicators of climate change [IPCC2022]. In addition, as a result of changes in land use and climatic conditions, new and emerging allergens are increasingly observed [Damialis2019, Kim2025, 2024]. This development is driven by various factors, such as the invasive nature of certain organisms and their expansion into new areas, the selection and planting of non-native plant species in urban green spaces, changes in soil conditions due to human activities, and changes in climatic phenomena that favour long-distance transport. Moreover, allergens themselves may have stronger effects either on their own, or through synergistic interactions with pollutants or other biological particles [Damialis2021].

While bioaerosols have increased in quantity and/or shifted towards earlier seasonal occurrence, little is known about their indoor abundance [Damialis2025]. It is evident that status of openings (e.g. windows) plays an important role in the exchange of bioaerosols between indoor and outdoor environments; however, a direct quantitative relationship has not yet been established. This may be related to the different methodologies applied to date for air sampling in these two environments, highlighting the need for low-cost, compact, low-noise, lightweight, and easy-to-operate automated sensing systems that can reliably operate in both indoor and outdoor environments. Some efforts have recently been undertaken in this direction; however, these systems are still in their early to intermediate stages of development and are competing with well-established, high-cost systems that have benefited from substantial investment and are aggressively promoted.

Indoor environments, although offering a high degree of controllability compared with outdoor environments, remain generally understudied. As a result, mechanisms governing the dispersal and growth of bioaerosols indoors are still not fully understood. Bioaerosols in indoor environments can be present through two processes:

- originating from the outdoor environment (e.g. through incoming air from windows, being transported by occupants, or ventilation systems), or
- growing on the indoor surfaces or within materials (primarily for fungi and bacteria).

It is therefore evident that the indoor environment is strongly influenced by the outdoor environment in terms of bioaerosol (and allergen) content, and this relationship should be further investigated, at least on a seasonal scale. Additionally, the movement of bioaerosols within indoor environments remains insufficiently studied, as does their interaction with other airborne chemical or biological compounds [Ofremu2024].

Measurement & Assessment Guidance

To date, measurements have focused primarily on outdoor environments, covering several methodological approaches in an attempt to gather as much information as possible on both the abundance of bioaerosols and their biodiversity.

The ‘gold-standard’ methodology has typically involved either ELISAs-based methods and the use of dust filters for allergen detection, or volumetric/gravimetric sampling of major pollen and fungal spores (e.g. cyclone, ChemVol, Hirst-type, Durham, Rotorod) [Kim2025, Damialis2025]. Few attempts have been made to apply eDNA-based approaches; however, these methods can be very costly and remain far from allowing automatic, near-real-time detection and data provision.

In the context of automatic and near-real-time monitoring of bioaerosols, only a few new-generation devices have been developed so far, operating either based on fluorescence spectroscopy or optical light microscopy [Maya-Manzano2023]. These are generally high-cost, both in terms of acquisition and operation/maintenance, and are often large, heavy and noisy, which limits their suitability for indoor bioaerosol monitoring. Apart from convenience, detection accuracy has recently improved significantly; however, this improvement is mainly limited to airborne pollen. For fungal spores, detection capacity is still in its infancy or has only been developed for 1 or 2 taxa. It is therefore necessary to invest in low-cost, automated, near-real-time, sensing systems that are compact, low-noise, and lightweight, and that can facilitate indoor monitoring. Such developments would also encourage continuous and accurate measurements (e.g. full seasonal coverage and the full spectrum of biodiversity), enabling the investigation of the entire indoor exposome and the development of indoor air allergen profiles. Such profiles can provide direct benefits for exposed populations (e.g. in workplaces, schools, hospitals), and indirect benefits by providing information on load-bearing elements (e.g. deterioration of buildings due to fungi) or cultural heritage components (e.g. deterioration caused by fungi and bacteria in museums and libraries). In all cases, it is necessary to follow appropriate measurement methodologies based on certified guidelines and adhere to specified rules, for example the inclusion of major aeroallergen types across all regions of the EU, covering both local populations and international visitors. The establishment of thresholds is not necessary at this stage, since different populations are sensitive to different quantities of bioaerosols and aeroallergens, which sensing systems should collectively account for.

Based on the methodologies developed to date, the prevailing conditions, and existing gaps, the following recommendations can help ensure adequate indoor air bioaerosol and (aero)allergen management practices:

- A minimum spectrum of bioaerosol/aeroallergen types such as pollen, fungi, viruses, bacteria, biological debris, house dust mites, cat and dog dander should be established for monitoring indoor concentrations, taking into account outdoor air composition.
- Establishment of continuous monitoring in schools and other public places and develop sustainable indoor-outdoor monitoring networks, with appropriate alert systems for precautionary and mitigation measures.

Actions for IAQ Improvement

Although there is currently no universal practice for directly improving indoor air quality in relation to bioaerosols and allergens, several measures can help prevent its deterioration:

1. **Exposure reduction**
   - Reducing bioaerosol entry: Keep windows and other openings closed during peak pollen or mould seasons and at times of day when concentrations are highest. Consult local/regional pollen/mould forecasts for guidance.
   - Use blinds and shutters properly: When windows are kept open, blinds or shutters should remain rolled up or closed to prevent accumulation of bioaerosols. Where used, window or door screens can help reduce indoor bioaerosol penetration but must be cleaned frequently.
2. **Ventilation and Humidity Control**
   - Daily ventilation: Implement daily ventilation during periods considered allergy-safe to reduce bioaerosol concentrations, while avoiding exposure during high-pollen periods.
   - Humidity control: Maintain indoor humidity at low levels to minimize the growth of fungi and dust mites. Use dehumidification equipment if necessary.
3. **Cleaning and Maintenance**
   - Frequent cleaning: Perform regular (at least weekly) cleaning and disinfection using materials that do not pose allergy risks or health hazards. This helps remove settled bioaerosols, prevent bioaerosol resuspension, and eliminate potential sources (e.g. fungal growth).
   - HEPA filter use: Use cleaning devices and HVAC systems equipped with HEPA filters to effectively capture bioaerosols and minimize indoor exposure.
   - Inspect indoor structures: Conduct monthly inspections of structural elements (e.g. walls, plumbing) and decorative features to detect damage caused by humidity or mould. Promptly address identified issues to prevent further bioaerosol generation.

4. **Material and Furniture Choices**
   - Avoid porous surfaces: Minimize or eliminate porous and adhesive surfaces (e.g. thick carpets, blankets, untreated curtains) on walls or floors that can trap and support the accumulation of bioaerosols. Where possible, select synthetic or non-porous materials, particularly in sensitive spaces such as schools, hospitals, and libraries.
   - Furniture positioning: Position large furniture items and other bulky items at least 10 cm away from walls and windows to ensure adequate airflow. This helps prevent dust and fungal accumulation.

5. **Plant Management**
   - Plant maintenance: For potted plants or planted walls, increase ventilation and cleaning routines during periods of high outdoor bioaerosol levels. This mitigates the risk of indoor bioaerosol build-up associated with these features.

4.7 Summary of Actions

Table 3: Overview of parameters and relevant actions

IAQ FACTOR	MAIN SOURCES / DRIVERS	KEY INDICATORS	MAIN RECOMMENDED ACTIONS	PRIORITY
Temperature	HVAC settings, building envelope, outdoor conditions	Indoor temperature (°C)	Maintain recommended comfort range, optimize HVAC operation, improve insulation and shading (for further actions or detailed information, see Section 3.2.1).	Medium
Relative Humidity	Ventilation, moisture sources (cooking, showers), climate	Relative humidity (%)	Maintain 30–60 % RH, use humidifiers/dehumidifiers, improve ventilation, control moisture sources (for further actions or detailed information, see Section 3.2.2).	High
CO_2	Occupancy, inadequate ventilation	CO_2 concentration (ppm)	Increase ventilation (natural/mechanical), prevent overcrowding, implement CO_2-based demand-controlled ventilation (for further actions or detailed information, see Section 3.3.1).	High
CO	Combustion appliances, smoking	CO concentration (mg/m^3 or ppm)	Maintain appliances, ensure proper ventilation, install CO detectors, avoid indoor smoking (for further actions or detailed information, see Section 3.3.2).	High
Radon			(for further actions or detailed information see Section 3.3.3).	
Ozone	Outdoor air infiltration, indoor devices	O_3 concentration (µg/m^3)	Use activated carbon filtration, limit ozone-generating devices, optimize ventilation timing (for further actions or detailed information, see Section 3.3.4).	Medium
NO_2 / NO_X	Gas appliances, outdoor traffic	NO_2 concentration (µg/m^3)	Replace or limit combustion sources, improve ventilation, manage outdoor air intake (for further actions or detailed information, see Section 3.3.5).	Medium

VOCs / SVOCs	Building materials, cleaning products, consumer products	TVOC, specific compounds (e.g. formaldehyde)	Select low-emission materials, reduce use of chemical products, increase ventilation after emission events (for further actions or detailed information, see Section 3.3.6).	High
Microorganisms/ Bioaerosols	Humidity, High occupancy, Outdoor Air, surfaces	Microbial contamination (counts and identification), High CO_2 resulting from occupancy.	**Humidity and occupancy:** Use mechanical ventilation or dehumidification in damp areas. Optimize seasonal ventilation to reduce bioaerosols and control humidity (30–60 %), using short, frequent window opening, cross-ventilation, or smart systems based on occupancy/air quality. Increase ventilation based on high CO_2 as indicator for high occupancy. **Outdoor air:** Ensure outdoor air quality is acceptable before ventilation (consider local outdoor sources of bioaerosols such as composting, or seasonality). **Surfaces:** Avoid excessive use of antibacterial products to preserve beneficial microbiota and reduce antimicrobial resistance risk (for further actions or detailed information, see Section 3.4).	High
PM ($PM_{2,5}$/PM_{10})	Cooking, combustion, outdoor infiltration, resuspension	PM concentration (µg/m^3)	Use extraction hoods, avoid indoor combustion, apply HEPA filtration, improve cleaning practices (for further actions or detailed information, see Section 3.5.1).	High
Microplastics	Indoor materials, textiles, dust resuspension	Particle number / mass	Reduce sources, improve cleaning practices, limit dust resuspension (for further actions or detailed information, see Section 3.5.4).	Low (emerging)
Allergens	Outdoor air, indoor reservoirs, ventilation	Pollen, spores, allergen levels	Filter incoming air, monitor exposure, adapt ventilation strategies seasonally (for further actions or detailed information, see Section 3.6).	Medium

5. GENERAL RECOMMENDATIONS AND ACTIONS TO IMPROVE INDOOR AIR QUALITY

5.1 General Recommendations

Regional- or national-level policies are essential to reduce IAP-related health effects at the population level. However, such policies take time to be implemented and, despite all upstream efforts to reduce IAP, pandemic outbreaks, wildfires and individual risk factors may require personal-level interventions. Therefore, healthcare professionals and the public must be empowered to mitigate exposure to and risk from IAP after careful consideration of the benefits of any intervention in relation to its potential adverse health effects, discomfort, inconvenience, and cost. [Laumbach2021; Laumbach2015; Rajagopalan2020; Carlsten2020]

Collective awareness-raising is key to promoting healthy habits and improving indoor environments, whether at home, in schools, offices or public spaces [Carlsten2020]. Raise awareness for the relevance of air quality with your family, friends and community.

Possible basic personal-level interventions to be considered include the following actions: [Laumbach2021; Laumbach2015; Rajagopalan2020; Carlsten2020]

- Avoidance of air pollution sources (e.g. adjustment of cooking and cleaning habits, use of fragrances, removal of dampness and mould).
- Optimisation of natural ventilation (e.g. opening windows and doors) considering local outdoor air pollution with possible daytime fluctuations, and seasonal allergens.
- Implementation of basic hygiene measures (e.g. in case of a pandemic) such as physical distancing, hand hygiene, and cough etiquette.

Rather than serving as a general recommendation, the use of face masks can be considered a targeted mitigation measure in specific scenarios. Face masks have long been used for workplace protection or in some parts of the world with more extreme air pollution levels. However, in the EU, the non-occupational use of face masks was less common until the COVID-19 pandemic. Unlike face masks used to prevent the spread of COVID-19, face masks for air pollution are intended to protect the wearer. Face masks are air-filtering devices that cover the nose and mouth and provide a highly variable level of protection. They may include certified respirators used for workplace protection, unregulated respirators, dust masks, surgical masks, cloth masks, and other improvised face coverings. The filtering material typically protects against airborne particles, although some types may also include adsorbent materials for the removal of gases. To maintain a high level of protection, an appropriate face mask must be selected and used correctly. In addition, the burden placed on the user and on society should be considered. However, the short-term use can be an effective mitigation measure, for example during a pandemic or extreme air pollution events such as wildfires. [Boulos2023; Chu2020; Greenhalgh2024; Laumbach2021; Laumbach2015; Rajagopalan2020; Carlsten2020]

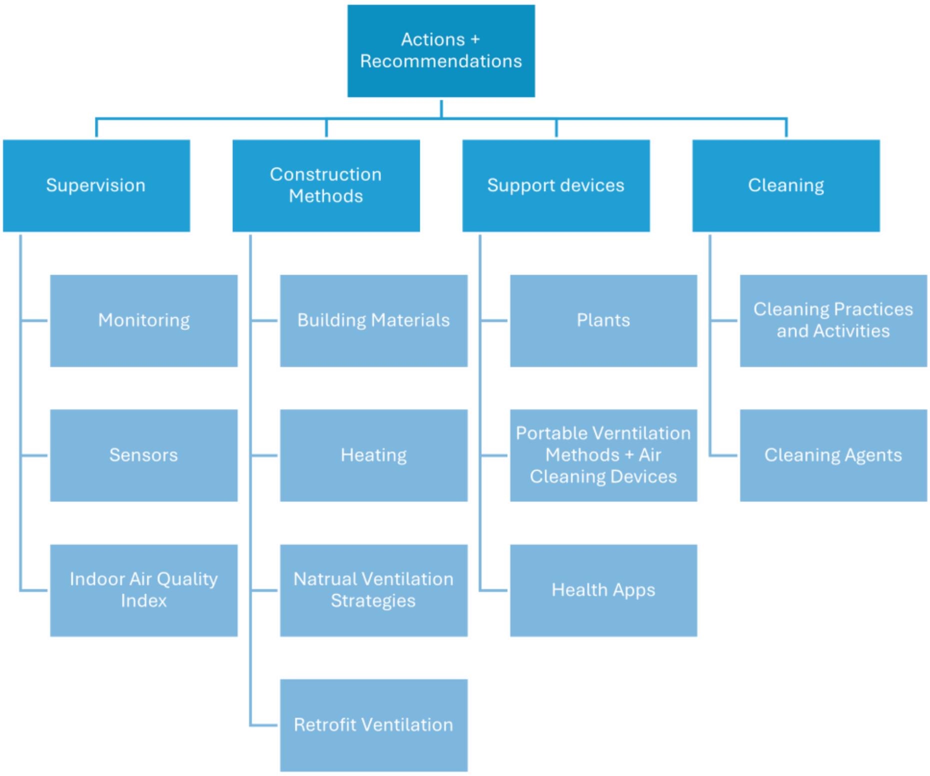

Fig. 3: Overview of actions and recommendations to improve indoor air quality

- Turn on ventilation or ventilate naturally: Turn on the mechanical ventilation system if available and operational. If not available, open doors and windows to promote fresh air intake and indoor air renewal.
- Identify and eliminate the source of pollution: Try to locate the possible source of the pollutants (e.g. chemicals, cleaning materials, specific activities) and remove or isolate it from the common space to avoid further deterioration of air quality.
- General cough etiquette and hygiene: cough etiquette, general hygiene (washing hands, ….)

