ROYAL SOCIETY OF CHEMISTRY

Indoor Air Quality

A workshop report on the contribution chemical sciences can make to improving indoor air quality in the UK

Executive Summary

The Royal Society of Chemistry's Analytical Science Community (ASC), the Environment, Sustainability and Energy Community (ESEC) and the Faraday Community for Physical Chemistry (FCPC) held an online workshop on indoor air quality on 9 November 2022.

The workshop brought together experts and stakeholders from industry, academia, research institutes, funding bodies, policymakers, and UK government departments and agencies. This report summarises these discussions. While this report focuses on indoor air quality research, policy, and funding within the UK and from the chemical sciences viewpoint, the role of other disciplines (e.g., physical, life, and social sciences, and engineering) are equally critical, and many of the challenges, solutions and opportunities highlighted in this report may also be relevant worldwide.

There is growing evidence that indoor air pollution has significant short and long-term health impacts. The World Health Organisation (WHO) estimates that more than 3 million people worldwide die every year due to illnesses resulting from harmful indoor air in their homes.[1] Yet, while outdoor air pollution has been studied extensively, indoor air quality is not yet as well understood.

Indoor air quality is incredibly complex. Many sources and various factors affect the amount, type, and distribution of pollutants in an environment, including features of the building (such as size, materials, use, and location) and occupants' behaviour. Unlike outdoor air pollution, indoor emissions are not easily dispersed, and pollutants can accumulate, for example, on surfaces. While ventilation can help, several factors influence its effectiveness, such as local outdoor air quality.

There is a need for more developed and coordinated policy and regulation. UK regulation and policy on indoor air quality is not yet as well developed as for outdoor air quality and is somewhat fragmented, with responsibility distributed across government departments and agencies. There is an opportunity to build on good practice from other countries.

Regulation and policymaking require a holistic approach. For example, consideration of links and interplays between net zero policies and indoor air quality. Data protection and privacy must also be considered, as research will require large-scale measurement across locations, such as homes, schools, hospitals, and workplaces.

There is a need to establish reliable measurement approaches, datasets and models. Given its complexity, measuring indoor air quality is challenging. A national baseline assessment of pollutants and how to measure them in various indoor environments would be a useful first step in developing a nationwide inventory to facilitate research and monitoring of pollution levels and health impacts. Data could also be integrated from existing sources, e.g. building management systems. As larger datasets are collected, AI, machine learning and methods such as statistical clustering could be used to identify patterns.

Stable long-term funding is needed for research and monitoring given the complexity of the topic and the collaboration required. While there have been several funding calls for indoor air quality research in recent years, concerns remain about what happens when these funding streams end. For example, funding for a long-term systematic indoor air quality and health surveillance project would improve understanding of health effects and how the presence of pollutants may evolve over time.

Mechanisms are needed to enable collaboration between disciplines, sectors, and settings. Researching indoor air quality requires the involvement of multiple disciplines (such as physical sciences, engineering, social sciences, and life sciences), policymakers, regulators, industry, academia, government departments and agencies, and the public, as well as involving different types of buildings such as homes, schools and workplaces.

There are considerable opportunities for innovation. This includes developing specialist measurement techniques such as practical and low-cost sensors and developing technologies to help reduce or control pollutants within an indoor environment, particularly when ventilation is not a practical or effective option.

Scientists need to engage with policymakers, stakeholders and the wider public to inform policy, engage them in research and to support people in making informed choices and mitigating risks. For example, many everyday activities such as cooking, cleaning, DIY, or opening windows can significantly alter indoor air quality.

Recommendations from the workshop

For Government, policymakers, and funding bodies:

- Continue to enhance collaboration and coordination of indoor air quality policy and regulation across government departments and regulatory bodies to develop standards and implement policy options to improve indoor air quality to encompass all indoor environments.
- Consider the links between air quality and net zero when designing policy and supporting technology solutions for both.
- Provide support in establishing a national baseline assessment of pollutants and how to measure them in various indoor environments to enable a nationwide inventory of pollutants and reference values.
- Invest in innovation and establish and maintain dedicated, stable long-term funding to conduct research, maintain air quality and health surveillance, and enable multidisciplinary collaborations. This could build on recent funding streams and could use existing cross-sector funding mechanisms, such as the Strategic Priorities Fund.

For researchers in academia and industry:

- Develop collaborations between scientific and technical disciplines and sectors (e.g., industry, academia, Government) to establish key scientific and technical questions, share knowledge, develop best practice for measurement, to enable linking between studies and a holistic view of the research solutions.
- Engage with the Government and regulatory bodies to inform effective policymaking and regulation on indoor air quality and inform public health messaging.
- Work with wide variety of stakeholders and engage with the public in research on indoor air quality and increase awareness of how to mitigate the risks.

Glossary and abbreviations

The following terms and abbreviations are used throughout this report.

AI	artificial intelligence
AQEG	Air Quality Expert Group
anthropogenic	caused by humans or their activities
ASC	Analytical Science Community
chemometrics	the science of extracting information from chemical systems by data-driven means
CO	carbon monoxide
CO_2	carbon dioxide
Defra	Department for the Environment, Food and Rural Affairs
ESEC	Environment, Sustainability and Energy Community
FCPC	Faraday Community for Physical Chemistry
HSE	Health and Safety Executive
ISO	International Organisation for Standardisation
metadata	data providing information about one or more aspects of the data; used to summarise basic information about data to make tracking and working with data easier
NAEI	National Atmospheric Emissions Inventory
NHS	National Health Service
NICE	National Insitute for Health and Care Excellence
NO	nitric oxide
NO_2	nitrogen dioxide
NO_x	nitrogen oxides
O_3	ozone
off-gassing	to give off a chemcial, often a harmful one, in the form of a gas
PAHs	Polycyclic Aromatic Hydrocarbons
PHE	Public Health England
PM	particulate matter
RSC	Royal Society of Chemistry
SPF	Strategic Priorities Fund
SVOC	Semi-volatile organic compounds
UKRI	UK Research and Innovation
UV	ultra violet
VOCs	volatile organic compounds
WELs	workplace exposure limits
WHO	World Health Organisation

Introduction

Background

Indoor air quality refers to the air quality within indoor environments and arises from both indoor emissions and the infiltration of outdoor air.[2,3]

It is estimated that in high income countries, such as the UK, humans spend about 90% of their time indoors.[4,5] Yet, while outdoor air pollution has been studied and regulated extensively, indoor air quality is not as well understood.

This is an increasingly important topic as we better understand and quantify the significant potential health impacts of short-term or long-term exposure to indoor air pollution.

Chemistry has an important role to play in improving indoor air quality, along with many other disciplines, including physics, engineering, biology, sociology, and medicine.

Chemical scientists can help understand and manage indoor air quality in a range of ways, from identifying pollutant sources via source apportionment to measuring the concentration of pollutants; predicting and understanding key chemical reactions and the variables affecting the relative rates and products of such reactions;[6] as well as contributing towards the understanding of the health effects of exposure. They can also help to develop solutions, such as developing better ventilation, air filtration and purification systems.