5.2 Supervision of Indoor Air Quality

5.2.1 Improve Monitoring of IAQ

To enhance indoor air quality (IAQ) monitoring, it is recommended to combine objective measurements (sensors and sampling campaigns) with occupant-based information collection tools and with walkthrough survey checklists to retrieve important contextual information (as mentioned above). A particularly useful approach is the implementation of structured questionnaires addressed to building users (e.g. families, students, teachers, or workers) in order to assess levels of awareness regarding indoor air pollution and its health effects, identify main sources of information, and detect knowledge gaps or inequalities in access to relevant information (associated with socioeconomic context, building type, or usage conditions). The results can support the design of more targeted training and communication strategies.

In addition, it is advisable to establish clear IAQ assessment protocols defining what is measured, how and when measurements are performed, by whom, and according to which quality criteria (e.g. sensor location, minimum campaign duration, recording of occupancy, ventilation patterns, and pollutant-generating activities). Standards addressing specific pollutants and how to measure them exist at national, European, and international levels. Basic, publicly accessible search tools are available on the websites of the relevant standardization organizations.[2,3] Standardizing these procedures improves comparability between buildings and time periods and enhances the reliability and interpretation of results.

To increase participation and representativeness in monitoring campaigns, context-adapted recruitment and dissemination strategies may be implemented, such as distributing informational materials (e.g. flyers or posters) in buildings, schools, or through local media, as well as outreach via social media, radio, or community events, and the provision of short awareness-raising lectures in schools or public spaces. These actions help broaden engagement and reach groups that might otherwise remain under-represented.

Finally, it is recommended to integrate rapid perception-collection systems using QR codes or other digital tools, allowing occupants to record real-time perceptions related to IAQ (e.g. odours, sensation of stuffy air, or thermal discomfort). When synchronized with sensor data, this complementary information improves data interpretation and enables assessment of the extent to which occupants' perceptions align with objectively measured indoor environmental conditions, thereby supporting more effective prioritization of corrective actions.

5.2.2 Sensors

Low-cost sensors (LCSs) enable continuous, high-frequency monitoring of indoor air quality and can be deployed in large numbers to achieve fine spatial and temporal coverage. They are particularly valuable for identifying pollution dynamics, hotspots, occupancy-linked events, and ventilation performance – use cases for which laboratory-based methods would be impractical or overly expensive.

However, the accuracy and reliability of LCSs depend on multiple factors: the pollutant being measured, environmental conditions (e.g. temperature and humidity), sensor calibration, temporal drift, and cross-sensitivity to other pollutants. These limitations mean that LCS data should be interpreted with caution, and that a combined approach involving laboratory-based analysis is recommended for any assessment requiring regulatory compliance, chemical speciation, or toxicological interpretation.

Regulatory-grade instrumentation and laboratory-based analytical methods offer higher measurement precision and greater chemical specificity. They are essential for accurately quantifying pollutants that cannot be reliably measured or distinguished using LCSs, such as certain VOCs or coarse particulate matter (e.g. PM_{10}). Although these approaches are typically more resource-intensive and lack the spatio-temporal resolution offered by LCSs, they are essential when high accuracy, chemical speciation, toxicological interpretation, and in-depth characterization of indoor air pollution are required (see Chapter 4 for more details).

[2] https://www.iso.org/standards.html
[3] https://standards.cencenelec.eu/ords/f?p=CEN:105

Known systematic biases

For PM, high relative humidity can cause hygroscopic particle growth, leading optical sensors without inlet dryers to overestimate concentrations. Conversely, larger particles, particularly those outside the detection range of laser-based measurement principles, may not be properly detected or counted, resulting in an underestimation of PM levels. For gaseous pollutants such as VOCs, LCSs also exhibit limited chemical selectivity. This lack of specificity can lead to cross-sensitivity with other gases, and sensors may report concentrations as 'aggregated' signals (e.g. total VOCs), thereby limiting the ability to distinguish between individual compounds and complicating source identification. In addition, temporal degradation – a common issue in LCSs and one that is more pronounced in gaseous sensors – leads to gradual changes in sensor response over time. This can result in systematic over-estimation or under-estimation of pollutant concentrations if not properly addressed, as it becomes difficult to differentiate true changes in pollutant concentrations from variations caused by sensor drift.

LCSs require regular calibration against reference-grade instruments to ensure accurate and reliable measurements. This process corrects systematic biases and improves comparability across devices. In practice, calibration may include co-location with reference instruments or the use of established baseline conditions (e.g. outdoor CO_2 levels) to adjust sensor responses and maintain data quality.

Recommended combined approach

LCSs and laboratory-based methods are complementary rather than competing approaches. A combined strategy is therefore recommended, integrating LCSs and laboratory-based analyses to leverage the strengths of both methods.

Use LCS for: Indoor air quality sensors provide valuable insights into environmental conditions and human exposure when analysed systematically.

LCSs are particularly useful for screening and continuous monitoring, as they provide high-resolution temporal data that can reveal pollution dynamics. The analysis of temporal patterns in air pollutants captures how pollutant levels vary over time, often reflecting occupancy schedules and indoor activities such as cooking and cleaning. The identification of hotspots in indoor spaces can be achieved through using LCSs where pollutant concentrations are consistently higher, for example in poorly ventilated rooms or areas close to emission sources. Ventilation performance can be evaluated using sensor data, particularly CO2, to determine how effectively indoor air is renewed, often by examining how quickly pollutant levels decrease after peak events. LCSs are also valuable for assessing occupant exposure patterns and supporting real-time feedback, which can enhance awareness and engagement.

In summary, LCSs are particularly useful for:

- rapid screening before laboratory confirmation
- occupancy-related exposure analysis
- pilots and intervention studies
- ventilation assessments,
- educational and citizen-science activities, including awareness-raising campaigns.

Use laboratory analysis for: confirmation of LCS findings, chemical speciation, regulatory comparisons, health-related interpretation, research-grade accuracy.

What LCS can measure

Based on research within the IDEAL Cluster, the following pollutants and parameters are commonly measured and used in indoor air quality studies to assess changes in air pollution in absolute or relative terms using commercially available LCSs:

- CO_2 (ventilation indicator),

- Particulate matter (PM_1, $PM_{2.5}$, and PM_{10}, as well as particle number concentrations, depending on the manufacturer; only $PM_{2.5}$ shows comparable concentrations to those obtained with reference instruments),
- Comfort parameters (air pressure, air temperature, and relative humidity),
- NO_2 and O_3 (to be interpreted with caution due to cross-sensitivities and environmental interferences; recalibration is required to minimize temporal drift),
- TVOCs (With limited chemical resolution, and depending on the manufacturer, they are reported either in concentration units or as an index. TVOCs should be interpreted with caution and are generally not suitable for direct use in health-impact analyses.)

What LCSs cannot accurately measure:

- individual VOCs (formaldehyde, benzene, toluene, PAHs),
- microplastics,
- microbiological contaminants,
- chemical speciation (such as the detailed composition of PM)

5.2.3 Indoor Air Quality Index

A scoping review found that, among classified IAQ indices, 18 % were subjective, assessing occupant comfort, while 82 % were objective and based on measurements. The latter encompass a wide range of measurable parameters, including chemical, physical and biological pollutants and contaminants, as well as climatic indicators such as temperature and humidity. Furthermore, factors such as gender, age, health status, and other related characteristics influence the perceived IAQ and associated health risks. Two commonly used parameters are CO_2 and PM_{10}. [Pourkiaei2023] Although both parameters can be used as indirect indicators of bioaerosols – since CO_2 levels can provide information about ventilation rates and airborne particles can act as carriers of microorganisms affecting the respiratory tract – there remains a need for further research to determine which indicators are most appropriate for assessing microbial contamination. The selection of indicators should depend on the specific setting being evaluated and the objectives of the assessment. In addition, as mentioned previously, common protocols from field sampling to laboratory analysis – including result interpretation and recommendations – should follow a harmonized approach. While for most chemical contaminants legal and/or technical frameworks already exist that support consensus in assessment procedures, the same does not apply to bioaerosols. In this context, further research is required to establish standardized criteria and guidelines. This need is becoming even more pressing in the context of climate change, which alters outdoor microbial profiles and, consequently, indoor environments, potentially contributing to the spread of antimicrobial resistance (AMR).

Simple and user-friendly IAQ indices can support:

- risk assessment of health effects caused by IAP,
- decision-making for the adaptation of the indoor environment, and
- the evaluation of mitigation measures as an efficacy parameter.

To provide a meaningful assessment, IAQ indices should be adapted to specific indoor environments, such as residential homes, offices, schools, medical facilities or sports areas, as well as to the health-risk profiles of their occupants in relation to IAP exposure Currently, no single globally accepted and applied IAQ index exists, due to several challenges such as the diversity of different indoor environments, their use and occupant characteristics, substantial geographical differences, the involvement of multidisciplinary stakeholders and the lack of cohesive guidelines. [Pourkiaei2023]

5.3 Construction Methods

5.3.1 Building Materials

Building materials are among the most influential determinants of indoor air quality. They act as primary sources of volatile organic compounds (VOCs), carbonyl compounds, semi-volatile organic compounds (SVOCs), acidic species, and particulate debris, particularly in new and recently renovated buildings. Their emissions are strongly influenced by material formulation, installation conditions, ageing processes, environmental parameters (temperature and humidity), and interactions between indoor surfaces and reactive oxidants. Understanding how materials contribute to indoor pollutant loads is therefore essential for both construction practices and IAQ management.

Primary emissions from materials

Extensive evidence shows that construction products emit a complex mixture of VOCs and carbonyl compounds during the weeks and months following installation. European Collaborative Action (ECA) reports consistently identify paints, adhesives, engineered wood products, flooring, sealants, and insulation materials as major contributors to indoor pollutant loads in new and refurbished buildings [ECA2005; ECA2012].

Results from the HOMEChem campaign further demonstrate that emissions from the building envelope and static indoor materials can dominate the indoor VOC burden even in the absence of occupants, with organic acids and alcohols among the most abundant compounds [Arata et al., 2021]. Wood and wood-based panels are widely used as interior construction and finishing materials due to their aesthetic, structural, and sustainability advantages. However, recent studies demonstrate that wood products can be significant sources of VOCs and very volatile organic compounds (VVOCs), with emission intensity and chemical profiles strongly dependent on wood species and surface treatments. Measurements of commercially available interior wood panels show that untreated softwoods such as pine, as well as hardwoods such as oak, can exhibit relatively high emission levels dominated by terpenes, aldehydes, and oxygenated compounds, whereas spruce and aspen generally present lower-emission profiles. Importantly, appropriate surface treatments (e.g. painting or glazing) can substantially reduce total emissions and shift high-emission woods towards profiles comparable to low-emitting materials, while other treatments (e.g. staining) may increase specific compounds such as aldehydes. These findings highlight that both wood type and finishing strategy are critical determinants of indoor air quality when wood is used in interior applications [Jabbari2025].

Influence of temperature and humidity

Emission rates from building materials are strongly modulated by indoor temperature and relative humidity. Experimental studies show that moderate increases in temperature can substantially enhance VOC emissions, while formaldehyde emissions are particularly sensitive to both temperature and humidity due to resin hydrolysis and increased vapour pressure [ECA; Sharma2021]. Maintaining stable indoor environmental conditions can therefore help limit emission peaks and reduce occupant exposure.

Surface interactions and secondary processes

Beyond primary emissions, building materials can act as sinks and secondary sources of pollutants through sorption and re-emission processes. Interactions between indoor surfaces and reactive oxidants, such as ozone, may generate secondary pollutants, including aldehydes, organic acids, and ultrafine particles, particularly from polymer-based materials and coatings [NASEM2022; Salthammer2023].

Particles, fibres, and microplastics

In addition to gaseous pollutants, construction materials can release particles, fibres, and polymer-derived debris. Recent reviews highlight flooring, coatings, and textiles as relevant sources of indoor microplastics, contributing to long-term low-level exposure in indoor environments. [Martins2025]

Standards, certification, and regulatory frameworks

European efforts have produced a robust framework for evaluating and selecting low-emitting building materials. ECA Report 27 provides the foundation for harmonized testing and labelling schemes in the EU, emphasising standardized chamber methods (ISO 16000 series; CEN/TC 351) and evaluation criteria that combine:

- absence of carcinogens detected after 3 days,
- compliance with individual EU-LCI values (Lowest Concentration of Interest) for more than 180 VOCs[4], and
- use of TVOC only as a complementary metric.

Certification schemes such as AgBB, AFSSET/ANSES, M1, Blue Angel, EMICODE, and DICL apply these principles with varying degrees of stringency and have driven substantial reductions in emissions from European products. [ECA2005; ECA2012]

Integration with international certification systems

In addition to EU harmonisation efforts, several international building certification schemes incorporate material emission requirements that align closely with ISO and CEN standards. BREEAM (Hea 02) and LEED v4.1 (Low-Emitting Materials) require construction products – such as paints, adhesives, flooring and furniture – to comply with chamber testing protocols defined in the ISO 16000 series and, in many cases, with schemes such as AgBB, CDPH v1.2, M1 or Blue Angel. These certifications reinforce the market relevance of selecting low-emitting materials and demonstrate convergence between voluntary building rating systems and the EU-LCI framework. Their adoption in public procurement and private construction projects across Europe provides an additional driver for harmonized emission criteria and improved IAQ.

Recommendations

Based on current evidence, the selection and management of building materials should follow these principles:

- Prioritize low-emission materials certified under recognized European schemes.
- Avoid or limit materials with high reactivity (e.g. terpene-rich coatings, certain polymeric surfaces) in environments with elevated ozone infiltration or strong oxidant sources.
- Ensure enhanced ventilation during and immediately after installation, particularly during the first 2–4 weeks when emissions are highest, to promote the release and removal of primary emissions, in accordance with recognized “flush-out” best practices.
- Manage indoor temperature and humidity during unoccupied curing phases to support controlled emission release and effective removal, avoiding extreme conditions that may lead to material degradation or unstable emission behaviour.
- Minimize the use of materials requiring high-solvent adhesives or coatings, preferring water-based and certified low-VOC formulations.

[4] https://webgate.ec.europa.eu/circabc-ewpp/d/d/workspace/SpacesStore/5a1ce5d0-b945-480b-b7aa-8848864a5d4e/download

- Consider the particulate contribution of materials – especially polymer-based flooring, composites, and textiles – and implement cleaning strategies that limit resuspension of microplastics and dust.
- Plan for material ageing, including the potential for degradation and secondary pollutant formation, when selecting finishes or exposed surfaces in sensitive environments such as schools, nurseries, and healthcare facilities.

Collectively, these measures support healthier indoor environments by reducing primary emissions, limiting the formation of secondary pollutants, and aligning construction practices with the European vision for sustainable, low-pollution buildings.

5.3.2 Heating

Heating systems play a critical role in determining indoor air quality (IAQ) because they can act as direct sources of pollutants, modify the thermal and ventilation conditions of indoor environments, and influence emission dynamics from building materials and furnishings. Residential heating technologies vary widely in their emission profiles, energy performance, and impacts on occupant exposure, ranging from combustion-based systems that introduce pollutants directly indoors to electric or district heating systems that do not emit contaminants at the point of use.

Primary emissions from heating systems

Combustion-based heating devices – including gas boilers, unvented gas heaters, kerosene heaters, wood and pellet stoves, fireplaces, and biomass boilers – are among the most significant indoor sources of pollutants in dwellings. Studies show that gas-fired appliances can release nitrogen dioxide (NO_2), carbon monoxide (CO), ultrafine particles, formaldehyde, and other VOCs, particularly when poorly vented or improperly maintained. Biomass-based heating systems, such as wood stoves and fireplaces, emit substantial amounts of $PM_{2.5}$, black carbon, PAHs, benzene, formaldehyde and ultrafine particles, and are associated with elevated indoor particulate levels when doors or loading ports are opened or when air infiltration occurs during operation.