Sources of indoor pollution

Indoor emissions stem from many sources, from cooking, cleaning, and personal care products to building materials, furnishings, heating, combustion appliances, and building occupants.

These sources can produce many different pollutants, including (but not limited to) volatile organic compounds (VOCs), particulate matter (PM), carbon monoxide (CO) and nitrogen oxides (NO_X). Outdoor pollutants can also enter the indoor environment, thus impacting indoor air quality, which is particularly relevant in urban locations or near busy roads or industrial sites.

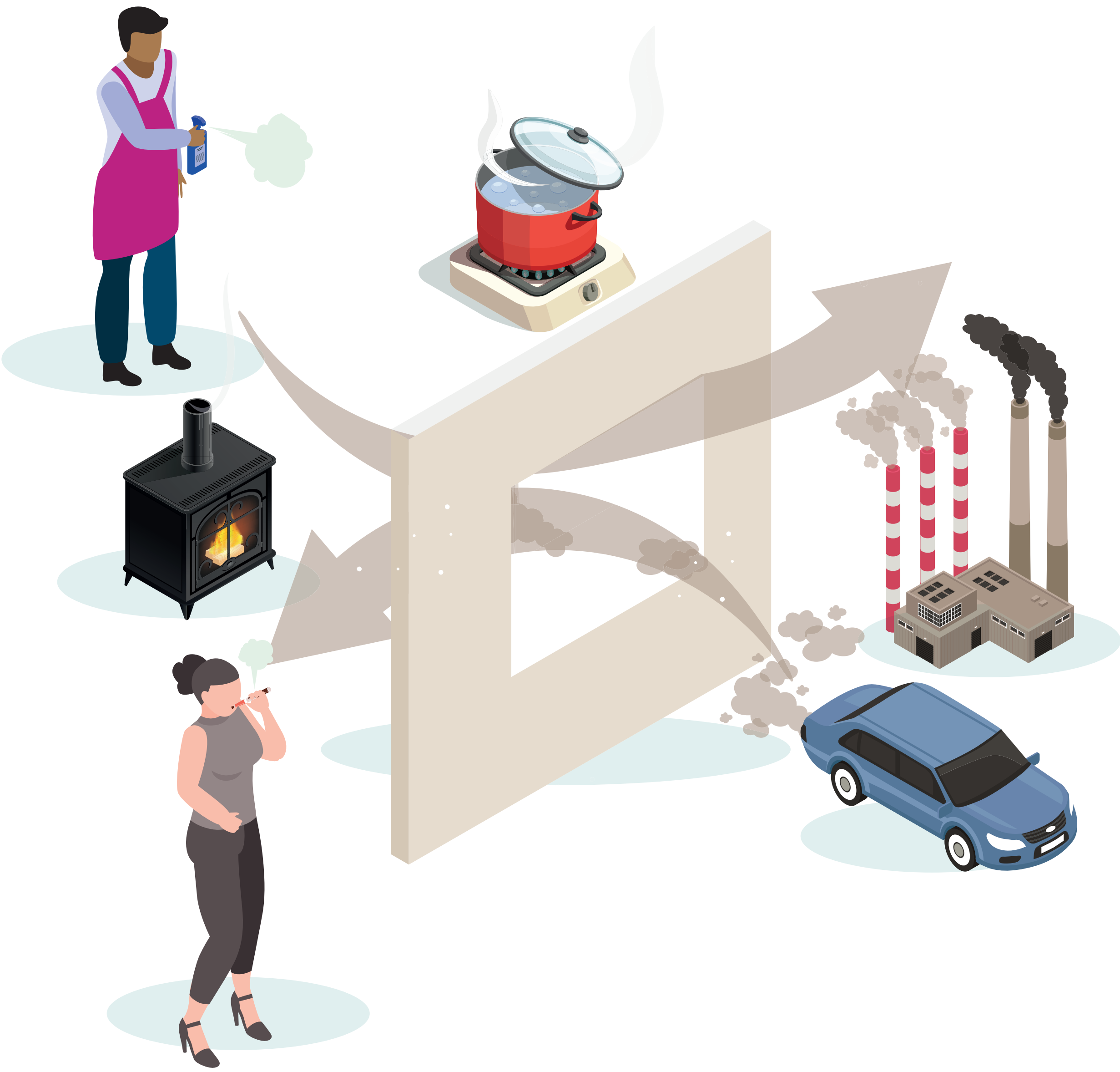
Unlike outdoor air pollution, indoor emissions are not easily dispersed, leading to the accumulation of some pollutants that are typically diluted outdoors, such as CO. This is also true for respiratory pathogens such as corona and influenza viruses, which can build up and spread more readily in indoor environments.[7]

Figure 1: Some of the main pollutants and example sources in the home.[7,8]

Impact of ventilation on indoor air pollution

Ventilation offers a possible solution to reducing unavoidable indoor air pollution. However, several factors need to be considered, including the quality of the outdoor air, the room volume, the air flow rate, and the specifics of the indoor environment type.[8]

In countries with a climate like the UK, there is also a balance to be struck between increasing ventilation whilst keeping homes warm in winter and cool in the summer. Improving energy efficiency by increasing insulation and introducing double glazing may help limit the ingress of outdoor pollutants. However, without adequate ventilation this is likely to increase the concentration of several indoor pollutants.[9]



Health impacts

The World Health Organisation (WHO) estimates that more than 3 million people worldwide die every year due to illnesses resulting from harmful air in their homes.[1] In the UK, anthropogenic air pollution is estimated to be responsible for 28,000-36,000 early deaths per year.[10,11]

Deaths linked to air pollution are commonly attributed to heart disease and strokes. However, it can also impact in other ways depending on the nature of the pollutant and exposure type.[7] For example, exposure to high concentrations of nitrogen dioxide (NO_2) may contribute to the development of emphysema, while exposure to carcinogens in wood smoke could cause lung cancer.[12]

Additionally, emerging research is linking air pollution with the increased risk of other health conditions, such as dementia,[13, 14] even in cases where the exact pollutant causing the effect has yet to be identified.[13]

Understanding what is harmful is essential to enable governments and regulators to develop effective policies and standards for indoor air quality. See **Table 1** for some of the major known indoor air pollutants, their sources and health effects.

Table 1: Sources and health impacts of some of the major known indoor air pollutants.

Pollutant	Description	Common sources	Potential health effects
Volatile Organic Compounds (VOCs)[7, 8, 15, 16]	• A large group of organic chemical compounds that vaporise easily and enter the environment. • Examples include alkanes, aldehydes, aromatic hydrocarbons, ketones, esters, terpenes, and chlorinated hydrocarbons.	• Paints and solvents • Personal care products • Building materials • Construction products • Cleaning products • Air fresheners • Carpets, laminates, and furniture • Combustion sources, such as stoves, ovens, and fireplaces	• Carcinogenic • Irritation, for instance, to airways, eyes, and skin • Respiratory problems • Nervous system damage
Nitrogen Oxides (NO_x)[7, 17-21]	• The two most common forms are nitric oxide (NO) and nitrogen dioxide (NO_2).	Outdoors: • Power generation • Industrial combustion • Road transport Indoors: • Combustion sources such as stoves, ovens, and fireplaces	• Respiratory diseases • Wheezing • Irritative cough • Asthma • Respiratory infections in children
Radon[7, 8, 17]	• A naturally occurring radioactive, colourless, and odourless gas formed from the decay of uranium.	• Soil and rocks beneath buildings • Building materials, e.g., granite	• Lung cancer
Carbon dioxide (CO_2)[8, 17, 22, 23]	• A colourless and odourless gas.	• Respiration • Combustion sources	• Poor attention levels • Headaches • Dizziness • Nausea • Vomiting
Carbon Monoxide (CO)[7, 8, 12, 17]	• A colourless, odourless, and tasteless gas. • Binds to haemoglobin, which reduces the carriage of oxygen.	• Combustion sources from many household appliances, running cars and cigarette smoke	• Fatal at high concentrations • Headaches • Dizziness • Nausea • Vomiting • Loss of consciousness
Particulate Matter (PM)[7, 8, 17, 24-29]	• The term used to describe a complex mixture of condensed phase (solid and liquid) particles suspended in the atmosphere. • The size of the particles and the length of exposure are directly linked to the health effects, with particles less than 2.5 µm (i.e., labelled as $PM_{2.5}$) in diameter having more adverse effects.	• Construction work • Industrial sources • Combustion of fossil fuels • Road traffic tyres and brakes	• Asthma • COPD • Lung Cancer • Dementia • Metabolic effects • Increased mortality from cardiovascular diseases (ischaemic heart disease, stroke, heart failure) • Impact on the reproductive system
Polycyclic aromatic hydrocarbons (PAHs)[7, 17]	• A large class of compounds that includes some highly toxic materials. • Some can be formed during the combustion process of organic sources.	• Motor vehicles • Biomass burning • Wildfires • Computers and other electronic equipment • Waste incineration	• Mutagenic, genotoxic • Carcinogenic • Respiratory diseases • Increased risk of cardiovascular diseases
Ozone (O_3)[7, 30, 31]	• A highly reactive and colourless or pale blue gas with a distinctive odour. • Can be found anywhere in the atmosphere but is found at higher concentrations in the upper atmosphere.	• Photochemical reactions with other pollutants such as NO_x and VOCs	• Wheezing • Coughing • Throat irritation • Chest tightness • Shortness of breath • Reduction in lung function • Asthma
Bioaerosols[7, 31-34]	• Liquid or solid particles in the air of biological origin, such as moulds and fungal spores. • It may be caused by dampness and inadequate ventilation in the indoor environment.	• Moulds • Fungal spores • Viruses • Plant and animal matter	• Coughing • Wheezing • Allergic Rhinitis • Asthma • Infectious diseases • Chronic obstructive pulmonary disease

Indoor air pollution and inequalities

Research suggests that the impacts of indoor air pollution are unequally distributed. Most of the deaths linked to indoor air quality occur in low and middle-income countries, where indoor air pollution results from exposure to high concentrations of smoke produced by biomass burning from cooking.[17]

Workshop participants also noted that in the UK, in general, people of different socioeconomic backgrounds may experience different levels of indoor air quality for various reasons, including differences in location, ownership and condition of buildings, but that exposure disparities have not been fully explored.[7, 31, 33, 35]

For example, households of low socioeconomic status can experience higher levels of some pollutants, such as indoor PM, NO_X and VOCs, as they may be closer to high-traffic areas, and are more likely to live in homes in poorer condition with issues such as damp or mould.[31, 35]

Conversely, in geological areas where radon concentrations are highest, larger homes are more likely to be affected by higher radon concentrations.[31, 35]

Also, those in vulnerable groups, such as very young children, older people, and those with respiratory conditions, such as chronic obstructive pulmonary disease (COPD), are at greater risk from exposure to indoor air pollution.

The role of policy, regulation, and behaviour

Policy and regulation in the UK

The UK has national minimum air quality standards for outdoor air pollution, which have developed from multiple legislative sources.[8] However, the regulation, legislation and guidance on indoor air quality is not yet as well developed, with no regulations specifically dedicated to determining limits for indoor air pollution.[7, 8]

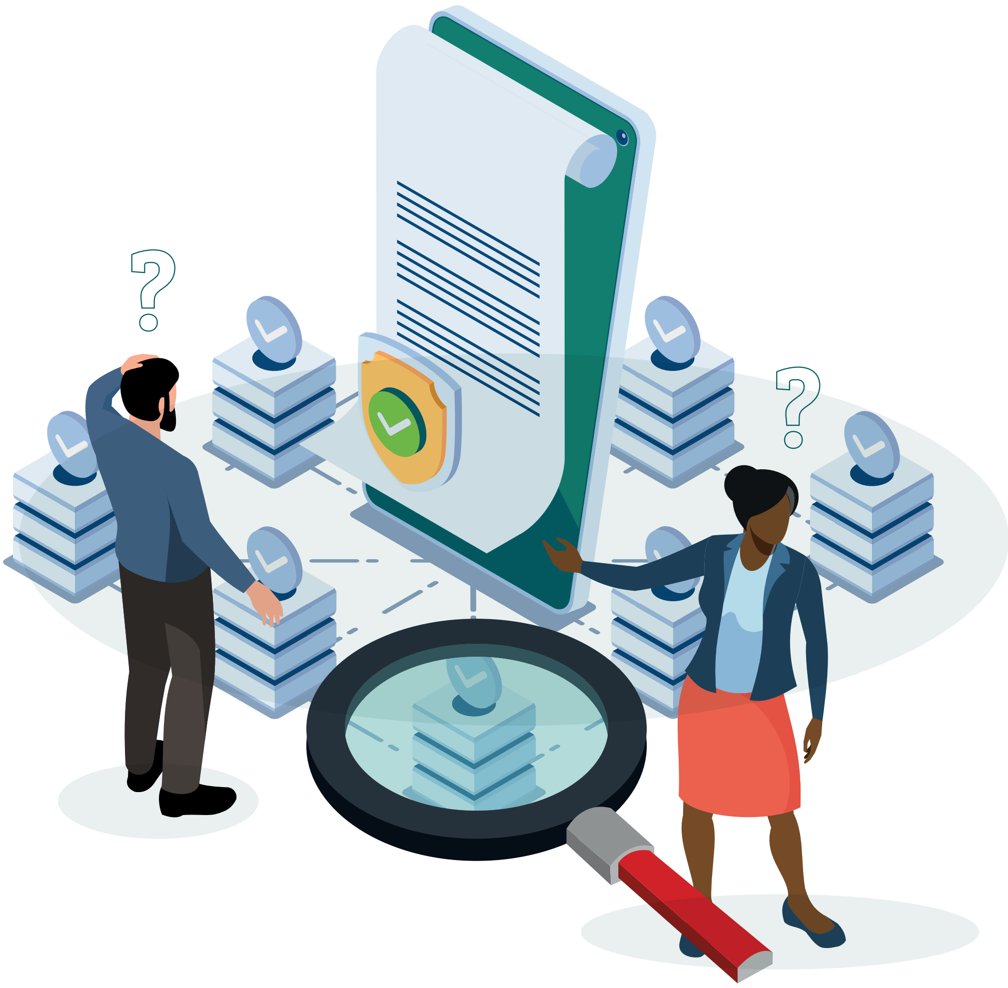
Policy levers to address indoor air quality are spread across UK Government

Workshop participants highlighted that responsibility for regulating, monitoring, and addressing indoor air quality in the UK is spread across multiple government departments.