It was shown that different heating technologies are associated with distinct indoor emission profiles. Solid fuel combustion generally produces the highest emissions of PM and PAHs, whereas gas appliances predominantly contribute NO_x and CO, and fuel-oil heaters generate sulphur dioxide (SO_2), PM, and secondary sulphate aerosols [Mahmoud2021]. In contrast, electric heating and heat pumps produce no direct indoor emissions, and their indirect environmental impact depends on electricity generation. Heat pumps may nevertheless influence IAQ indirectly through changes in humidity, airflow patterns and interactions with building materials.

Evidence from energy-efficient dwellings indicates that heating methods interact strongly with building airtightness. In airtight homes, gas boilers and fireplaces may cause pollutant accumulation unless exhaust ventilation is adequate, whereas heat pumps and electrically powered heating systems generally maintain lower indoor pollutant levels [Sharma2021]. In naturally ventilated homes, heating-related pollutant levels vary with seasonal ventilation patterns, thermal stratification (i.e. the presence of temperature layer in rooms), and outdoor infiltration rates.

Interactions with ventilation, building tightness and thermal conditions

Heating systems influence IAQ not only through emissions, but also by altering airflow, ventilation rates, humidity, and indoor chemical processes. Energy-efficient retrofits that increase building airtightness without upgrading ventilation often leads to elevated concentrations of CO_2, VOCs, formaldehyde, and particulate matter, especially in winter when ventilation rates are reduced [Baeza-Romero2022].

Standards such as EN 16798-1 and ISO 17772-1 emphasize the need to integrate heating and ventilation design, ensuring that thermal comfort is achieved without compromising IAQ. Improperly balanced HVAC systems can lead to depressurisation and back-drafting from combustion appliances, increasing indoor concentrations of CO and NO_2 [ASHRAE2019].

Heating systems also influence indoor humidity levels. Combustion appliances typically reduce relative humidity, which can exacerbate dryness and respiratory irritation. Conversely, some heat pumps and radiant heating systems may increase relative humidity, thereby affecting microbial survival, VOC off-gassing, and occupant comfort. The WHO Housing and Health Guidelines recommend maintaining indoor temperatures of at least 18 °C during winter, noting that insufficient heating can increase humidity, condensation, mould growth and respiratory health risks. [WHO2018; ASHRAE2024; Sterling1985]

Secondary pollutant formation and interactions with indoor chemistry

Heating modifies temperature and moisture conditions, which in turn affect chemical emissions from building materials and furnishings. Higher temperatures accelerate emissions of formaldehyde, acetic acid, and other VOCs from paints, adhesives, engineered wood products, and plastics. It was demonstrated that heating cycles can enhance the sorption and desorption of VOCs and may increase secondary chemical processes involving ozone, nitrogen oxides, and organic surfaces, leading to the formation aldehydes, organic acids and secondary organic aerosols.

Combustion sources introduce radicals and NO_x that enhance oxidation chemistry. Gas heaters have been shown to increase indoor concentrations of nitrous acid (HONO), a precursor for hydroxyl radicals, which drive oxidative chemistry and the formation of secondary pollutants. Similarly, biomass combustion emits semi-volatile compounds that partition to particulate matter and undergo further oxidation within indoor environments.

Temperature and humidity effects on VOC and formaldehyde emissions during heating

Heating systems influence indoor IAQ not only through combustion emissions but also by modifying indoor temperature and humidity, which in turn alter VOC emission kinetics. Controlled studies show that VOC emissions can double with temperature increases from 16 to 23 °C [Arata2021], and that even small thermal increases (approximately 1.5 °C) can significantly increase emission rates [ECA1999]. Formaldehyde concentrations in real dwellings also fluctuate as a function of temperature and humidity, largely due to increased vapour pressure and resin hydrolysis under warm and humid conditions [Sharma2021].

Therefore, improper heating – leading to either excessively high indoor temperatures or poorly controlled humidity – can amplify VOC and formaldehyde concentrations, particularly in well-insulated homes where ventilation is limited.

Maintaining indoor temperature within the range of 20–25 °C and relative humidity between 40–60 % is recommended across all building types and heating systems, as elevated temperatures significantly accelerate VOC and formaldehyde emissions from materials, while inadequate humidity control increases both emissions and microbial risks.

Health relevance

The WHO Household Fuel Combustion Guidelines (2014) identify unvented gas heaters, kerosene heaters, coal stoves, and traditional biomass stoves as major sources of household air pollution linked to respiratory infections, asthma exacerbation, reduced lung function, cardiovascular disease, and premature mortality. Indoor $PM_{2.5}$ levels during biomass heating can exceed WHO guideline values by more than an order of magnitude. NO_2 concentrations from gas heating also regularly exceed WHO 24-hour guideline values in poorly ventilated homes.

Electric heating and heat pumps do not generate combustion-related pollutants indoors and are therefore recommended in environments housing children, older adults, and individuals with respiratory conditions. District heating systems similarly reduce household-level exposure by relocating combustion processes away from the indoor environment.

Regulatory frameworks, standards, and European policy context

European policy is increasingly oriented towards the decarbonisation and electrification of heating. The *Energy Performance of Buildings Directive (EPBD)* Recast 2024 sets out requirements for phasing out fossil-fuel boilers and for promoting heat pumps, district heating, and high-efficiency systems with minimal local emissions. The EcoDesign and Energy Labelling Regulations establish emission and efficiency requirements for solid-fuel boilers and local space heaters (e.g. EN 303-5 and the EN 16510 series), including limits for particulate matter, CO, organic gaseous carbon, and NO_x emissions.

Standards such as EN 16798-1 and ISO 17772-1 emphasize the integration of thermal comfort, ventilation, and IAQ, particularly in airtight buildings. Certification schemes such as BREEAM and LEED include requirements related to combustion sources, ventilation, and pollutant control, discouraging the installation of unvented combustion appliances and promoting clean heating technologies.

National and EU-level policies increasingly restrict the installation of high-emission biomass stoves in urban areas with poor air quality. The European Commission and the EEA have identified residential biomass combustion as a major contributor to wintertime $PM_{2.5}$ pollution, reinforcing the need to avoid inefficient wood-burning appliances and to ensure proper operation and maintenance of certified low-emission heaters.

Recommendations

1. Avoid unvented combustion heaters, including unvented gas, kerosene or portable LPG heaters, due to their substantial emissions of NO_2, CO, PM, and VOC.
2. Ensure proper exhaust ventilation for all combustion appliances and perform regular maintenance to prevent incomplete combustion and pollutant release.
3. Prioritize electric heating and heat pumps in residential and sensitive environments, as they produce no direct indoor emissions and improve IAQ when paired with adequate ventilation.
4. Use modern, certified low-emission biomass stoves only when necessary, ensuring compliance with EN 16510 or local standards, and avoid their use during episodes of poor outdoor air quality.
5. Manage humidity and ventilation together with heating, especially in airtight buildings, to reduce VOC emissions, condensation, and mould growth.
6. Install CO and NO_2 detectors in homes using combustion-based heating.
7. Integrate heating and ventilation design, following EN 16798-1 and ISO 17772-1, to ensure sufficient dilution of pollutants and prevent back-drafting.

Promote district heating networks and heat-pump deployment in line with EU decarbonisation and health-protection objectives.

5.3.3 Natural Ventilation strategies

When equipped with filters and used properly, ventilation systems can significantly enhance indoor air quality by capturing fine particles and potential pathogens, such as aerosol-borne viruses. However, it is important to note that many buildings, in which ventilation systems are installed fail to operate them effectively or keep them fully functional. Proper maintenance and usage are key to realising their full benefits.

It is also important to underline that air filtration does not reduce the concentration of carbon dioxide (CO_2) and other gaseous pollutants such as ozone (O_3) or nitrogen dioxide (NO_2). Therefore, the only effective way to reduce the levels of these gases is through air renewal, i.e. natural or mechanical (forced) ventilation using outside air.

Natural ventilation can be an effective tool for maintaining good indoor air quality, including in educational establishments. However, it is important to understand its limitations and its role in relation to other systems. Key principles for effective natural ventilation include:

- Cross and distributed ventilation:
- Place openings (windows or doors) on opposite walls and distribute them throughout the room to ensure complete air movement and avoid poorly ventilated areas.
- Ventilation of corridors, which directly influence air circulation in adjacent classrooms or offices.
- Adjustment to weather conditions: on windless days or on days with similar indoor and outdoor temperatures, it may be necessary to open windows wider to achieve adequate air renewal.
- Aim for continuous ventilation during occupancy, not only during breaks.
- During cold weather, it may be necessary to ventilate during breaks only. Adequate airing during breaks can be ensured by fully opening windows for short periods (approximately 5–10 minutes) to achieve rapid air exchange, preferably using cross-ventilation by opening windows or doors on opposite sides of the room. Ventilation should be carried out during every break as part of a routine, and CO_2 monitoring can be used, where available, to confirm that IAQ remains acceptable.

Basic ventilation protocol:

- Keep interior doors open.
- Open windows in a cross-ventilation and distributed configuration.
- Start with a total opening area equivalent to approximately 0.80 m^2 (slightly less than A0 paper size).
- Take CO_2 readings until they stabilize.
- Gradually adjust window openings to achieve a balance between ventilation efficiency and thermal comfort.

For indoor air management in situations of high occupancy without the possibility of natural ventilation (either due to extreme weather conditions, high outdoor pollution levels or other constraints), the following measures are recommended:

- Incorporate mechanical ventilation systems equipped with high efficiency filters that allow indoor air to be safely renewed by removing particles and pollutants without introducing low-quality outdoor air.
- This measure is especially critical in public buildings and facilities housing vulnerable populations, such as educational institutions, hospitals, residential care facilities, or day-care centres.
- Ensure adequate and regular maintenance of ventilation systems, including proper cleaning, timely filter replacement, and verification that all equipment is functioning correctly.
- Use of CO_2 meters: Carbon dioxide (CO_2) is an effective indicator of ventilation adequacy.

To get the most out of this means:

- Use correctly calibrated analysers, preferably located in the centre of the room at a height of more than 1.5 metres, away from direct ventilation sources and occupants.
- Allow the equipment to stabilize before taking readings (5-10 minutes, depending on the model).
- Monitor CO_2 levels continuously or at least every 15 minutes to adjust window openings.

- Keep CO_2 levels below 700-800[5] ppm, as recommended by the scientific community (e.g. the Aireamos platform or the Harvard School of Public Health). Please be aware that there are national thresholds to be considered.

In the absence of a CO_2 meter, it is recommended to:

- Ventilate spaces mechanically or naturally.
- If full opening is not feasible, maintain at least a permanent partial opening and carry out frequent full ventilation periods.
- Keep in mind that without measurements, ventilation is effectively undertaken „blind“ and there is an increased risk of CO_2 levels exceeding healthy thresholds, thereby increasing the possibility of aerosol transmission of pathogens.

Natural ventilation refers to air-exchange processes driven primarily by natural forces such as wind pressure, thermal buoyancy, infiltration through the building envelope, and intermittent window opening, rather than by mechanical systems. Although relatively simple, natural ventilation offers limited and highly variable control over air exchange, making it an important factor for IAQ, particularly in buildings with increasing airtightness.

Evidence from residential IAQ studies shows that naturally ventilated homes frequently experience insufficient air renewal, especially during winter or in warm climates where temperature gradients are minimal (Baeza-Romero et al., 2022). Reduced ventilation leads to the accumulation of pollutants originating from indoor sources, including CO_2, VOCs, formaldehyde, $PM_{2.5}$ and humidity-related contaminants. Window opening patterns strongly influence IAQ: concentrations of CO_2, HCHO, and TVOCs typically rise when windows remain closed for extended periods, while brief window-opening episodes may not provide adequate dilution of pollutants.

Natural ventilation can also facilitate the infiltration of outdoor pollutants such as $PM_{2.5}$, NO_2 and ozone, particularly in buildings located near roads, bus stops, or other emission sources. Studies highlight that the positioning of vents and openings is critical: poorly placed air inlets or exhaust paths can draw polluted outdoor air directly into living spaces or create zones with limited airflow (Baeza-Romero et al., 2022).

Interactions with heating systems and building airtightness further complicate ventilation performance. In winter, increased heating reduces window-opening frequency and enhances airtightness, leading to elevated VOC and formaldehyde concentrations, especially given the temperature-dependent emission behaviour of materials and furnishings. In airtight dwellings, natural ventilation alone often fails to maintain IAQ within recommended ranges, as highlighted in JRC and ECA reports.

Despite these limitations, natural ventilation remains relevant when used strategically. Cross-ventilation, use of cooler morning or evening periods, and short, high-intensity airing episodes can improve air renewal without excessive heat loss. However, reliance on static ventilation alone is generally insufficient in highly sealed buildings or in regions with poor outdoor air quality.

Recommendations

1. Use cross-ventilation whenever possible to increase airflow efficiency.
2. Avoid window ventilation during episodes of poor outdoor air quality (e.g. high traffic-related pollution, elevated ozone levels).
3. Combine natural ventilation with air-quality indicators, such as CO_2 levels, to assess actual ventilation needs.

[5] Short time exposure to higher CO2-levels (approximately 1000 ppm) will have no significant impact but these levels should be avoided on a long-time scale.

4. Complement natural ventilation with mechanical ventilation where feasible, especially in airtight buildings.
5. Consider timing and outdoor conditions: short, intensive airing during periods with favourable outdoor air quality typically provides more effective dilution.

5.3.4 Retrofit Ventilation

Retrofit ventilation refers to the process of adding or upgrading ventilation systems in existing buildings to improve fresh-air supply and indoor air quality, often without major structural changes. Retrofit ventilation with integrated air filtration allows existing buildings to significantly improve indoor air quality without major structural changes, while also reducing energy consumption. By adding decentralized or ducted mechanical ventilation units equipped with high-efficiency filters (e.g. ePM1 or HEPA-class, depending on the application), outdoor pollutants such as fine dust, pollen, and soot, as well as indoor contaminants such as VOCs and bioaerosols, can be effectively removed. When combined with heat- or energy-recovery systems (HRV/ERV), these solutions transfer heat – and often moisture – between exhaust and supply air, thereby reducing heating and cooling demand compared with simple window airing and helping to stabilize indoor temperature and humidity. Modern retrofit solutions may also include demand-controlled ventilation using CO_2, humidity, or particle sensors, which automatically adjust airflow in response to occupancy and pollutant loads, further optimizing energy use while maintaining comfort. Typical benefits include healthier indoor environments (fewer allergens and pathogens), improved comfort and noise reduction (reduced need to open windows on busy streets), extended service life of HVAC equipment due to cleaner coils and ducts, and potential compliance with increasingly strict building and workplace air-quality regulations, often achievable with relatively quick installation and limited disruption to occupants.

5.4 Support devices

5.4.1 Plants

Indoor plants can contribute to a healthier and more comfortable indoor environment through:

- photosynthesis (CO_2 uptake under sufficient light conditions)
- transpiration (effects on indoor humidity and thermal comfort), and
- phytoremediation/biofiltration (uptake and transformation of certain airborne pollutants, especially specific VOCs, often mediated by the root zone and its microbiome).

Beyond direct effects on indoor air chemistry, plants have been associated with reduced stress, improved perceived air quality, and increased wellbeing and productivity [Nieuwenhuis2014; Bringslimark2009]. These psychosensory effects are increasingly recognized as part of holistic IAQ and healthy building strategies.

While indoor plants should not be considered replacements for mechanical ventilation or source control, evidence suggests they can function as complementary nature-based solutions within healthy building strategies [Bringslimark2009; Torpy2014].

The mechanisms underlying pollutant removal involve several pathways. Gaseous compounds can be absorbed through leaf stomata, adsorbed onto plant and substrate surfaces, and metabolized by microorganisms inhabiting the rhizosphere. The growing medium often functions as the primary bioactive zone, where microbial communities degrade organic pollutants into less harmful compounds

[Orwell2004; Torpy2014]. Airflow across biologically active surfaces is therefore a key determinant of system performance, which explains the higher efficiency observed in active botanical biofiltration systems compared with passive plant installations.

Controlled chamber studies and field research have shown that plants and their associated root microbiome can remove harmful VOCs from indoor air [Wolverton1989; Orwell2004; Irga2017]. More recent investigations into active botanical biofiltration systems, in which air is continuously circulated through inorganic substrates, show substantially higher pollutant removal efficiencies and measurable clean-air delivery rates in real indoor environments compared to passive potted plants [Pettit2018; Torpy2014].

Which plants can be used (practical selection principles)

Plant performance depends strongly on species, leaf area, health status, light availability, and the planting system (e.g. potted soil, hydroponic systems, or active green walls), with the best results achieved when plants are healthy, adequately illuminated, and sufficiently sized for the space (i.e. providing adequate total leaf area).

Among the most commonly studied general-purpose indoor species is the spider plant (Chlorophytum comosum), along with other species frequently evaluated for VOC and CO_2 removal in chamber and room experiments.

If the objective is broader biofiltration (particularly for VOCs), active green walls or botanical biofilters may outperform passive potted plants, as they force air through the plant–substrate system; however, they require more careful operation and hygiene control.

How to use plants effectively (deployment)

- Define the objective: Use plants for supportive benefits (e.g. wellbeing, modest CO_2 and VOC moderation under favourable conditions) and rely on ventilation and filtration as the primary strategies for exposure reduction.
- Maximize functional leaf area (without overcrowding): Effects scale with leaf area and plant vitality; a few small plants rarely produce measurable changes in indoor air quality in real-world spaces.
- Provide adequate lighting: CO_2 uptake and several pollutant-removal mechanisms are light-dependent; insufficient lighting can reduce benefits and may even result in net respiration during nighttime.
- Prefer low-emission configurations: Select low-odour plants, avoid strongly scented flowers if occupants are sensitive, and place plants in clean, low-dust areas (away from zones with high resuspension).
- Avoid contamination via plants (risk management)

Avoid negative influences of plants on indoor air quality

Indoor plants can also introduce or amplify exposures if they are not properly maintained. Reported concerns include:

- microbial growth in potting media,
- allergen or mould issues when moisture is not adequately controlled
- potential release of biogenic VOCs from certain aromatic plants, and
- in some active systems, conditions that may support the proliferation of unwanted microorganisms if hygiene is inadequate.

Good practice measures to minimize risk:

- Moisture control: Avoid chronically wet soil; ensure proper drainage; do not allow standing water in trays; maintain indoor relative humidity within appropriate ranges; and prevent damp microenvironments around pots or walls.
- Substrate hygiene: Use high-quality, low-mould potting mixes; consider covering the topsoil with inert decorative materials to reduce soil aerosolization and resuspension; replace the substrate if mould develops.
- Routine maintenance: Remove decaying leaves; clean surrounding surfaces to prevent dust accumulation; avoid over-fertilization, which can promote microbial growth and pest infestations.
- Placement and protection of vulnerable occupants: In spaces occupied by individuals with asthma or immunocompromised conditions, as well as in hospitals or care facilities, avoid poorly controlled active green walls and any plants with visible mould; prioritize ventilation and filtration, and use plants only under strict maintenance protocols.

Do not oversell plants as "air purifiers": Treat plants as a supportive measure and verify their impact through measurements when improving indoor air quality is an explicit project objective.

5.4.2 Portable Ventilation Methods and Air-Cleaning Devices

Portable ventilation and air-cleaning devices provide a practical way to improve indoor air quality when building-integrated ventilation is insufficient or when opening windows is not advisable. Their main advantages are flexibility, rapid deployment, and targeted control in specific rooms (e.g. classrooms, bedrooms, meeting rooms, dining areas). Unlike natural ventilation, portable systems can operate independently of weather conditions and can help reduce exposure to particles ($PM_{2.5}$/PM_{10}), allergens, and bioaerosols, and – when equipped with appropriate media – odours and certain gaseous pollutants (e.g. VOCs).

Natural ventilation through windows can be effective for CO_2 control and moisture removal; however, it is not always reliable or safe. Portable systems offer advantages when outdoor air is polluted or when comfort, noise, or security constraints limit window opening.

- Open windows: weather-dependent, uncontrolled incoming air quality, potential introduction of outdoor pollution, noise and security concerns, increased energy loss.
- Portable systems: weather-independent, capable of filtering pollutants, support stable thermal conditions, more controllable, compatible with secure operation.

In practice, the most effective strategy is often a hybrid approach: use portable filtration continuously and open windows briefly and strategically when outdoor air quality allows, primarily to control CO_2 levels and indoor humidity.

Portable solutions typically fall into two categories:

1. Portable mechanical ventilation units, designed to exchange indoor air with outdoor air (sometimes with heat recovery). These are particularly useful for reducing the accumulation CO_2 and humidity.
2. Portable air purifiers, which recirculate indoor air through filters and return cleaned air to the same room. These are especially effective for reducing particulate pollution, including fine particles and some bioaerosols.

Both approaches are complementary: ventilation addresses stale air and CO_2 accumulation, while filtration directly reduces pollutant concentrations, particularly particles.

Portable devices are particularly recommended in the following scenarios:

- High outdoor pollution levels, where opening windows would introduce PM or other outdoor pollutants and compromise indoor air quality.
- Extreme weather conditions (e.g. heat waves, cold spells, storms), which make natural ventilation impractical or energy inefficient.
- Spaces with strong indoor sources, such as kitchens, workshops, rooms with printers or copiers, and high-occupancy areas.
- Urban buildings exposed to traffic emissions, where outdoor PM and NOx infiltration is frequent.
- Environments requiring controlled conditions, such as healthcare spaces, certain laboratories, and clean-room-adjacent areas.
- Spaces occupied by sensitive populations, including people with asthma, allergies, or cardiovascular and respiratory vulnerabilities.

How to use portable air purifiers effectively

1. **Proper sizing (capacity and CADR)**

Select a purifier with an appropriate Clean Air Delivery Rate (CADR) for the room volume. As a general rule, the device should be sized to achieve approximately 4–6 equivalent air changes per hour (ACH) through filtration. Undersized devices may run continuously without producing meaningful reductions in pollutant concentrations. When in doubt, select a unit rated for a room 20–30 % larger than the actual space.

2. **Strategic placement**

Place the unit to promote effective mixing and avoid short-circuiting of airflow. A good rule is central placement or positioning near the dominant pollution or occupancy zone, while maintaining at least 45 cm (approximately 18 inches) clearance around inlets and outlets. Avoid corners, placement behind furniture, and positions where air jets blow directly into obstacles. Where possible, place the unit roughly at breathing-zone height (approximately 1–1.5 m), or ensure that airflow patterns adequately cover the occupied zone.

3. **Continuous operation during occupancy**

Operate air purifiers continuously while the room is occupied, and ideally for 30 minutes before and after occupancy to pre-clean the air and remove residual pollutants. Use lower fan speeds when noise is a concern but ensure that performance remains sufficient for the target ACH.

4. **Maintenance and filter management**

Establish a maintenance routine:

- Monthly inspection (pressure drop, noise levels, and visible dust loading).
- Clean or replace pre-filters (on a weekly to monthly basis, depending on the dust load).
- Replace HEPA filters, typically every 6–12 months (or as specified by the manufacturer, depending on usage patterns and pollution levels).

Document filter replacements and note any changes in performance or noise that may indicate filter clogging or air bypass.

5. **Integration with IAQ monitoring**

Use low-cost sensors (or built-in indicators, with caution) to monitor $PM_{2.5}$ concentrations and confirm that device operation results in a measurable reduction. Monitoring supports evidence-based adjustment of fan settings and helps identify situations in which outdoor infiltration or indoor pollution sources dominate.

Excursus: Filtration technologies and what they address

Portable air purifiers often combine several technologies to address different pollutants:

- HEPA filtration: primary control for particles; effective for $PM_{2.5}$/PM_{10}, pollen, dust, and many bioaerosol-sized particles.
- Pre-filters: protect HEPA media by capturing larger particles such as dust and hair; essential for maintaining airflow and extending filter service life.
- Activated carbon (or other sorbents): targets odours and VOCs but requires adequate carbon mass and timely replacement (commonly 3–6 months, depending on the pollutant load).
- UV-C: can inactivate microorganisms but is most effective when combined with filtration; requires proper shielding and maintenance.
- Ionization: may reduce particle concentrations through agglomeration but should be approached with caution due to the potential for ozone generation; only devices certified for low or zero ozone emissions should be used.

Key principle: particle filters do not remove gases, and gas filters do not effectively remove particles – each pollutant class requires different filter media.

Recommendations for implementation (checklist)

- Assess the room: room volume, occupancy, indoor sources, existing ventilation, outdoor pollution context.
- Define the target: particles vs. CO_2 vs. odours/VOCs.
- Select appropriate equipment: CADR/ACH targets, filter media (HEPA, carbon), noise constraints.
- Optimize placement: avoid corners and obstructions; ensure good circulation in the occupied zone.
- Implement monitoring: establish baseline and verify improvement.
- Establish maintenance protocols: inspection routines, cleaning procedures, replacement schedule, documentation.
- Consider multiple devices in large rooms or under high pollutant loads rather than relying on a single oversized unit.
- Coordinate with HVAC systems (if present): avoid counter-productive airflow patterns and ensure adequate air mixing.
- Educate users: ensure correct operation, awareness of limitations, and realistic expectations.

5.4.3 Health Apps

Health (mHealth) applications have emerged as promising tools to support chronic disease management, medication adherence, and patient self-care. With over 300 000 health-focused apps available worldwide and approximately 90 000 new digital health apps released in 2020 alone, these technologies offer unprecedented accessibility and convenience for patients. Health apps perform a wide range of functions, including symptom tracking, medication reminders, behaviour-change support, patient-provider communication, and the delivery of educational content. Health apps are not intended to replace face-to-face consultations but rather to function as complementary tools for patient monitoring. [King2023; Liu2020; Whitehead2016]

In parallel, health applications are increasingly recognized as valuable support tools for monitoring indoor air quality (IAQ) and mitigating the health effects associated with indoor air pollution (IAP).

When combined with sensor-based monitoring systems, these tools enable real-time assessment of environmental exposure and facilitate evidence-based behavioural and preventive interventions.

Recommendations for implementing health apps:

1. **Integrate Real-Time Monitoring for Indoor Air Quality (IAQ)** [Lowther2019; Chojer2020; Saini2021; Marques2020; Pitarma2017]**:**
   - Health applications should integrate data from low-cost air quality sensors to monitor key pollutants such as $PM_{2.5}$, PM_{10}, VOCs, carbon monoxide, and nitrogen dioxide. This enables real-time environmental assessment to identify acute pollutant spikes and their potential impact on users' health.
   - Validate and calibrate low-cost sensors against reference-grade instruments to improve data accuracy, particularly when the resulting information is used to inform health-related decisions.
2. **Facilitate Evidence-Based Behavioural and Preventive Actions** [Lowther2019; Chojer2020; Saini2021; Marques2020; Robertson2024; Asikainen2016; Newman2020; Sousa-Pinto2021]**:**
   - Applications should display health-based pollutant thresholds, provide temporal trends, and issue exposure alerts when pollutant levels exceed recommended limits.
   - Offer actionable recommendations, such as improving ventilation, using air purifiers, optimizing filtration systems, reducing indoor smoking, modifying cooking practices, or avoiding the use of VOC-emitting products, to mitigate health risks associated with indoor air pollution.
3. **Support Vulnerable Populations** [Maung2022; Ntiamoah2025; Vardoulakis2020; Rabdel2024]**:**
   - Deploy features tailored to sensitive groups, such as children, older adults, and individuals with asthma, allergies, or other chronic respiratory diseases, as these populations are more vulnerable to the health effects of indoor air pollution.
   - Enable users to track symptoms (e.g. asthma exacerbations) and correlate them with environmental exposure data to enable personalized health management.
4. **Integrate Multifunctional Health Monitoring** [Maung2022; Ntiamoah2025; Vardoulakis2020; Rabdel2024]**:**
   - Combine environmental exposure data with health-tracking tools, such as symptom diaries and digital health platforms. This allows users and clinicians to better understand exposure-health correlations and tailor treatment approaches. This comprehensive picture of environmental trends and pollutant dynamics supports data-driven decision-making.
5. **Address Risks of Health Apps** [King2023; Lin2025; Wyatt2018]**:**
   - Ensure that applications adhere to robust data protection and security standards, transparently communicate data-collection practices, and provide options for data access and deletion to protect user information.
   - Emphasize accuracy by ensuring apps deliver evidence-based recommendations and avoid misleading or irrelevant advice that could result in patient harm. Include disclaimers directing users to seek professional assistance in emergency situations.
6. **Continuous Monitoring and Long-Term Analysis:**
   - Encourage real-time and long-term integrated monitoring of bioaerosols and pollutant levels using continuous data-collection methods. This approach provides a comprehensive picture of environmental trends and pollutant dynamics, thereby supporting data-driven decision-making.

7. **Recognize Limitations in Sensor Technology** [Chojer2020; Saini2021; Marques2020; Pitarma2017]**:**
   - Acknowledge and address the variability in low-cost sensor performance, which may be influenced by factors such as humidity, temperature, and sensor drift over time.
   - Ensure accuracy by implementing rigorous calibration and validation procedures for sensors used in health-related applications.

5.5 Cleaning Recommendations

5.5.1 Cleaning Practices and Activities

Cleaning activities can have a significant impact on indoor air quality, particularly through the resuspension of particles and the emission of volatile compounds. To minimize these effects [Salonen2024]:

- Avoid methods that resuspend particulate matter, such as dry sweeping. The use of wet mopping or mechanical vacuum cleaners is recommended.
- If cleaning is carried out prior to periods of prolonged use, aim to do so with natural ventilation whenever conditions permit.
- Assess cleaning effectiveness.
- Schedule cleaning activities based on facility operations.
- Use appropriate protective clothing, gloves, and equipment.
- Prevent cross-contamination; by defining clear requirements for cleaning tools and cleaning agents.

5.5.2 Cleaning Agents

The use of indoor cleaning products can significantly heighten exposure to various harmful environmental toxicants, such as volatile organic compounds (VOCs), particulate matter (PM), and nitrogen dioxide. [Salonen2024] Common cleaning practices, like mopping floors and spraying windows with glass cleaner, introduce fragrances and aerosols into the air, burdening indoor environments. Some household cleaning agents are known sensitizers or airway irritants and have been linked to impaired respiratory health in both children and adults. Particularly, cleaning products applied as sprays are suggested to have the most harmful effects on the respiratory system, increasing risks of asthma incidence, current asthma, and poorly controlled asthma in adults, as well as wheezing in children.

To mitigate exposure to cleaning chemicals and disinfectants, several strategies are suggested:

- Reduce the use of cleaning products and air fresheners that emit volatile organic compounds (VOCs). If such products need to be used, cleaning should be carried out when no subsequent prolonged occupancy is expected.
- Always check product labels and avoid those without environmental certifications or those containing fragrances.
- Define requirements for cleaning agents and chemicals.

- Optimize cleaning practices and product selection.
- Ensure the correct storage and maintenance of cleaning tools.
- Provide adequate and well-functioning ventilation.
- Educate and raise awareness of safe use practices and potential health risks associated with cleaning products and chemicals; foster collaboration between scientific communities and health and safety authorities; and ensure accurate safety data sheets and labelling for cleaning and disinfecting products [Salonen2024].

6. OUTLOOK

This guideline provides an initial overview of practical measures to improve indoor air quality, drawing on the experience and results of the IDEAL Cluster. Further information and updates are available via the IDEAL Cluster website. A Version 2, including annexes dedicated to specific target groups (e.g. older adults, schools, hospitals), is planned for publication by the end of 2026.