For example, the Department of Transport (DfT) is responsible for public transport, vehicles, and hubs; the Department for Business and Trade oversees product and chemicals regulation; responsibility for housing and planning regulations lies with the Department for Housing, Levelling up and Communities; and outdoor air pollution is within the remit of the Department for the Environment, Food and Rural Affairs (Defra).

Several other government departments and bodies in the UK also have responsibility for air quality. For example, the Department for Education and the Health and Safety Executive (HSE) oversee this in relation to schools and workplaces, while the UK Health Security Agency (UK HSA) and local authorities are responsible for aspects of monitoring and enforcement.

In 2021, a Cross Government Working Level Group on indoor air pollution was set up to coordinate Government efforts on indoor air pollution.[8] Workshop participants noted this was a step in the right direction, with some observing that continued and further collaboration and coordination across Government is needed to develop and implement policy, ideally with a named lead agency. Some workshop participants suggested such an agency could include or consult with local councils and public groups.



Regulation and guidance are fragmented and confusing

A comprehensive summary of UK regulations relevant to indoor air quality was included in the Air Quality Expert Group's (AQEG's) Indoor Air Quality report (Defra, 2022).[8]

Workshop participants highlighted that there are no statutory specific targets for indoor air pollution comparable with those that exist for outdoor air[8] and that there is a lack of consistency between indoor air quality standards and guidelines. Instead, there is a range of regulations and guidance used by different bodies and departments across Government. For example:

- Health-based guideline values for selected indoor pollutants are included in the Revised Building Regulations and the Future Homes and Building Standards, referenced as "performance criteria". These are based on guidance from the WHO (WHO, 2010)[17] and Public Health England (PHE, 2019).[36-38]
- The HSE's Control of Substances Hazardous to Health (COSHH) statutory regulations use workplace exposure limits that cover some indoor air pollutants.[39, 40]

These government bodies and departments set different guideline values for different contexts, making it challenging to compare and assess levels of specific pollutants and whether those levels are harmful. Further complicating matters, several settings could equally apply different regulations. For example, a care home could be considered both a workplace and a residence.

Additionally, some workshop participants noted that these guideline values are for individual, pure compounds and assume that values for mixtures are a sum of the individual component limits. However, they were not aware of much toxicological evidence to support this approach.

The UK has an opportunity to stimulate innovation and build on good practice from other countries.

Several participants highlighted that regulation could drive investment and innovation. For example, the United States Clean Air Act (1990) led to the development of, and investment in catalytic converters in cars to meet the required reduction in exhaust emissions.

Participants also highlighted several examples of good practice in other countries that the UK could build on, including:

- **A focus on baseline detection and monitoring** in countries such as Germany and France.[41, 42]
- **Regulations, labelling and monitoring systems for construction and decoration products.** For example, France has compulsory labels (from A+ to C) to show the classes of VOC emissions from construction, DIY and decoration products, e.g., paints, flooring, insulation, floor coatings, wall coverings and sealants. [43, 44]
- **Labelling and monitoring systems for ventilation** as a proxy for air quality. For instance, the German Committee on Indoor Air Guide Values uses a system of monitoring CO_2 levels with labels of "green" (up to 1000 ppm, harmless, no intervention required), "yellow" (1000-2000 ppm, hygienically conspicuous, in need of ventilation) and "red" (above 2000 ppm, unacceptable, in need of much more ventilation).[45]
- **Greater awareness and different customs to manage indoor air quality** in some countries. For instance, regularly airing out rooms (Germany) or waiting for the smell of VOCs to dissipate before using new cars or houses (China).

UK funding landscape

Several workshop participants noted funding calls for indoor air quality research in recent years and were supportive of the approach taken by UK Research and Innovation (UKRI) and cross-research council funding initiatives through the Strategic Priorities Fund, e.g., the Clean Air Programme.[46]

However, many remained concerned about what will happen when these funding streams end in 2025,[47] and how this might impact future research and innovations in the field. They suggested that a long-term systematic indoor air quality and health surveillance project is needed to enable long-term monitoring of pollutants and how their presence may evolve over time, as well as a greater understanding of long-term health effects. This would require dedicated, stable long-term funding due to the complexity of the topic and the range of players and settings, including different scientific disciplines (such as physical sciences, engineering, social sciences, and life sciences), sectors (industry, academia, government, and regulators) and types of building space.

In addition to funding, measures such as collaborative platforms and skills development for researchers will be needed to enable this kind of complex multidisciplinary research.

Data protection and privacy considerations

Workshop participants noted that research and regulation related to indoor air quality will require taking measurements in homes, schools, nurseries, hospitals, and workplaces, possibly on large scales.

Regulatory effectiveness and cost must be balanced with individuals' privacy, which will require appropriate safeguards to govern data collection and use. Examples of best practice and guidance are available, for instance, the NHS Health Research Authority and UKRI websites have guidance related data protection and privacy for health research involving the public.[48, 49]

The interplay between net zero policies and indoor air

Governments, organisations, and individuals worldwide are implementing measures to drastically reduce CO_2 emissions to limit climate change. Many net zero initiatives will positively impact indoor air quality but there are complex interplays that mean some interventions could have unintended consequences.

Workshop participants highlighted the importance of a holistic approach to the transition to net zero that considers the impacts of related measures on indoor air quality. For example:

Building materials

New construction materials are entering the market to help achieve net zero targets, for example ultrathin insulation panels to improve the heat performance of buildings and reduce energy use. The performance of such materials in relation to indoor air quality must be understood and managed, alongside the environmental impacts across their lifecycle.

Changes in the internal environment

Balancing energy efficiency and ventilation considerations will be critical. Maximising the air tightness of buildings to improve energy efficiency from heating may lead to changes in ventilation and therefore the concentrations of certain pollutants within indoor environments.

Changes to the air and heat tightness of buildings can also affect internal temperature and humidity, which could affect the balance and composition of primary and secondary pollutants alongside chemical or biological contaminants. For example, it is known that O_3 decay rates increase as humidity or temperature increase.[6, 50]

Changes to heating methods

New heating methods have the potential to both reduce environmental impacts and improve air quality, but consideration needs to be given to affordability and accessibility.

For example, switching from burning fuels to heat pumps, or from gas to electric stoves, would reduce pollutants such as CO_2, CO, NO_x, unburned methane and PM.[8, 51] If such low-carbon heating and cooking methods are supported by low-carbon electricity generation, they should significantly improve both indoor and outdoor air quality. However, high equipment and electricity costs may make such low-carbon switches unaffordable for some households.