7. REFERENCES

[Agache2025] Agache, I., Annesi-Maesano, I., Cecchi, L., Biagioni, B., Chung, F., D'Amato, G., Damialis, A., Del Giacco, S., Ortega, J. D., Galán, C., Gilles, S., Holgate, S., Jeebhay, M., Kazadzis, S., Nadeau, K., Papadopoulos, N. G., Quirce, S., Sastre, J., Traidl-Hoffmann, C., . . . Akdis, C. A. (2025a). EAACI Guidelines on Environmental Science for Allergy and Asthma—Recommendations on the Impact of Indoor Air Pollutants on the Risk of New-Onset Asthma and on Asthma-Related Outcomes. *Allergy*, *80*(3), 651–676. https://doi.org/10.1111/all.16502

[Ahdoot2015] Ahdoot, S., Pacheco, S. E., Paulson, J. A., Ahdoot, S., Baum, C. R., Bole, A., Brumberg, H. L., Campbell, C. C., Lanphear, B. P., Lowry, J. A., Pacheco, S. E., Spanier, A. J. & Trasande, L. (2015). Global Climate Change and Children's Health. *PDIATRICS*, *136*(5), e1468–e1484. https://doi.org/10.1542/peds.2015-3233

[Akdis2021] Akdis, C. A. (2021). Does the epithelial barrier hypothesis explain the increase in allergy, autoimmunity and other chronic conditions? *Nature Reviews. Immunology*, *21*(11), 739–751. https://doi.org/10.1038/s41577-021-00538-7

[Alemany2018] Alemany, S., Vilor-Tejedor, N., García-Esteban, R., Bustamante, M., Dadvand, P., Esnaola, M., Mortamais, M., Forns, J., Van Drooge, B. L., Álvarez-Pedrerol, M., Grimalt, J. O., Rivas, I., Querol, X., Pujol, J. & Sunyer, J. (2018). Traffic-Related Air Pollution, APOE ε4 Status, and Neurodevelopmental Outcomes among School Children Enrolled in the BREATHE Project (Catalonia, Spain). *Environmental Health Perspectives*, *126*(8), 087001. https://doi.org/10.1289/ehp2246

[Alter2024] Alter, N. C., Whitman, E. M., Bellinger, D. C. & Landrigan, P. J. (2024). Quantifying the association between PM2.5 air pollution and IQ loss in children: a systematic review and meta-analysis. *Environmental Health*, *23*(1), 101. https://doi.org/10.1186/s12940-024-01122-x

[Arata2021] Arata, C., Misztal, P. K., Tian, Y., Lunderberg, D. M., Kristensen, K., Novoselac, A., Vance, M. E., Farmer, D. K., Nazaroff, W. W. & Goldstein, A. H. (2021). Volatile organic compound emissions during HOMEChem. *Indoor Air*, *31*(6), 2099–2117. https://doi.org/10.1111/ina.12906

[Aretaki2024] Aretaki, M. A., Desmet, J., Viana, M. & Van Drooge, B. L. (2024). Comprehensive methodology for semi-volatile organic compound determination in ambient air with emphasis on polycyclic aromatic hydrocarbons analysis by GC–MS/MS. *Journal Of Chromatography A*, *1730*, 465086. https://doi.org/10.1016/j.chroma.2024.465086

[ASHRAE2016] ANSI/ASHRAE Addendum ae to ANSI/ASHRAE Standard 62.1-2016. Ventilation for Acceptable Indoor Air Quality. ISSN 1041-2336.

[ASHRAE2019] Ashrae. (2018). *Residential Indoor Air Quality Guide: Best Practices for Acquisition, Design, Construction, Maintenance and Operation*.

[ASHRAE2024] *ASHRAE HANDBOOK: Heating, Ventilating, and Air-conditioning Systems and Equipment*. (2024).

[Asikainen2016] Asikainen, A., Carrer, P., Kephalopoulos, S., De Oliveira Fernandes, E., Wargocki, P. & Hänninen, O. (2016). Reducing burden of disease from residential indoor air exposures in Europe (HEALTHVENT project). *Environmental Health*, *15*(S1), 35. https://doi.org/10.1186/s12940-016-0101-8

[ASTM-D7297-21] ASTM D7297-21: *Standard practice for evaluating residential indoor air quality concerns* ASTM International. (2021)..

[Atalay2023] Atalay, Y. A., Mengistie, E., Tolcha, A., Birhan, B., Asmare, G., Gebeyehu, N. A. & Gelaw, K. A. (2023). Indoor air bacterial load and antibiotic susceptibility pattern of isolates at Adare General Hospital in Hawassa, Ethiopia. *Frontiers in Public Health*, *11*, 1194850. https://doi.org/10.3389/fpubh.2023.1194850

[Baeza-Romero2022] Baeza_Romero, M. T., Dudzinska, M. R., Torkmahalleh, M. A., Barros, N., Coggins, A. M., Ruzgar, D. G., Kildsgaard, I., Naseri, M., Rong, L., Saffell, J., Scutaru, A. M. & Staszowska, A. (2022). A review of critical residential buildings parameters and activities when investigating indoor air quality and pollutants. *Indoor Air*, *32*(11), e13144. https://doi.org/10.1111/ina.13144

[Baloch2020] Ba Baloch, R. M., Maesano, C. N., Christoffersen, J., Banerjee, S., Gabriel, M., Csobod, É., De Oliveira Fernandes, E., Annesi-Maesano, I., Csobod, É., Szuppinger, P., Prokai, R., Farkas, P., Fuzi, C., Cani, E., Draganic, J., Mogyorosy, E. R., Korac, Z., De Oliveira Fernandes, E., Ventura, G., . . . Krugly, E. (2020). Indoor air pollution, physical and comfort parameters related to schoolchildren's health: Data from the European SINPHONIE study. *The Science Of The Total Environment*, *739*, 139870. https://doi.org/10.1016/j.scitotenv.2020.139870

[Bani2024] Bani, A., Whitby, C., Colbeck, I., Dumbrell, A. J. & Ferguson, R. M. W. (2024). Rapid In-Field Detection of Airborne Pathogens Using Loop-Mediated Isothermal Amplification (LAMP). *Microorganisms*, *12*(12), 2578. https://doi.org/10.3390/microorganisms12122578

[Bell2026] Bell, M. L., Gasparrini, A. & Benjamin, G. C. (2024). Climate Change, Extreme Heat, and Health. *New England Journal Of Medicine*, 390(19), 1793–1801. https://doi.org/10.1056/nejmra2210769. Erratum in: Climate Change, Extreme Heat, and Health. (2026b). *New England Journal Of Medicine*, 394(12), 1248. https://doi.org/10.1056/nejmx250020

[Bluyssen1996] Bluyssen, P. M., Fernandes, E. O., Groes, L., Clausen, G., Fanger, P. O., Valbjorn, O., Bernhard, C. A. & Roulet, C. A. (1996). European Indoor Air Quality Audit Project in 56 office buildings. *Indoor Air*, *6*(4), 221–238. https://doi.org/10.1111/j.1600-0668.1996.00002.x

[Boulos2023] Boulos, L., Curran, J. A., Gallant, A., Wong, H., Johnson, C., Delahunty-Pike, A., Saxinger, L., Chu, D., Comeau, J., Flynn, T., Clegg, J. & Dye, C. (2023). Effectiveness of face masks for reducing transmission of SARS-CoV-2: a rapid systematic review. *Philosophical Transactions Of The Royal Society A Mathematical Physical And Engineering Sciences*, 381(2257), 20230133. https://doi.org/10.1098/rsta.2023.0133

[Bringslimark2009] Bringslimark, T., Hartig, T. & Patil, G. G. (2009). The psychological benefits of indoor plants: A critical review of the experimental literature. *Journal Of Environmental Psychology*, 29(4), 422–433. https://doi.org/10.1016/j.jenvp.2009.05.001

[Bulut2024] Bulut, H. A. & Şahin, R. (2024). Radon, Concrete, Buildings and Human Health—A Review Study. *Buildings*, *14*(2), 510. https://doi.org/10.3390/buildings14020510

[Bush2021] Bush, A. (2021). Impact of early life exposures on respiratory disease. *Paediatric Respiratory Reviews*, *40*, 24–32. https://doi.org/10.1016/j.prrv.2021.05.006

[Canada2021] Health Canada. (2021). Carbon dioxide in your home. https://www.canada.ca/en/health-canada/services/publications/healthy-living/carbon-dioxide-home.html (accessed 4th June 2026)

[Carlsten2020] Carlsten, C., Salvi, S., Wong, G. W. & Chung, K. F. (2020). Personal strategies to minimise effects of air pollution on respiratory health: advice for providers, patients and the public. *European Respiratory Journal*, *55*(6), 1902056. https://doi.org/10.1183/13993003.02056-2019

[Carrazana2023] Carrazana, E., Ruiz-Gil, T., Fujiyoshi, S., Tanaka, D., Noda, J., Maruyama, F. & Jorquera, M. A. (2023). Potential airborne human pathogens: A relevant inhabitant in built environments but not considered in indoor air quality standards. *The Science Of The Total Environment*, *901*, 165879. https://doi.org/10.1016/j.scitotenv.2023.165879

[Cervantes2025] Cervantes, R., Pena, P., Riesenberger, B., Rodriguez, M., Henderson, D., Gonçalves, S., Newire, E., Pogner, C., Salonen, H., Silva, M. A., Ferguson, R. M. W., Haverinen-Shaughnessy, U. & Viegas, C. (2025). Critical insights on fungal contamination in schools: a comprehensive review of assessment methods. *Frontiers in Public Health*, *13*, 1557506. https://doi.org/10.3389/fpubh.2025.1557506

[Chawla2023] Chawla, H., Anand, P., Garg, K., Bhagat, N., Varmani, S. G., Bansal, T., McBain, A. J. & Marwah, R. G. (2023). A comprehensive review of microbial contamination in the indoor environment: sources, sampling, health risks, and mitigation strategies. *Frontiers in Public Health*, *11*, 1285393. https://doi.org/10.3389/fpubh.2023.1285393

[Chen2015] Chen, Z., Salam, M. T., Eckel, S. P., Breton, C. V. & Gilliland, F. D. (2015). Chronic effects of air pollution on respiratory health in Southern California children: findings from the Southern California Children's Health Study. *PubMed*, *7*(1), 46–58. https://doi.org/10.3978/j.issn.2072-1439.2014.12.20

[Chojer2020] Chojer, H., Branco, P., Martins, F., Alvim-Ferraz, M. & Sousa, S. (2020). Development of low-cost indoor air quality monitoring devices: Recent advancements. *The Science Of The Total Environment*, *727*, 138385. https://doi.org/10.1016/j.scitotenv.2020.138385

[Chu2020] Chu, D. K., Akl, E. A., Duda, S., Solo, K., Yaacoub, S., Schünemann, H. J., Chu, D. K., Akl, E. A., El-Harakeh, A., Bognanni, A., Lotfi, T., Loeb, M., Hajizadeh, A., Bak, A., Izcovich, A., Cuello-Garcia, C. A., Chen, C., Harris, D. J., Borowiack, E., . . . Schünemann, H. J. (2020). Physical distancing, face masks, and eye protection to prevent person-to-person transmission of SARS-CoV-2 and COVID-19: a systematic review and meta-analysis. *The Lancet*, 395(10242), 1973–1987. https://doi.org/10.1016/s0140-6736(20)31142-9

[Coggins2021] Coggins, M., & Jones, S. (2021, Jul 1). VIP 43: Residential Ventilation and health. Air infiltration and Ventilation Centre (International Energy Agency) https://doi.org/10.13025/15613.

[Cox2020] Cox, J., Mbareche, H., Lindsley, W. G. & Duchaine, C. (2019). Field sampling of indoor bioaerosols. *Aerosol Science And Technology*, *54*(5), 572–584. https://doi.org/10.1080/02786826.2019.1688759

[Crameri2013] Crameri, R., Garbani, M., Rhyner, C. & Huitema, C. (2013). Fungi: the neglected allergenic sources. *Allergy*, *69*(2), 176–185. https://doi.org/10.1111/all.12325

[Csobod2014] Csobod, É., Isabella, A., Carrer, P., Kephalopoulos, S., Joana, M., Péter, R., De Oliveira Fernandes, E., Josefa, B., Beregszászi, T., Anne, H., Moshammer, H., Dan, N., Páldy, A., Pándics, T., Piersante, S., Stranger, M., Martin, T., Mihály, J. V., Vasskövi, É., . . . Viegi, G. (2014). SINPHONIE – Schools Indoor Pollution and Health Observatory Network in Europe - Final Report. *Joint Research Centre (European Commission)*. https://doi.org/10.2788/99220

[Damialis2019] Damialis, A., Traidl-Hoffmann, C., Treudler, R. (2019). Climate Change and Pollen Allergies. In: Marselle, M., Stadler, J., Korn, H., Irvine, K., Bonn, A. (eds) *Biodiversity and Health in the Face of Climate Change.* Springer, Cham. https://doi.org/10.1007/978-3-030-02318-8_3

[Damialis2021] Damialis, A., Gilles, S., Sofiev, M., Sofieva, V., Kolek, F., Bayr, D., Plaza, M. P., Leier-Wirtz, V., Kaschuba, S., Ziska, L. H., Bielory, L., Makra, L., Del Mar Trigo, M., Group, C. S., Traidl-Hoffmann, C., Oliver, G., Pham-Thi, N., Thibaudon, M., Arino, A. H., . . . Jia, P. (2021). Higher airborne pollen concentrations correlated with increased SARS-CoV-2 infection rates, as evidenced from 31 countries across the globe. *Proceedings Of The National Academy Of Sciences*, *118*(12). https://doi.org/10.1073/pnas.2019034118

[Damialis2025] Damialis, A. & Gilles, S. (2025). Air quality in the era of climate change: Bioaerosols, multi-exposures, and the emerging threats of respiratory allergies and infectious diseases. *Current Opinion in Environmental Science & Health*, *46*, 100634. https://doi.org/10.1016/j.coesh.2025.100634

[Dannemiller2025] Dannemiller, K. C., Conrad, L. A., Haines, S. R., Huang, Y. J., Marr, L. C., Siegel, J. A., Hassan, S., King, J. C., Prussin, A. J., Shamblin, A. & Perzanowski, M. S. (2024). Indoor bioaerosols and asthma: Overview, implications, and mitigation strategies. *Journal Of Allergy And Clinical Immunology*, *155*(3), 714–725. https://doi.org/10.1016/j.jaci.2024.11.027

[Demirel2014] Demirel, G., Özden, Ö., Döğeroğlu, T. & Gaga, E. O. (2014). Personal exposure of primary school children to BTEX, NO2 and ozone in Eskişehir, Turkey: Relationship with indoor/outdoor concentrations and risk assessment. *The Science Of The Total Environment*, *473–474*, 537–548. https://doi.org/10.1016/j.scitotenv.2013.12.034

[Dias2024] Dias, M., Gomes, B., Pena, P., Cervantes, R., Beswick, A., Duchaine, C., Kolk, A., Madsen, A. M., Oppliger, A., Pogner, C., Duquenne, P., Wouters, I. M., Crook, B. & Viegas, C. (2024). Filling the knowledge gap: Scoping review regarding sampling methods, assays, and further requirements to assess airborne viruses. *The Science Of The Total Environment*, *946*, 174016. https://doi.org/10.1016/j.scitotenv.2024.174016

[Dias2025] Dias, M., Gomes, B., Pena, P., Cervantes, R., Rodriguez, M., Riesenberger, B., Marques, L., Carolino, E., Twarużek, M., Kosicki, R., Soszczynska, E., Caetano, L. A., Viegas, S. & Viegas, C. (2025). Boosting knowledge on occupational exposure to microbial contamination in Portuguese carpentries. *Frontiers in Public Health*, *13*, 1574881. https://doi.org/10.3389/fpubh.2025.1574881

[Dimitroulopoulou2023] Dimitroulopoulou, S., Dudzińska, M. R., Gunnarsen, L., Hägerhed, L., Maula, H., Singh, R., Toyinbo, O. & Haverinen-Shaughnessy, U. (2023). Indoor air quality guidelines from across the world: An appraisal considering energy saving, health, productivity, and comfort. *Environment International*, *178*, 108127. https://doi.org/10.1016/j.envint.2023.108127

[Din2023] Din, K. S., Khokhar, M. F., Butt, S. I., Qadir, A. & Younas, F. (2023). Exploration of microplastic concentration in indoor and outdoor air samples: Morphological, polymeric, and elemental analysis. *The Science Of The Total Environment*, *908*, 168398. https://doi.org/10.1016/j.scitotenv.2023.168398

[Dong2020] Dong, C., Chen, C., Chen, Y., Chen, H., Lee, J. & Lin, C. (2019). Polystyrene microplastic particles: In vitro pulmonary toxicity assessment. *Journal Of Hazardous Materials*, *385*, 121575. https://doi.org/10.1016/j.jhazmat.2019.121575

[ECA1999] DE BORTOLI M., KEPHALOPOULOS S., SCHAUENBURG M., VISSERS H. KIRCHNER S. ECA report no. 21 on „European Inter-laboratory Comparison on VOC emitted from building materials and products”. Joint Research Centre (European Commission). ISBN: 92-828-6480-4.