The role of outdoor air quality

It is expected that the transition to net zero, such as measures to reduce the use of fossil fuels, will lead to a reduction in outdoor air pollution, which would be expected to improve indoor air quality. However, this is a complex landscape with more research needed on how these issues interlink.[52] This includes, for example, understanding the impact of tree planting on air quality,[53, 54] quantifying the impact of PM from electric vehicle tyres (e.g., the increased weight of battery electric vehicles may increase PM emissions from tyres and brakes),[55] and the effect of increased use of hydrogen as an energy storage vector or fuel. For instance, hydrogen's use as an energy storage vector may discourage fossil fuel burning and could be used either in fuel cells or in direct burning. However, hydrogen burns at higher temperatures to methane and its use as a combustion fuel may lead to some increase in NO_x and PM emissions.[52]

The role of human behaviour

People's behaviour and activities can create completely different scenarios with different impacts on indoor air quality, even for similar buildings.[56] Examples shared by workshop participants include:

- **Cooking methods.** For example, gas hobs increase pollutants such as CO_2, CO, NO_x, and PM significantly more than those that do not burn fuels, such as electric and induction hobs.[51, 57]
- **Heating method and room temperature.** For example, wood burners and similar equipment produce significant amounts of PM, and gas heating leads to increased levels of pollutants such as CO_2, CO and methane.[7, 8] Inadequate heating can also lead to other issues, such as mould and damp, which can have significant health implications.[7, 8]
- **Levels of ventilation.** For example, the act of opening windows often varies by season, cultural or individual norms. This can positively or negatively impact indoor air quality depending on the outdoor air quality and the potential to build up pollutants.[8]
- **Smoking or vaping.** These practices can have long-lasting effects as, in addition to chemicals and PM released during the activity, furniture may absorb pollutants and release them back into the air over an extended period.[8] This is sometimes known as tertiary smoking or thirdhand smoke. In addition, whilst the toxicity of smoking is well established, the impacts of vaping need further study.
- **Cleaning methods.** Both the frequency and methods of cleaning can affect indoor air quality. Different cleaning products contain different chemicals or concentrations of chemicals. Activities such as vacuuming, dusting and mopping can remove pollutants, but can also be sources of pollutants such as PM.[58]
- **Consumer products, air fresheners and candles.** For example, air fresheners, candles and personal care products may emit VOCs and PM.[15, 59]
- **Drying clothes indoors.** This can affect a room's humidity and potentially release other pollutants, depending on the laundry products used.[8]
- **DIY building materials and decoration products** like paint can expose individuals to gases and PM.
- **Presence of occupants.** For example, the movement of individuals around a room can affect the chemical compositions of gases, airflow, ventilation and resuspension of particles.[59] The presence of people within an environment also increases the concentration of many pollutants, such as CO_2, O_3, PM, VOCs and chemicals contained in consumer products used by the occupants.[59]

Scientific and technical challenges and solutions

Workshop participants discussed several scientific challenges for the chemical sciences relating to the characterisation and measurement of pollutants, and limitations in data and models.

Research questions and solutions

Characterisation and monitoring of pollutants

CHALLENGES

Currently, there is no comprehensive quantitative inventory or characterisation of indoor pollutants. While there are some valuable inventories of pollutants emitted indoors, they are not comprehensive and there is little quantitative information linking the chemicals to, for instance, activities.

The National Atmospheric Emissions Inventory (NAEI) is a valuable list of pollutants released indoors and their sources but is not designed for evaluating indoor air quality. It does not include several sources of indoor emissions, such as cooking, building materials and furnishings, or provide data to enable detailed emission inventories of these sources.[8, 60]

For example, the NAEI reports that over 14% of VOCs in the UK are released indoors, but does not assign how much of each VOC is released during an activity or how that might be related to the frequency of that activity.[8, 60]

SOLUTIONS

Many workshop participants highlighted the need for a comprehensive, quantitative UK inventory of indoor pollutants and baseline measurements collected under controlled conditions using methods where data is comparable. This is necessary to:

- Inform knowledge-driven investigations.
- Enable systematic surveillance of pollutants.
- Understand the effect of the indoor environment on indoor air quality. For example,
  - Temperature (can affect reaction kinetics and equilibria).
  - Humidity (can affect reaction kinetics and equilibria).
  - Ventilation (can influence time and spatial-dependent composition or exchange of pollutants/gases, e.g., between indoor and outdoor environments).
- Understand the impact of light, particularly sun, and artificial UV and near-UV light (can affect photolysis reactions, which can change the pollutants present).
- Explore the use of proxies, i.e., inferring levels of pollutants by measuring levels of a proxy that is typically more straightforward to detect and measure.
- Build up an evidence base for decision-making regarding key pollutants in the indoor environment (both in the air and on surfaces).
- Measure the change of pollutants over time and thus assess how policies, technical or scientific interventions and environmental changes affect health endpoints.

Workshop participants also noted that, aside from PM, there is currently a lack of consensus on what should form part of a national inventory in terms of the substances that should be measured and the preferred methodology to measure them.

Establishing an agreed baseline assessment of what pollutants should be measured and how would be a useful first step in establishing a nationwide inventory of pollutants and reference values.

Some countries, such as Austria, France and Germany, have published reference values that can be used as guidelines for a range of pollutants.[42, 61, 62] Another example is the HOMEChem (House Observations of Microbial and Environmental Chemistry) experiment[63] carried out in the US in 2018 to better understand the most important aspects of the chemistry of the indoor environment.

One workshop participant pointed out that in the 1990s, there was an indoor air quality survey in England.[64-66] However, this was not subsequently followed up.

France's indoor air observatory

In 2001, France's Ministry of Housing commissioned the Indoor Air Quality Observatory (OQAI)[67] to provide information on indoor pollution.[67, 68] A national survey, based on a representative sample of around 500 homes, informed national guidelines on indoor air pollutants.[67] A second national campaign is now underway with plans to survey 750 homes.[68] The Observatory also regularly undertakes research and campaigns on specific priorities, such as air quality in schools.[68]

Understanding health impacts

CHALLENGES

There is currently no complete picture of which indoor pollutants people are regularly exposed to or at what levels. Participants highlighted a range of gaps in current understanding:

- Understanding the effects of a single pollutant within a mixture of pollutants present.
- Grouping pollutants into broad categories, such as VOCs, can increase complexity, as there can be a range of health effects within each grouping. This makes it difficult to relate pollutants to particular health outcomes.
- Assessments are mainly based on toxicological and animal studies, with few human cohort studies.
- Short-term health impacts are better characterised than long-term ones. While some information regarding chronic exposure can be drawn from occupational health and epidemiology studies, it is more straightforward to establish links between exposure and acute conditions, such as tracing a particular VOC to asthma exacerbation.
- It is only possible to establish statistical links between the occurrence of a compound in indoor air and an adverse human health effect, making it difficult to develop hazard-risk matrices.

SOLUTIONS

More collaboration is needed between disciplines to understand and track the complex real-world interactions between indoor air pollution and health as well as more long-term studies based on real-world health data are needed.

Understanding the impact of surfaces

CHALLENGES

The ability of surfaces to store pollutants can lead to interesting chemistries that significantly impact indoor air quality.[69, 70] Examples of the impact of surfaces include:

- In gaseous or solid form, pollutants can deposit on indoor surfaces, removing them from the atmosphere.
- Accumulated pollutants on surfaces can lead to dermal exposure or ingestion.[8]
- Surfaces can act as a reservoir of pollutants that can then subsequently partition back from the surface-bound particles into the air for many months. Off-gassing (i.e., releasing gaseous pollutants from surfaces) and dynamic transfer between indoor surfaces and air are also possible.
- Surfaces can promote or act as a catalyst to reactions between pollutants.[69-71]
- Surfaces themselves can have high surface-to-volume ratios indoors.

Although there have been studies into some aspects of the role of surfaces, there is still a lack of information about the fundamental chemical processes that occur.[72]

SOLUTIONS

More research is needed to map and understand and the role of surfaces, the chemistry at the surface and kinetics of partitioning in contributing to or mitigating indoor air pollution.[72]

Studying pollutants in indoor spaces

CHALLENGES

Workshop participants identified several challenges specific to studying indoor spaces:

- **Sources.** There are a wide variety of sources of pollutants within a building and they can have surprising impacts. Cooking methods (e.g. biomass, solid fuel burning, gas stoves, electric stove or ovens), styles (e.g. stir-frying, steaming, boiling, roasting), and ingredients (e.g. spices, oils and meats) strongly influence the amount of PM generated.[59] For example, a person in the UK can be exposed to more PM while cooking, for instance, on a gas stove and in an electric oven, than spending an equivalent amount of time next to a busy road.[24, 28, 63, 73]
- **Ventilation efficiencies.** These are dynamic and often not well understood and can be affected by many factors, including room usage, occupancy, layout, and temperature.
- **Available data or baselines.** Not all indoor spaces are being studied equally, nor are guidelines being issued equally. For instance, the WHO has developed a manual for schools,[74] containing guidelines on sampling analysis and sampling location, but has not issued similar guidance for other settings.
- **Emissions have not all been well studied.** Whilst there have been studies for some pollutants, e.g., formaldehyde, there are still gaps in understanding of pollutant emissions from some sources, particularly in real-world settings. For instance, a recent review noted that data are scattered, have unclear quality and structure, and there are limited individual VOC measurements, particularly in the UK.[15]
- **Different locations.** Some indoor environments can be in places with poor outdoor air. For example, more than two thousand UK schools and nurseries are located near roads with illegal air pollution levels.[75]

SOLUTIONS

Further studies and a systematic approach to researching indoor air pollutants is required with guidance regarding best practice in methodology.

Measurement challenges

Representative samples

CHALLENGES

Indoor air is extremely heterogeneous, and many factors can affect the concentration of pollutants being measured. It can, therefore, be difficult to ensure that samples collected or tested are representative.

Participants also pointed out that when thinking about exposure levels and linking these to health, it is important to consider when, where and how measurements are taken and translated to real-life situations.

Factors such as sampling location are extremely relevant, particularly for accurately assessing people's exposure to pollutants. For example, sampling the air in the areas where people spend time and accounting for activities in different parts of the home or building, as well as ventilation.

SOLUTION

It will be important to develop real-world approaches to measurement that consider how people use equipment and spaces.

Sampling locations can lead to variability

A simple example of how sampling at different locations can lead to variability comes from cooking. Sampling one meter above a stove while cooking will give very different results to sampling right next to it as key features, such as temperature, humidity, and concentration of pollutants, such as PM, VOCs, NO_x, CO, and CO_2 will be very different. Similarly, sampling one meter away in any direction will lead to different results.

Contamination and interference

CHALLENGES

As indoor air quality measurements are often taken on a large scale and are required to measure a small concentration of pollutants, there is the potential for contamination and interference in the measurements, highlighting the importance of baseline measurements, sample location, sample preparation and calibration of instruments.

SOLUTIONS

Researchers can overcome these challenges by:

- **Validating measurements.** This can range from validating the baseline reading to rule out any contamination issues of the instrument or the sample.
- **Addressing signal interference.** When measuring compounds in small concentrations, it can become difficult to differentiate a signal from the indoor air pollutant compared to a signal from another species present in a much higher concentration. For example, when using mass spectrometry, it can be difficult to differentiate between VOCs at low molecular mass owing to the fragmentation of larger VOCs into fragments of the same mass, and because of the possibility of isomers. Careful calibration and application of methods specifically for low molecular weight samples is needed to ensure the level of accuracy required.
- **Sampling techniques.** Active sampling techniques, like thermal desorption, typically involve pumps drawing air directly into an instrument or over sorbent materials. Passive sampling techniques typically involve diffusion or absorption. Each technique has advantages and limitations. For example, in situ passive sampling shows distributions of contaminants in real time and is less prone to matrix interference. Active sampling, however, allows for preconcentration, which can lead to improved selectivity and sensitivity.

Sensors, cost, and precision

CHALLENGES

A wide variety of sensors and sampling methods are available for sampling and analysing indoor air. Workshop participants highlighted the need for careful selection of appropriate techniques.

The availability of low-cost sensors to monitor pollutants will facilitate greater monitoring, but there are concerns about their accuracy, precision, performance, and calibration.[76-78] Lower cost sensors may only detect one type or grouping of pollutants (e.g. VOCs or a single type of VOC), to act as a proxy for air quality, which may mean other harmful pollutants are missed.

Some sensors have been demonstrated to have good in-laboratory performance but poor or variable real-world performance.[78] For example, some NO_x sensors have been demonstrated to work best in cases of high pollution, where their detectors can be saturated, but they can also react to other chemicals, such as CO_2 and hydrogen.[76]

There are some more precise instrumentation options available, however these tend to be more expensive and larger, and current options are limited. This means that there are limits on how widely such instruments can be deployed. Large equipment can also affect the local environment being tested, for example, by raising the local temperature or changing the ventilation parameters, for instance, by using a cooling fan.

Existing air samplers must follow International Organisation for Standardisation (ISO) standards.[79] Some workshop participants noted that ISO measurements are primarily aimed at monitoring occupational exposure and make several assumptions, including the homogeneity of airborne pollutant concentrations, which may not be the case when developing an air sampler for use in domestic indoor environments.

SOLUTIONS

Several workshop participants noted that work is required by the research community before they can support the wide acceptance and adoption of the different sensors. More data is needed comparing low-cost and high-precision instrumentation to guide the different applications.[76-78] In addition, standard methods with accurate sensors are needed for reliable data.

Fundamental aspects related to measurements or experimental research design need to be considered, including:

- **Sampling aerosol component.** To consider whether sampling in gas or aerosol will give the most useful data as it may not be possible to sample both at the same time.
- **Position in the room.** Where measurements are taken in a space plays a crucial role. The WHO has developed recommendations for schools, containing guidelines on sampling analysis, sampling location etc.[74] Similar guidelines for other settings would be beneficial.