[ECA2005] Kephalopoulos, S., Koistinen, K., Kotzias, D., Augustin, R., Cochet, C., Crump, D., De Oliveira Fernandes, E., Däumling, C., Loomans, M., Lundgren, B., Maupetit, F., Oppl, R., Pacary, T., Saarela, K., Seifert, B., Vankann, E., Witterseh, T., Wolkoff, P. ECA report no. 24 on “Harmonisation of indoor material emissions labelling systems in the EU: Inventory of existing schemes”. *Joint Research Centre (European Commission)*. ISBN: 92-79-01043-3.

[ECA2012] Kephalopoulos, S., Derrick, C., Däumling, C., Winther, F. L., Horn, W., Marion, K., Maupetit, F., Säteri, J., Saarela, K., Maria, S. A., Tirkkonen, T., Thomas, W. & Sperk, C. (2012c). ECA report no. 27 on “Harmonisation framework for indoor products labelling schemes in the EU”. *Joint Research Centre (European Commission)*. https://doi.org/10.2788/20292

[EEA2023a] European Environment Agency. (2023). *Harm to human health from air pollution in Europe: Burden of disease 2023*. https//doi.org/10.2800/721439

[EEA2023b] European Environment Agency. (2023). *Air pollution and children's* health. https//doi.org/10.2800/388668

[EEA2024] European Environment Agency. (2024). *Europe's air quality status 2024* https://doi.org/10.2800/5970

[EN14662-5] EN 14662-5:2005; *Ambient air quality - Standard method for measurement of benzene concentrations - Part 5: Diffusive sampling followed by solvent desorption and gas chromatography*

[EPA2025] U.S. Environmental Protection Agency. (2025). *Technical overview of volatile organic compounds.* https://www.epa.gov/indoor-air-quality-iaq/technical-overview-volatile-organic-compounds

[EPRS2021] European Parliamentary Research Service. (2021). *A universal right to a healthy environment.* https://www.europarl.europa.eu/thinktank/en/document/EPRS_ATA(2021)698846

[EU2012a] European Union. (2012). Treaty on the Functioning of the European Union. *Official Journal C* 326 , 26/10/2012 pp. 0001 – 0390 *https://eur-lex.europa.eu/eli/treaty/tfeu_2012/oj*

[EU2012b] European Union. (2012). Charter of Fundamental Rights of the European. Union. *Official Journal C 326,* 26.10.2012, pp. 391–407 http://data.europa.eu/eli/treaty/char_2012/oj

[EU2021] European Commission. (2021). *EU action plan: Towards zero pollution for air, water and soil.* https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52021DC0400

[EU2024] European Union. (2024). Directive (EU) 2024/2881 on ambient air quality and cleaner air for Europe (recast). *Official Journal L, 2024/2881, 20.11.2024, http://data.europa.eu/eli/dir/2024/2881/oj*

[Ferguson2019] Ferguson, R. M. W., Garcia-Alcega, S., Coulon, F., Dumbrell, A. J., Whitby, C. & Colbeck, I. (2019). Bioaerosol biomonitoring: Sampling optimization for molecular microbial ecology. *Molecular Ecology Resources*, *19*(3), 672–690. https://doi.org/10.1111/1755-0998.13002

[Ferguson2021] Ferguson, R. M., Neath, C. E., Nasir, Z. A., Garcia-Alcega, S., Tyrrel, S., Coulon, F., Dumbrell, A. J., Colbeck, I. & Whitby, C. (2020). Size fractionation of bioaerosol emissions from green-waste composting. *Environment International*, *147*, 106327. https://doi.org/10.1016/j.envint.2020.106327

[Furst2024] Furst, L., Cipoli, Y., Galindo, N., Yubero, E., Viegas, C., Pena, P., Nunes, T., Feliciano, M., & Alves, C. (2024). Comprehensive analysis of particulate matter, gaseous pollutants, and microbiological contamination in an international chain supermarket. Environmental Pollution, 363(2), Article 125236. https://doi.org/10.1016/j.envpol.2024.125236

[Furst2025] Furst, L., Cipoli, Y., Galindo, N., Yubero, E., Viegas, C., Gomes, B., Cervantes, R., Nunes, T., Feliciano, M. & Alves, C. (2025). Comprehensive analysis of particulate matter, gaseous pollutants, and microbiological contamination in a clothing store from an international chain in Europe. *Environmental Pollution*, *371*, 125836. https://doi.org/10.1016/j.envpol.2025.125836

[Gabriel2020] Gabriel, M. F., Felgueiras, F., Fernandes, M., Ribeiro, C., Ramos, E., Mourão, Z. & De Oliveira Fernandes, E. (2019). Assessment of indoor air conditions in households of Portuguese families with newborn children. Implementation of the HEALS IAQ checklist. *Environmental Research*, *182*, 108966. https://doi.org/10.1016/j.envres.2019.108966

[Gabriel2021] Gabriel, M. F., Paciência, I., Felgueiras, F., Rufo, J. C., Mendes, F. C., Farraia, M., Mourão, Z., Moreira, A. & De Oliveira Fernandes, E. (2021). Environmental quality in primary schools and related health effects in children. An overview of assessments conducted in the Northern Portugal. *Energy And Buildings*, *250*, 111305. https://doi.org/10.1016/j.enbuild.2021.111305

[Geiss2024] El Hadri, H., Giechaskiel, B., Al Wasif Ruiz, T., Putaud, J.-P., Geiss, O., & Barrero, J. (2024). *Micro- and nanoplastics in the air : sources, transport & analytical methods for their determination*, Publications Office of the European Union. https://data.europa.eu/doi/10.2760/028991

[Gordon2018] Gordon, K., Terry, P. D., Liu, X., Harris, T., Vowell, D., Yard, B. & Chen, J. (2018). Radon in Schools: A Brief Review of State Laws and Regulations in the United States. *International Journal Of Environmental Research And Public Health*, *15*(10), 2149. https://doi.org/10.3390/ijerph15102149

[Greenhalgh2024] Greenhalgh, T., MacIntyre, C. R., Baker, M. G., Bhattacharjee, S., Chughtai, A. A., Fisman, D., Kunasekaran, M., Kvalsvig, A., Lupton, D., Oliver, M., Tawfiq, E., Ungrin, M. & Vipond, J. (2024). Masks and respirators for prevention of respiratory infections: a state of the science review. *Clinical Microbiology Reviews*, 37(2), e0012423. https://doi.org/10.1128/cmr.00124-23

[Grydaki2024] Grydaki, N., Colbeck, I. & Whitby, C. (2024). Temporal changes in the size resolved fractions of bacterial aerosols in urban and semi-urban residences. *Scientific Reports*, *14*(1), 20238. https://doi.org/10.1038/s41598-024-70495-3

[Guarnieri2023] Guarnieri, G., Olivieri, B., Senna, G. & Vianello, A. (2023). Relative Humidity and Its Impact on the Immune System and Infections. *International Journal Of Molecular Sciences*, *24*(11), 9456. https://doi.org/10.3390/ijms24119456

[Guo2021] Guo, M., Du, C., Li, B., Yao, R., Tang, Y., Jiang, Y., Liu, H., Su, H., Zhou, Y., Wang, L., Yang, X., Zhou, M. & Yu, W. (2021). Reducing particulates in indoor air can improve the circulation and cardiorespiratory health of old people: A randomized, double-blind crossover trial of air filtration. *The Science Of The Total Environment*, *798*, 149248. https://doi.org/10.1016/j.scitotenv.2021.149248

[Halios2022] Halios, C. H., Landeg-Cox, C., Lowther, S. D., Middleton, A., Marczylo, T. & Dimitroulopoulou, S. (2022). Chemicals in European residences – Part I: A review of emissions, concentrations and health effects of volatile organic compounds (VOCs). *The Science Of The Total Environment*, *839*, 156201. https://doi.org/10.1016/j.scitotenv.2022.156201

[Hartiala2026] Hartiala, M., Elenius, V., Pesquera, A. A., Androulakis, S., Annesi-Maesano, I., Badyda, A., Brandsma, S., Chatziprodromidou, I., Gajski, G., Garcia-Aymerich, J., Giorio, C., Hugg, T., Jaakkola, J. J. K., Koch, S., Leonards, P. E. G., Matrali, A., Melymuk, L., Mueller, N., Muszyński, A., . . . Jartti, T. (2025). Exposures in indoor air affecting health. *Allergy*, *81*(3), 700–719. https://doi.org/10.1111/all.70179

[Hatem2025] Hatem, G., Faria, A. M., Pinto, M. B., Teixeira, J. P., Salamova, A., Costa, C. & Madureira, J. (2025). Association between exposure to airborne endocrine disrupting chemicals and asthma in children or adolescents: A systematic review and meta-analysis. *Environmental Pollution*, *369*, 125830. https://doi.org/10.1016/j.envpol.2025.125830

[Howsam1988] Howsam, M. & Jones, K. C. (1998). Sources of PAHs in the Environment. In *The handbook of environmental chemistry* (S. 137–174). https://doi.org/10.1007/978-3-540-49697-7_4

[IDEAL2025] IDEAL Cluster. (2025). Indoor air quality health policy brief I + II. https://www.idealcluster.eu/wp-content/uploads/2024/10/FINAL-Policy-Brief-IDEAL-Cluster.pdf

[IPCC2022] Intergovernmental Panel on Climate Change (IPCC). Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change; Pörtner, H.-O., Roberts, D.C., Tignor, M.M.B., Poloczanska, E., Mintenbeck, K., Alegría, A., Craig, M., Langsdorf, S., Löschke, S., Möller, V., et al., Eds.; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2022; pp. 1041–1170.

[Irga2017] Irga, P., Paull, N., Abdo, P. & Torpy. (2017). An assessment of the atmospheric particle removal efficiency of an in-room botanical biofilter system. *Building And Environment*, 115, 281–290. https://doi.org/10.1016/j.buildenv.2017.01.035

[ISO16000-1]. ISO 16000-1:2004 *Indoor air - Part 1: General aspects of sampling strategy*

[ISO16000-15] ISO 16000-15:2008 Indoor air - Part 15: Sampling strategy for nitrogen dioxide (NO2)

[ISO16000-3] ISO 16000-3:2006 *Indoor air - Part 3: Determination of formaldehyde and other carbonyl compounds - Active sampling method*

[ISO16000-9] ISO 16000-9:2014 *Indoor air - Part 9: Determination of the emission of volatile organic compounds from building products and furnishing - Emission test chamber method*

[ISO17772-1] ISO 17772-1:2017 *Energy performance of buildings - Indoor environmental quality*

[Jabbari2025] Jabbari, S. G., Domínguez, J. F., Sufuentes, S. R., Nyberg, S. O., Vehus, T. S. & Nielsen, H. K. (2025b). VOC emissions from commercial wood panels using PTR-MS for indoor air quality evaluation. *Frontiers in Built Environment*, *11*. https://doi.org/10.3389/fbuil.2025.1591669

[Kanchongkittiphon2015] Kanchongkittiphon, W., Mendell, M. J., Gaffin, J. M., Wang, G. & Phipatanakul, W. (2014). Indoor Environmental Exposures and Exacerbation of Asthma: An Update to the 2000 Review by the Institute of Medicine. *Environmental Health Perspectives*, *123*(1), 6–20. https://doi.org/10.1289/ehp.1307922

[Kazensky2024] Kazensky, L., Matković, K., Gerić, M., Žegura, B., Pehnec, G. & Gajski, G. (2024). Impact of indoor air pollution on DNA damage and chromosome stability: a systematic review. *Archives Of Toxicology*, *98*(9), 2817–2841. https://doi.org/10.1007/s00204-024-03785-4

[Kembel2012] Kembel, S. W., Jones, E., Kline, J., Northcutt, D., Stenson, J., Womack, A. M., Bohannan, B. J. M., Brown, G. Z. & Green, J. L. (2012). Architectural design influences the diversity and structure of the built environment microbiome. *The ISME Journal*, *6*(8), 1469–1479. https://doi.org/10.1038/ismej.2011.211

[Keyte2013] Keyte, I. J., Harrison, R. M. & Lammel, G. (2013). Chemical reactivity and long-range transport potential of polycyclic aromatic hydrocarbons – a review. *Chemical Society Reviews*, *42*(24), 9333. https://doi.org/10.1039/c3cs60147a

[Kim2025] Kim, S., Damialis, A., Charalampopoulos, A., Voelker, D. H. & Rorie, A. C. (2024). The Effect of Climate Change on Allergen and Irritant Exposure. *The Journal Of Allergy And Clinical Immunology in Practice*, *13*(2), 266–273. https://doi.org/10.1016/j.jaip.2024.12.019

[King2023] D. King, Margaret R Emerson, Steven R Chan, et al. Digital Mental Health 101: What Clinicians Need to Know When Getting Started, American Psychiatric Association (2023) https://www.psychiatry.org/getattachment/b250c6ff-d1f5-4c4f-8ad1-f478fba5773d/Resource-Document-Digital-Mental-Health-101.pdf

[Kornartit2010] Kornartit, C., Sokhi, R., Burton, M. & Ravindra, K. (2009). Activity pattern and personal exposure to nitrogen dioxide in indoor and outdoor microenvironments. *Environment International*, 36(1), 36–45. https://doi.org/10.1016/j.envint.2009.09.004

[Kristono2019] Kristono, G. A., Shorter, C., Pierse, N., Crane, J. & Siebers, R. (2018). Endotoxin, cat, and house dust mite allergens in electrostatic cloths and bedroom dust. *Journal Of Occupational And Environmental Hygiene*, *16*(1), 89–96. https://doi.org/10.1080/15459624.2018.1536827

[Kucuksezer2023] Kucuksezer, U. C., Ozdemir, C., Yazici, D., Pat, Y., Mitamura, Y., Li, M., Sun, N., D'Avino, P., Bu, X., Zhu, X., Akdis, M., Nadeau, K., Ogulur, I. & Akdis, C. A. (2023). The epithelial barrier theory: Development and exacerbation of allergic and other chronic inflammatory diseases. *Asia Pacific Allergy*, *13*(1), 28–39. https://doi.org/10.5415/apallergy.0000000000000005

[Kumar2021] Kumar, P., Kausar, M. A., Singh, A. B. & Singh, R. (2021). Biological contaminants in the indoor air environment and their impacts on human health. *Air Quality Atmosphere & Health*, *14*(11), 1723–1736. https://doi.org/10.1007/s11869-021-00978-z

[Lan2021] Lan, L., Tang, J., Wargocki, P., Wyon, D. P. & Lian, Z. (2021). Cognitive performance was reduced by higher air temperature even when thermal comfort was maintained over the 24–28°C range. *Indoor Air*, 32(1), e12916. https://doi.org/10.1111/ina.12916

[Laumbach2015] Laumbach, R., Meng, Q. & Kipen, H. (2015). What can individuals do to reduce personal health risks from air pollution? *PubMed*, 7(1), 96–107. https://doi.org/10.3978/j.issn.2072-1439.2014.12.21

[Laumbach2021] Laumbach, R. J. & Cromar, K. R. (2021). Personal Interventions to Reduce Exposure to Outdoor Air Pollution. *Annual Review Of Public Health*, 43(1), 293–309. https://doi.org/10.1146/annurev-publhealth-052120-103607

[Lemieux2019] Lemieux, J., Veillette, M., Mbareche, H. & Duchaine, C. (2019). Re-aerosolization in liquid-based air samplers induces bias in bacterial diversity. *Aerosol Science And Technology*, *53*(11), 1244–1260. https://doi.org/10.1080/02786826.2019.1652242

[Levermore2020] Levermore, J. M., Smith, T. E. L., Kelly, F. J. & Wright, S. L. (2020). Detection of Microplastics in Ambient Particulate Matter Using Raman Spectral Imaging and Chemometric Analysis. *Analytical Chemistry*, *92*(13), 8732–8740. https://doi.org/10.1021/acs.analchem.9b05445

[Lim2016] Lim, H., Kwon, H., Lim, J., Choi, J. H., Ha, M., Hwang, S. & Choi, W. (2016). Short-term Effect of Fine Particulate Matter on Children's Hospital Admissions and Emergency Department Visits for Asthma: A Systematic Review and Meta-analysis. *Journal Of Preventive Medicine And Public Health*, *49*(4), 205–219. https://doi.org/10.3961/jpmph.16.037

[Lin2025] Lin, J., Bates, S. M., Allen, L. N., Wright, M., Mao, L. & Kidd, M. (2025). Integrating Mobile Health App Data Into Electronic Medical or Health Record Systems and Its Impact on Health Care Delivery and Patient Health Outcomes: Scoping Review. *JMIR Mhealth And Uhealth*, *13*, e66650. https://doi.org/10.2196/66650

[Liu2020] Liu, K., Xie, Z. & Or, C. K. (2020). Correction: Effectiveness of Mobile App-Assisted Self-Care Interventions for Improving Patient Outcomes in Type 2 Diabetes and/or Hypertension: Systematic Review and Meta-Analysis of Randomized Controlled Trials. *JMIR Mhealth And Uhealth*, *8*(8), e23600. https://doi.org/10.2196/23600

[Lohmann2004] Lohmann, R. & Lammel, G. (2004). Adsorptive and Absorptive Contributions to the Gas-Particle Partitioning of Polycyclic Aromatic Hydrocarbons: State of Knowledge and Recommended Parametrization for Modeling. *Environmental Science & Technology*, *38*(14), 3793–3803. https://doi.org/10.1021/es035337q

[Lowther2019] Lowther, S. D., Jones, K. C., Wang, X., Whyatt, J. D., Wild, O. & Booker, D. (2019). Particulate Matter Measurement Indoors: A Review of Metrics, Sensors, Needs, and Applications. *Environmental Science & Technology*, *53*(20), 11644–11656. https://doi.org/10.1021/acs.est.9b03425

[Madsen2023] Madsen, A. M., Moslehi-Jenabian, S., Frankel, M., White, J. K. & Frederiksen, M. W. (2023). Airborne bacterial species in indoor air and association with physical factors. *UCL Open Environment*, *5*. https://doi.org/10.14324/111.444/ucloe.000056

[Mahmoud2021] Mahmoud, M., Ramadan, M., Naher, S., Pullen, K. & Olabi, A. (2020). The impacts of different heating systems on the environment: A review. *The Science Of The Total Environment*, *766*, 142625. https://doi.org/10.1016/j.scitotenv.2020.142625

[Mandin2017] Mandin, C., Trantallidi, M., Cattaneo, A., Canha, N., Mihucz, V. G., Szigeti, T., Mabilia, R., Perreca, E., Spinazzè, A., Fossati, S., De Kluizenaar, Y., Cornelissen, E., Sakellaris, I., Saraga, D., Hänninen, O., De Oliveira Fernandes, E., Ventura, G., Wolkoff, P., Carrer, P. & Bartzis, J. (2016). Assessment of indoor air quality in office buildings across Europe – The OFFICAIR study. *The Science Of The Total Environment*, *579*, 169–178. https://doi.org/10.1016/j.scitotenv.2016.10.238

[Marques2020] Marques G, Pitarma R. Particulate Matter Monitoring and Assessment through Internet of Things: a Health Information System for Enhanced Living Environments. J Med Syst. 2020 Nov 11;44(12):207. doi: 10.1007/s10916-020-01674-8

[Martins2025] Martins, C., Teófilo, V., Clemente, M., Corda, M., Fermoso, J., Aguado, A., Rodriguez, S., Moshammer, H., Kristian, A., Ferri, M., Costa-Ruiz, B., Pérez, L., Hanke, W., Badyda, A., Kepa, P., Affek, K., Doskocz, N., Martín-Torrijos, L., Mulayim, M. O., . . . Viegas, S. (2025). Sources, levels, and determinants of indoor air pollutants in Europe: A systematic review. *The Science Of The Total Environment*, *964*, 178574. https://doi.org/10.1016/j.scitotenv.2025.178574

[Maung2022] Maung, T. Z., Bishop, J. E., Holt, E., Turner, A. M. & Pfrang, C. (2022). Indoor Air Pollution and the Health of Vulnerable Groups: A Systematic Review Focused on Particulate Matter (PM), Volatile Organic Compounds (VOCs) and Their Effects on Children and People with Pre-Existing Lung Disease. *International Journal Of Environmental Research And Public Health*, *19*(14), 8752. https://doi.org/10.3390/ijerph19148752

[Maya-Manzano2023] Maya-Manzano, J. M., Tummon, F., Abt, R., Allan, N., Bunderson, L., Clot, B., Crouzy, B., Daunys, G., Erb, S., Gonzalez-Alonso, M., Graf, E., Grewling, Ł., Haus, J., Kadantsev, E., Kawashima, S., Martinez-Bracero, M., Matavulj, P., Mills, S., Niederberger, E., . . . Buters, J. (2022). Towards European automatic bioaerosol monitoring: Comparison of 9 automatic pollen observational instruments with classic Hirst-type traps. *The Science Of The Total Environment*, 866, 161220. https://doi.org/10.1016/j.scitotenv.2022.161220

[Mayer2003] Mayer, P., Tolls, J., Hermens, J. L. M. & Mackay, D. (2003). Peer Reviewed: Equilibrium sampling devices. *Environmental Science & Technology*, 37(9), 184A-191A. https://doi.org/10.1021/es032433i

[Moelling2020] Moelling, K. & Broecker, F. (2020). Air Microbiome and Pollution: Composition and Potential Effects on Human Health, Including SARS Coronavirus Infection. *Journal Of Environmental And Public Health*, *2020*, 1–14. https://doi.org/10.1155/2020/1646943

[Mortamais2017] Mortamais, M., Pujol, J., Van Drooge, B. L., Macià, D., Martínez-Vilavella, G., Reynes, C., Sabatier, R., Rivas, I., Grimalt, J., Forns, J., Alvarez-Pedrerol, M., Querol, X. & Sunyer, J. (2017). Effect of exposure to polycyclic aromatic hydrocarbons on basal ganglia and attention-deficit hyperactivity disorder symptoms in primary school children. *Environment International*, *105*, 12–19. https://doi.org/10.1016/j.envint.2017.04.011

[Murray2006] Murray, C. S. (2005). Study of modifiable risk factors for asthma exacerbations: virus infection and allergen exposure increase the risk of asthma hospital admissions in children. *Thorax*, 61(5), 376–382. https://doi.org/10.1136/thx.2005.042523

[NASEM2022] Technology, B. O. C. S. A., Studies, D. O. E. A. L. & Medicine, N. A. O. S. E. A. (2022). Why indoor chemistry matters. In *National Academies Press eBooks*. https://doi.org/10.17226/26228

[Ndlovu2024] Ndlovu, N. & Nkeh-Chungag, B. (2024). Impact of Indoor Air Pollutants on the Cardiovascular Health Outcomes of Older Adults: Systematic Review. *Clinical Interventions in Aging*, *Volume 19*, 1629–1639. https://doi.org/10.2147/cia.s480054

[Newman2020] Newman, J. D., Bhatt, D. L., Rajagopalan, S., Balmes, J. R., Brauer, M., Breysse, P. N., Brown, A. G., Carnethon, M. R., Cascio, W. E., Collman, G. W., Fine, L. J., Hansel, N. N., Hernandez, A., Hochman, J. S., Jerrett, M., Joubert, B. R., Kaufman, J. D., Malik, A. O., Mensah, G. A., . . . Brook, R. D. (2020). Cardiopulmonary Impact of Particulate Air Pollution in High-Risk Populations. *Journal Of The American College Of Cardiology*, *76*(24), 2878–2894. https://doi.org/10.1016/j.jacc.2020.10.020

[Nieuwenhuis2014] Nieuwenhuis, M., Knight, C., Postmes, T. & Haslam, S. A. (2014). The relative benefits of green versus lean office space: Three field experiments. *Journal Of Experimental Psychology Applied*, 20(3), 199–214. https://doi.org/10.1037/xap0000024

[Ntiamoah2025] Ntiamoah, I., Ikuma, L. H., Solaru, I. R., Nahmens, I. & Champney, R. (2025b). Guidelines for IAQ monitoring with low-cost air sensors in homes with asthmatic patients. *Journal Of The Air & Waste Management Association*, 76(2), 81–90. https://doi.org/10.1080/10962247.2025.2576666

[Ofremu2024] Ofremu, G. O., Raimi, B. Y., Yusuf, S. O., Dziwornu, B. A., Nnabuife, S. G., Eze, A. M. & Nnajiofor, C. A. (2024). Exploring the relationship between climate change, air pollutants and human health: Impacts, adaptation, and mitigation strategies. *Green Energy And Resources*, 3(2), 100074. https://doi.org/10.1016/j.gerr.2024.100074

[Olesen2002] Olesen, B. & Parsons, K. (2002). Introduction to thermal comfort standards and to the proposed new version of EN ISO 7730. *Energy And Buildings*, *34*(6), 537–548. https://doi.org/10.1016/s0378-7788(02)00004-x

[Oliveira2019] Oliveira, M., Slezakova, K., Delerue-Matos, C., Pereira, M. C. & Morais, S. (2019). Children environmental exposure to particulate matter and polycyclic aromatic hydrocarbons and biomonitoring in school environments: A review on indoor and outdoor exposure levels, major sources and health impacts. *Environment International*, *124*, 180–204. https://doi.org/10.1016/j.envint.2018.12.052

[Orwell2004] Orwell, R. L., Wood, R. L., Tarran, J., Torpy, F. & Burchett, M. D. (2004). Removal of Benzene by the Indoor Plant/Substrate Microcosm and Implications for Air Quality. *Water Air & Soil Pollution*, 157(1–4), 193–207. https://doi.org/10.1023/b:wate.0000038896.55713.5b

[Papadopoulos2023] Papadopoulos, N. G., Akdis, C. A., Akdis, M., Damialis, A., Esposito, G., Fergadiotou, I., Goroncy, C., Guitton, P., Gotua, M., Erotokritou, K., Jartti, T., Murray, C., Nenes, A., Nikoletseas, S., Finotto, S., Pandis, S. N., Ramiconi, V., Simpson, A., Soudunsaari, A., . . . Annesi-Maesano, I. (2023). Addressing adverse synergies between chemical and biological pollutants at schools—The 'SynAir-G' hypothesis. *Allergy*, 79(2), 294–301. https://doi.org/10.1111/all.15857

[Pettit2018] Pettit, T., Irga, P. & Torpy. (2018). Towards practical indoor air phytoremediation: A review. *Chemosphere*, 208, 960–974. https://doi.org/10.1016/j.chemosphere.2018.06.048

[Pitarma2017] Pitarma, R., Marques, G. & Ferreira, B. R. (2016). Monitoring Indoor Air Quality for Enhanced Occupational Health. *Journal Of Medical Systems*, *41*(2), 23. https://doi.org/10.1007/s10916-016-0667-2

[Pourkiaei2023] Pourkiaei, M. & Romain, A. (2023). Scoping review of indoor air quality indexes: Characterization and applications. *Journal Of Building Engineering*, *75*, 106703. https://doi.org/10.1016/j.jobe.2023.106703

[Rabdel2024] Radbel, J., Rebuli, M. E., Kipen, H. & Brigham, E. (2024). Indoor air pollution and airway health. Journal Of Allergy And Clinical Immunology, 154(4), 835–846. https://doi.org/10.1016/j.jaci.2024.08.013

[Rajagopalan2020] Rajagopalan, S., Brauer, M., Bhatnagar, A., Bhatt, D. L., Brook, J. R., Huang, W., Münzel, T., Newby, D., Siegel, J. & Brook, R. D. (2020). Personal-Level Protective Actions Against Particulate Matter Air Pollution Exposure: A Scientific Statement From the American Heart Association. *Circulation*, 142(23), e411–e431. https://doi.org/10.1161/cir.0000000000000931

[Raju2020] Raju, S., Siddharthan, T. & McCormack, M. C. (2020). Indoor Air Pollution and Respiratory Health. *Clinics in Chest Medicine*, *41*(4), 825–843. https://doi.org/10.1016/j.ccm.2020.08.014

[Robertson2024] Robertson, N. M., Qiu, A., Raju, S., McCormack, M. C. & Koehler, K. (2024). Cleaning indoor air—what works for respiratory health: An updated literature review and recommendations. *Journal Of Allergy And Clinical Immunology*, *154*(4), 847–860. https://doi.org/10.1016/j.jaci.2024.08.011

[Rook2023] Rook, G. A. W. (2023). The old friends hypothesis: evolution, immunoregulation and essential microbial inputs. *Frontiers in Allergy*, *4*, 1220481. https://doi.org/10.3389/falgy.2023.1220481

[Saini2021] Saini, J., Dutta, M. & Marques, G. (2021). Sensors for indoor air quality monitoring and assessment through Internet of Things: a systematic review. *Environmental Monitoring And Assessment*, *193*(2), 66. https://doi.org/10.1007/s10661-020-08781-6

[Salonen2018] Salonen, H., Salthammer, T. & Morawska, L. (2018). Human exposure to ozone in school and office indoor environments. *Environment International*, *119*, 503–514. https://doi.org/10.1016/j.envint.2018.07.012

[Salonen2019] Salonen, H., Salthammer, T. & Morawska, L. (2019). Human exposure to NO2 in school and office indoor environments. *Environment International*, *130*, 104887. https://doi.org/10.1016/j.envint.2019.05.081

[Salonen2024] Salonen, H., Salthammer, T., Castagnoli, E., Täubel, M. & Morawska, L. (2024). Cleaning products: Their chemistry, effects on indoor air quality, and implications for human health. *Environment International*, *190*, 108836. https://doi.org/10.1016/j.envint.2024.108836

[Salonen2025] Salonen, H., Salthammer, T., Alapieti, T., Shirazi, A., Mikkola, R. & Morawska, L. (2025). Indoor radon concentrations in European kindergartens and other educational facilities. *Environment International*, *205*, 109877. https://doi.org/10.1016/j.envint.2025.109877

[Salthammer2023] Salthammer, T. (2022). Acetaldehyde in the indoor environment. *Environmental Science Atmospheres*, *3*(3), 474–493. https://doi.org/10.1039/d2ea00146b

[Seinfeld2016] Seinfeld, J. H. & Pandis, S. N. (1998). *Atmospheric Chemistry and Physics: From Air Pollution to Climate Change*. Wiley-Interscience.