- **Emissions from walls, floors, furniture etc.** These contribute to indoor air quality and guidance on best practice would be helpful for characterising these emissions.
- **Validation of methods for indoor air quality measurement** is needed to determine the most suitable method to use alongside understanding and defining the uncertainty that exists within the measurement technique.
- **Application of chemometrics** to process data and establish relationships, such as source apportionment, requires that the correct metadata is collected and that the data is of high quality and comparable between different studies.
- **Design of experiment** to ensure the right data is collected in the correct way to avoid missed data or to identify opportunities or to avoid duplication.
- **Agreed-on calibrations are needed.** For example, for different sample matrices, to ensure that all measurements give comparable results across studies and in inventories.
- **Quantifying emissions is challenging**, and different methodologies can introduce different baseline errors and biases. A standardised method with defined and minimised measurement bias is required. One potential way to achieve this is to perform intercomparisons where the same pollutant is measured using more than one technique. If there is good agreement, this lends more confidence to the measurement.
- **A comprehensive suite of chemical kinetics measurements** determined in the laboratory, such as reaction rate coefficients, product branching ratios and other mechanistic detail, is needed as input into process models which are used to calculate the concentrations of key target species (for example, free radicals, intermediates, or specific secondary pollutants) for comparison with indoor measurements. The levels of agreement would enable a statistical analysis to be made of how well we understand indoor air chemistry and emissions sources.
- **Developing models for multi-faceted problems**, such as when multiple pollutants are present.

Comparing low-cost and high-precision instrumentation

■ The INGENIOUS project[80] at the University of York is taking a multipronged approach. All homes taking part in the study have low-cost, low-precision sensors, a subset of which are taking samples in canisters for later analysis, and a subset of those are collecting filter samples for particle analysis. The aim is to combine data from these sources with models to understand if low-cost sensors can be used as a proxy for measurement with high-cost equipment.[80]

■ The WellHome project at Imperial College London is targeting one cohort (asthmatic children) and is taking a similar approach to the INGENIOUS project to collect and analyse the data on a smaller-scale[81] and linking these to a particular cohort.

Practicalities and acceptability

CHALLENGES

Participants highlighted that there are considerable practical constraints in deploying equipment for real-world measurements of air quality, often due to the impacts on indoor locations or their inhabitants. Equipment can be:

- **Intrusive.** For example, vacuum pumps, which are necessary to operate some instruments (such as aerosol instruments), are noisy and might not be appropriate for some settings, such as bedrooms.
- **Impractical.** For example, some equipment can be awkward or difficult to use, repair or upgrade routinely in the field.
- **Heavy or physically bulky.** For example, backpacks containing equipment might not be practical or acceptable for continuous monitoring to measure personal exposure, or the equipment itself might be too heavy or bulky to carry.

Data and models

Good and reliable data

Workshop participants noted that an ongoing research challenge involves establishing good, reliable, quantifiable datasets or models. Some of the key challenges highlighted include:

- **How measurements are taken.** Agreement is needed among researchers on how indoor air quality measurements are best taken, in terms of sample location or sampling method.
- **Standardised measurements and references.** For example, establishing a standard measurement set to ensure consistency between measurements and studies.
- **External influences.** Greater understanding to quantify pollutants when even subtle changes can affect the profile. For example, the types of oil and spices used during cooking, the amount used, and the sequence of their use alongside other external factors, such as ventilation, can affect the chemical profile of the pollutants within a kitchen from cooking.[59, 82-85]
- **Use of non-target analysis.** Non-target analysis (to try to analyse all chemicals present in a sample) can help to identify many components of the mixture, but it has limitations in its ability to quantify them, or to guarantee that all the components of the mixture have been correctly found and identified.
- **Use of proxies with data sets.** In some cases, proxies are used to estimate concentrations of pollutants or to infer airflow.[86, 87] However, this does not necessarily give an accurate picture and is an area that is continually being explored. For example, CO_2 has been found to be a useful proxy for ventilation and thus, to some degree, air quality in some indoor environments, but was a poor predictor of some pollutants, such as traffic-related pollutants.[87, 88]

- **Identifying the most harmful pollutants to human health.** It is challenging to definitively establish which pollutants or combinations of pollutants are the most harmful or risky from a health endpoint perspective, as current approaches can only lead to statistical links, which do not necessarily prove causation, between pollutants and health endpoints.
- **Integrating chemical kinetics with other modelling** to understand the complex mixtures of compounds and the interactions between them. For instance, combining chemical kinetics models with air mixing models and iterating is complex, time-consuming, and computationally intensive.
- **Type and features of indoor environment.** Indoor spaces vary significantly both in type (homes, workplaces, transport etc.) and other aspects such as occupant behaviour, construction, maintenance, and set-up. Each has a unique and complex mixture of primary (directly emitted), secondary (formed by chemical reactions), classic (known and characterised) and emerging (newly discovered to be of concern) pollutants.[89-92] This further increases the complexity of both data collection and modelling. At the same time areas of commonality can be found to streamline models.

Approaches to indoor air quality research

Workshop participants highlighted two different approaches that could be used to understand the pollutant:

Table 2: Approaches to indoor air quality research highlighted at the workshop

Approach	Advantages	Limitations
Start by looking at the chemistry of pollutants. Look at existing pollutants, inventories, emissions, chemical reactions, and the processes that occur and assess the effects on health.	This type of approach has been used to study outdoor air pollution and would offer a valuable starting point in understanding indoor air quality.	• It is challenging to build up a complete picture of the chemical fingerprint of an indoor environment, e.g., building, and the effect of activities by focusing on individual pollutant emissions. • Modelling can give lots of chemical detail and predict compounds that may be indoors, but there may be limited data on their health effects in real-life settings. • Attempting to map the entire landscape of pollutants can take significant time.
Start with the health impacts. Look at the impacts on health and track back to the pollutants and their chemistries and processes.	This approach may give a more accessible way to address indoor air quality than constant measuring of environments by allowing for direct access to health-related information and filtering out extraneous detail.	• The link between health and pollutant exposure can be unclear, particularly where there are limited existing studies, and so it can be difficult to prioritise which pollutants to look at. • Focusing on the health impacts first makes the exposure risk unclear without understanding the pollutants' chemistry, concentration, and relevant processes.

Some workshop participants suggested following a mixture of chemistry-driven and health-driven approaches, further highlighting the need for multidisciplinary collaboration and research programmes.

The measurement toolkit could be refined as investigations continued, with continuous feedback between the chemistry and health aspects. This could combine with a targeted analysis of well-known pollutants and their effects with a non-target analysis or screening of homes to produce a more comprehensive sample set for future work.

Opportunities for research and innovation

Advances in science and technology

Workshop participants highlighted several opportunities for indoor air quality research and innovation, including improved understanding, measurements, and data, and using proxies to improve data collection.