[Sequeira2024] Sequeira, S., Pasnak, E., Viegas, C., Gomes, B., Dias, M., Cervantes, R., Pena, P., Twarużek, M., Kosicki, R., Viegas, S., Caetano, L., Penetra, M., Silva, I., Caldeira, A. & Pinheiro, C. (2024). Microbial Assessment in A Rare Norwegian Book Collection: A One Health Approach to Cultural Heritage. *Microorganisms*, *12*(6), 1215. https://doi.org/10.3390/microorganisms12061215

[Sharma2021] Sharma, et al. (2021). Heating systems, ventilation, and IAQ in energy-efficient buildings. Buildings, 11, 591.

[Silverforsen2021] Silverforsen, D., Theorell-Haglöw, J., Ljunggren, M., Middelveld, R., Wang, J., Franklin, K., Norbäck, D., Lundbäck, B., Forsberg, B., Lindberg, E. & Janson, C. (2021). Snoring and environmental exposure: results from the Swedish GA2LEN study. *BMJ Open*, *11*(6), e044911. https://doi.org/10.1136/bmjopen-2020-044911

[SINPHONIE2015] Csobod, É., Isabella, A., Carrer, P., Kephalopoulos, S., Joana, M., Péter, R., De Oliveira Fernandes, E., Josefa, B., Beregszászi, T., Anne, H., Moshammer, H., Dan, N., Páldy, A., Pándics, T., Piersante, S., Stranger, M., Martin, T., Mihály, J. V., Vaskövi, É., . . . Viegi, G. (2014). SINPHONIE – Schools Indoor Pollution and Health Observatory Network in Europe - Final Report. *Joint Research Centre (European Commission)*. https://doi.org/10.2788/99220

[Solórzano2025] Solórzano, L. A., Gavilanes, D., Cadena, F., Irusta, L., González, A. & Aldas, M. (2025). A Review of the Sampling, Analysis, and Identification Techniques of Microplastics in the Air: Insights into PM2.5 and PM10. *Polymers*, *17*(22), 3045. https://doi.org/10.3390/polym17223045

[Soppa2017] Soppa, V. J., Schins, R. P., Hennig, F., Nieuwenhuijsen, M. J., Hellack, B., Quass, U., Kaminski, H., Sasse, B., Shinnawi, S., Kuhlbusch, T. A. & Hoffmann, B. (2017). Arterial blood pressure responses to short-term exposure to fine and ultrafine particles from indoor sources – A randomized sham-controlled exposure study of healthy volunteers. *Environmental Research*, *158*, 225–232. https://doi.org/10.1016/j.envres.2017.06.006

[Soppa2019] Soppa, V. J., Shinnawi, S., Hennig, F., Sasse, B., Hellack, B., Kaminski, H., Quass, U., Schins, R. P., Kuhlbusch, T. A. & Hoffmann, B. (2019). Effects of short-term exposure to fine and ultrafine particles from indoor sources on arterial stiffness – A randomized sham-controlled exposure study. *International Journal Of Hygiene And Environmental Health*, *222*(8), 1115–1132. https://doi.org/10.1016/j.ijheh.2019.08.002

[Sousa-Pinto2021] Sousa-Pinto, B., Eklund, P., Pfaar, O., Klimek, L., Zuberbier, T., Czarlewski, W., Bédard, A., Bindslev-Jensen, C., Bedbrook, A., Bosnic-Anticevich, S., Brussino, L., Cardona, V., Cruz, A. A., De Vries, G., Devillier, P., Fokkens, W. J., Fuentes-Pérez, J. M., Gemicioğlu, B., Haahtela, T., . . . Fonseca, J. A. (2021). Validity, reliability, and responsiveness of daily monitoring visual analog scales in MASK-air®. *Clinical And Translational Allergy*, *11*(7), e12062. https://doi.org/10.1002/clt2.12062

[Souza2020] De O Souza, M., Sánchez, B., Fuentes, M., Gilaranz, J. & Canela, M. C. (2020). Analytical validation using a gas mixing system for the determination of gaseous formaldehyde. *Analytical Methods*, *12*(43), 5247–5256. https://doi.org/10.1039/d0ay01363c

[Sterling1985] Sterling, E. M., Arundel, A., & Sterling, T. D. (1985). Criteria for human exposure to humidity in occupied buildings. *ASHRAE Transactions, 91*(1), 611–622.

[Šunić2026] Šunić, I., Šarac, J., Auguštin, D. H., Pozdniakova, S., Ferguson, R. M. W., Jergović, M., Visentin, D., Borràs, S., Archer, E., Henderson, D. K., Vitko, S., Ašić, A., Bošnjaković, A., Maglica, Ž., Viegas, C., Novokmet, N., Karlović, N., Marjanović, D., Muszyński, A., . . . Lovrić, M. (2026). The Indoor Microbiome: Sampling, Analysis and Emerging Trends. *Environmental Microbiology Reports*, *18*(2), e70272. https://doi.org/10.1111/1758-2229.70272

[Torpy2014] Torpy, Irga, P. & Burchett, M. (2014b). Profiling indoor plants for the amelioration of high CO2 concentrations. *Urban Forestry & Urban Greening*, 13(2), 227–233. https://doi.org/10.1016/j.ufug.2013.12.004

[Torres-Agullo2021] Torres-Agullo, A., Karanasiou, A., Moreno, T. & Lacorte, S. (2021). Overview on the occurrence of microplastics in air and implications from the use of face masks during the COVID-19 pandemic. *The Science Of The Total Environment*, *800*, 149555. https://doi.org/10.1016/j.scitotenv.2021.149555

[Torres-Agullo2022] Torres-Agullo, A., Karanasiou, A., Moreno, T. & Lacorte, S. (2022). Airborne microplastic particle concentrations and characterization in indoor urban microenvironments. *Environmental Pollution*, *308*, 119707. https://doi.org/10.1016/j.envpol.2022.119707

[Torres-Agullo2025] Torres-Agullo, A., Karanasiou, A., Charres, I., Alves, C. & Lacorte, S. (2025). Airborne microplastics and plastic additives in a school environment: identification, quantification, and associated inhalation risks. *Environment International*, *203*, 109753. https://doi.org/10.1016/j.envint.2025.109753

[UN1948] UN, 1948. Universal Declaration of Human Rights. https://www.un.org/en/about-us/universal-declaration-of-human-rights

[UN1989] UN, 1989. Convention on the Rights of the Child. General Assembly resolution 44/25. https://www.ohchr.org/en/instruments-mechanisms/instruments/convention-rights-child

[UN2022] UN, 2022. UN Resolution A/RES/76/300. The human right to a clean, healthy and sustainable environment. https://digitallibrary.un.org/record/3983329/files/A_RES_76_300-EN.pdf

[UN2023] UN, 2023. UN Committee on the Rights of the Child, General Comment No. 26 (2023) on children's rights and the environment with a special focus on climate change. https://www.ohchr.org/en/documents/general-comments-and-recommendations/crccgc26-general-comment-no-26-2023-childrens-rights

[VanDrooge2013] Van Drooge, B. L. (2013). Human Exposure to Polycyclic Aromatic Hydrocarbons in Urban and Rural Ambient Air. In *ACS symposium series* (S. 59–82). https://doi.org/10.1021/bk-2013-1149.ch004

[Vardoulakis2020] Vardoulakis, S., Giagloglou, E., Steinle, S., Davis, A., Sleeuwenhoek, A., Galea, K. S., Dixon, K. & Crawford, J. O. (2020b). Indoor Exposure to Selected Air Pollutants in the Home Environment: A Systematic Review. *International Journal Of Environmental Research And Public Health*, *17*(23), 8972. https://doi.org/10.3390/ijerph17238972

[Viegas2019a] Viegas, C., Almeida, B., Monteiro, A., Caetano, L. A., Carolino, E., Gomes, A. Q., Twarużek, M., Kosicki, R., Marchand, G. & Viegas, S. (2019). Bioburden in health care centers: Is the compliance with Portuguese legislation enough to prevent and control infection? *Building And Environment*, *160*, 106226. https://doi.org/10.1016/j.buildenv.2019.106226

[Viegas2019b] Viegas, C., Santos, P., Almeida, B., Monteiro, A., Carolino, E., Gomes, A. Q. & Viegas, S. (2019b). Electrostatic dust collector: a passive screening method to assess occupational exposure to organic dust in primary health care centers. *Air Quality Atmosphere & Health*, *12*(5), 573–583. https://doi.org/10.1007/s11869-018-0650-9

[Viegas2022] Viegas, C., Dias, M. & Viegas, S. (2022). Electrostatic Dust Cloth: A Useful Passive Sampling Method When Assessing Exposure to Fungi Demonstrated in Studies Developed in Portugal (2018–2021). *Pathogens*, *11*(3), 345. https://doi.org/10.3390/pathogens11030345

[Viegas2023] Viegas, C., Cervantes, R., Gomes, B., Moreira, S., Dias, M., Pena, P., Carolino, E., Twaruzek, M., Kosicki, R., Caetano, L. A. & Viegas, S. (2023). 87 Portuguese Groceries: A Potential Indoor Environment to Be Used as Public Health Sentinel for Fungal and Mycotoxins Contamination. *Annals Of Work Exposures And Health*, *67*(Supplement_1), i24. https://doi.org/10.1093/annweh/wxac087.064

[Viegas2024] Viegas, C., Peixoto, C., Gomes, B., Dias, M., Cervantes, R., Pena, P., Slezakova, K., Pereira, M. D. C., Morais, S., Carolino, E., Twarużek, M., Viegas, S. & Caetano, L. A. (2024). Assessment of Portuguese fitness centers: Bridging the knowledge gap on harmful microbial contamination with focus on fungi. *Environmental Pollution*, *350*, 123976. https://doi.org/10.1016/j.envpol.2024.123976

[Vorkamp2024] Vorkamp, K., Viegas, C., Almeida, M., Aretaki, M. A., Bossi, R., Castagnoli, E., Cervantes, R., Desmet, J., Diapouli, E., Domínquez, A., Fabian, C. M., Fauser, P., Ferguson, R. M. W., Haverinen-Shaughnessy, U., Hugg, T., Kuurola, P., Lazaridis, M., Massling, A., Paciência, I., ... Salonen, H. (2024). *The InChildHealth Walkthrough Survey - towards a standardized characterization of classrooms for Indoor Air Quality studies in Europe*. Abstract from International Conference on Indoor Air Quality and Climate, Honolulu, Hawaii, United States.

[Vornanen-Winqvist2020] Vornanen-Winqvist, C., Järvi, K., Andersson, M. A., Duchaine, C., Létourneau, V., Kedves, O., Kredics, L., Mikkola, R., Kurnitski, J. & Salonen, H. (2020). Exposure to indoor air contaminants in school buildings with and without reported indoor air quality problems. *Environment International*, 141, 105781. https://doi.org/10.1016/j.envint.2020.105781

[Wallace1989] Wallace, L. A. (1989). The Total Exposure Assessment Methodology (TEAM) Study: An Analysis of Exposures, Sources, and Risks Associated with Four Volatile Organic Chemicals. *Journal Of The American College Of Toxicology*, *8*(5), 883–895. https://doi.org/10.3109/10915818909018049

[Wang2019] Wang, J., Pindus, M., Janson, C., Sigsgaard, T., Kim, J., Holm, M., Sommar, J., Orru, H., Gislason, T., Johannessen, A., Bertelsen, R. J. & Norbäck, D. (2019). Dampness, mould, onset and remission of adult respiratory symptoms, asthma and rhinitis. *European Respiratory Journal*, 53(5), 1801921. https://doi.org/10.1183/13993003.01921-2018

[Wargocki2020] Wargocki, P., Porras-Salazar, J. A., Contreras-Espinoza, S. & Bahnfleth, W. (2020). The relationships between classroom air quality and children's performance in school. *Building And Environment*, *173*, 106749. https://doi.org/10.1016/j.buildenv.2020.106749

[Weschler1994] Weschler, C. J., Shields, H. C. & Naik, D. V. (1994). Indoor Chemistry Involving O3, NO, and NO2 as Evidenced by 14 Months of Measurements at a Site in Southern California. *Environmental Science & Technology*, *28*(12), 2120–2132. https://doi.org/10.1021/es00061a021

[Whitby2022] Whitby, C., Ferguson, R. M., Colbeck, I., Dumbrell, A. J., Nasir, Z. A., Marczylo, E., Kinnersley, R., Douglas, P., Drew, G., Bhui, K., Lemon, M., Jackson, S., Tyrrel, S. & Coulon, F. (2022). Compendium of analytical methods for sampling, characterization and quantification of bioaerosols. In *Advances in ecological research/Advances in Ecological Research* (S. 101–229). https://doi.org/10.1016/bs.aecr.2022.09.004

[Whitehead2016] Whitehead, L. & Seaton, P. (2016). The Effectiveness of Self-Management Mobile Phone and Tablet Apps in Long-term Condition Management: A Systematic Review. *Journal Of Medical Internet Research*, *18*(5), e97. https://doi.org/10.2196/jmir.4883

[WHO1988] WHO, 1988. Man-made Mineral Fibres and Radon. IARC Monographs on the Evaluation of the Carcinogenic Risks to Humans Volume 43. Lyon, France.

[WHO2010] WHO, 2010. WHO guidelines for indoor air quality: selected pollutants. https://www.who.int/publications/i/item/9789289002134

[WHO2018] World Health Organization. (2018). WHO Housing and health guidelines. Geneva: World Health Organization. Available at: WHO Publication Website.

[WHO2021] WHO, 2021. Screening questionnaire for selection of sampling sites for assessment of risks from combined exposure to multiple chemicals in indoor air. Supplementary publication to the screening tool for assessment of health risks from combined exposure to multiple chemicals in indoor air in public settings for children. https://www.who.int/europe/publications/i/item/9789289055635

[WHO2025] WHO, 2025. Air quality, energy and health. https://www.who.int/teams/environment-climate-change-and-health/air-quality-energy-and-health/health-impacts

[Wolverton1989] Wolverton, Bill C., Willard L. Douglas, and Keith Bounds. A study of interior landscape plants for indoor air pollution abatement. No. REPT-6. 1989. NASA-TM-108061. https://ntrs.nasa.gov/citations/19930072988

[Wright2019] Wright, S. L., Levermore, J. M. & Kelly, F. J. (2019). Raman Spectral Imaging for the Detection of Inhalable Microplastics in Ambient Particulate Matter Samples. Environmental Science & Technology, 53(15), 8947–8956. https://doi.org/10.1021/acs.est.8b06663

[Wyatt2018] Wyatt, J. C. (2018). How can clinicians, specialty societies and others evaluate and improve the quality of apps for patient use? *BMC Medicine*, 16(1). https://doi.org/10.1186/s12916-018-1211-7

[Zhang2023] Zhang, Z. & Lin, H. (2023). Air Pollution: A Pressing Threat to Functioning in the Older Adults. The Journals Of Gerontology Series A, 78(12), 2307–2308. https://doi.org/10.1093/gerona/glad145

[Zhen2023] Zhen, H., Zhang, F., Cheng, H., Hu, F., Jia, Y., Hou, Y., Shang, M., Yu, H. & Jiang, M. (2023). Association of polycyclic aromatic hydrocarbons exposure with child neurodevelopment and adult emotional disorders: A meta-analysis study. Ecotoxicology And Environmental Safety, 255, 114770. https://doi.org/10.1016/j.ecoenv.2023.114770

[Zheng2021] Zheng, X., Orellano, P., Lin, H., Jiang, M. & Guan, W. (2021). Short-term exposure to ozone, nitrogen dioxide, and sulphur dioxide and emergency department visits and hospital admissions due to asthma: A systematic review and meta-analysis. Environment International, 150, 106435. https://doi.org/10.1016/j.envint.2021.106435

[Zuri2026] Zuri, G., Lacorte, S. & Karanasiou, A. (2026). Quantification of Airborne Microplastics in Public Libraries by Pyr-GC-Orbitrap-MS and Human Exposure Assessment. Indoor Air, 2026(1). https://doi.org/10.1155/ina/5757232