Improved understanding

Understanding and quantifying the effects of pollutants in an indoor environment is a complicated, multi-faceted challenge requiring careful study of their source, chemistries, and interactions with other chemical species or within spaces. Areas that workshop participants identified further research is needed include:

- **Time-evolution** of pollutants.
- **Effects on pollutant concentration** and behaviour of changes to factors such as humidity and temperature.
- **Reaction rate coefficients**, product branching ratios, equilibria constants and other mechanistic details, for example, of gases or chemicals from cleaning products or other activities such as cooking that can lead to secondary indoor pollutants.
- **Photolytic reactions** (i.e., chemical reactions brought about by exposure to light).
- **Chemical interactions or reactions**, e.g., with radicals or other reactive chemistry species, to understand what secondary pollutants are likely or possible.
- **Characterising the speciation** (i.e., identity and quantity) and absolute emission rates of pollutants, such as VOCs, from indoor sources and activities.
- **Surface chemistry**, catalysis, and the contribution of effects such as off-gassing, absorption of pollutants onto surfaces, and surface reactions of pollutants to form other species.
- **Ventilation and air exchange rates** and how they affect the local environment and the pollutants present.
- **Development of methods to extract data** and ensuring the data are of high quality and comparable between different sources.

Better measurements and data

There is an opportunity for innovation and further development of specialist measurement techniques specifically for indoor air quality measurement.[93]

Measurement technologies

Indoor air quality measurement typically uses a range of measurement technologies, including gas chromatography (GC) with detection techniques such as mass spectrometry (MS), flame ionisation detector (FID), photoionisation detector (PID) or, thermal conductivity detector (TCD), liquid chromatography-mass spectrometry (LCMS), proton-transfer-reaction mass spectrometry (PTR MS), selective reagent ion-time of flight (SRI-TOF) and spectrophotometry.

Advances in the underlying technologies or underpinning analytical chemistry, such as developing novel columns for gas and liquid chromatography, are continuously ongoing and could potentially lead to improved sensitivity or resolution, allowing for better identification and quantification of the analytes.

Measurement techniques

In situ and offline approaches may be used. Whilst in situ measurements allow for real-time measurements, they may require large or bulky equipment. Offline measurements, for example, taking gas samples via adsorptive filter or aerosols via filters, offer the opportunity for further study using more complex, laboratory-based instrumentation, but do not allow real-time measurement. Potential for advances in the technologies for in situ measurements include, for example, surface catalyst and electrochemical sensing methods.

Complementary measurements

Small volatile compounds, such as some VOCs, can be challenging to detect and/or quantify by mass spectrometry due to similar molecular weights and lower resolution of some instruments at low molecular weights or short environmental half-lives of pollutants.

It could be helpful to consider using other potential approaches if needed. For example, source fingerprinting (i.e., identifying all pollutants present) and toxicological assays could be another way to assess indoor air quality.

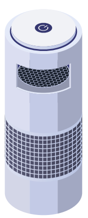
Improving sensors

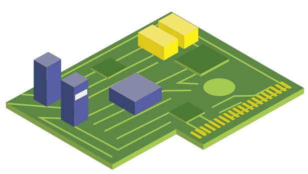
Developing advanced sensors that can detect and measure with high specificity in a wide range of conditions, as well as being low-cost, would allow air quality monitoring at scale and could revolutionise data collection.

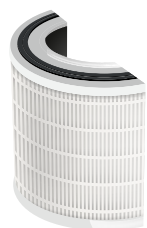
Workshop participants suggested that the ideal future sensor would be small (e.g., the size of a wristband or badge), wearable, simple to use, inexpensive, accurate and precise, reliable over time, have high specificity (i.e., detect and distinguish between different pollutants), able to collect large quantities of context-specific data such as metadata and usable in a variety of indoor conditions or locations.

The potential benefits of such small and inexpensive sensors include:

- Large numbers of measurements could be taken due to the sensors' low relative cost, allowing for larger-scale monitoring (and more data).
- The ability to aggregate data from multiple sensors, for example, distributed widely around the indoor area, may enable a more representative picture of the spatial distribution of indoor air quality.
- Smaller sensors could potentially be incorporated into other technologies, such as robot vacuum cleaners, which can then be targeted to clean particular areas, and fans that self-activate to increase ventilation when high pollution levels are detected.
- They do not adversely affect the surrounding environment.
- Individually worn sensors may allow for personal exposure monitoring.





Integrating and sharing data from different sources

Identifying and utilising data from other sources may be possible and could be extremely valuable to indoor air quality research.

For instance, there may be routine commercial studies where sharing of non-sensitive data, such as the control or background data (i.e., the data taken to determine the baseline readings), could be aggregated and anonymised.

Other data sources could also add richness to existing data, aid models and support understanding of the underlying chemistries of buildings. Examples include:

- Data taken during energy performance measurements of buildings.
- Data from buildings management systems, which are used in many buildings to monitor and control various aspects of the operations of the building, including the ventilation systems.
- Data taken from office buildings that have switched from mechanical to natural ventilation. Some workshop participants observed that several buildings are starting to do this and are monitoring CO_2 levels throughout their facilities to help determine their ventilation efficiencies before and after switching.

As more and more data are generated, there is an opportunity for fit-for-purpose AI tools, machine learning and techniques such as statistical clustering methods on ever larger datasets to find and establish patterns that would be difficult for humans to do alone due to the large amount of data collected.

Use of proxies

The use of proxies in indoor air quality research can also be extremely valuable. Workshop participants shared the benefits of their use:

- **Allows for wider understanding.** For example, building up a picture of air exchange rates of buildings, particularly houses, is extremely beneficial. CO_2 is used as a proxy for measuring air exchange rates and ventilation efficiencies, as factors such as the properties, concentrations, and diffusion rates have been well characterised.[94]
- **Enables citizen science approaches.** If simple proxies can be found, measurement of these proxies can lead to an extensive database being built up far more quickly. Additionally, having fewer and simpler things to measure makes it more feasible to engage the public in gathering small amounts of sample data, e.g., from simple and low-cost sensors. These larger datasets may make it possible to infer a great deal of useful information. The rise of smart homes and smart technology will likely make data collection via this route more straightforward.

Interventions to reduce pollutants or purify indoor air

Developing technologies to help reduce or control pollutants within an indoor environment would be a great advantage, particularly in cases where other solutions, such as improving ventilation are impossible, impractical, or not optimal.

When aiming to improve air quality in the indoor environment by removing pollutants, it is important to consider how this is accomplished, as there is typically no single technology capable of removing all indoor air pollutants, especially cost-effectively, and there could be unintended consequences.[95] Workshop participants highlighted the following examples:

- Some air cleaning devices work best for short periods and/or on limited classes of pollutants. For instance, by utilising readily available and inexpensive activated carbon filters.
- PM can be removed by filtration, for instance by using good quality high efficiency particulate air (HEPA) filters.
- VOCs are probably best sequestered via a sorbent trap.
- Technologies that utilise catalytic or UV or electrically ionising cleaning or sterilisation methods. However, caution must be taken with these to guard against unintended consequences.[96] For instance, devices that use ultraviolet light, which is effective at killing some pathogens, are also known to contribute to increases in pollutants such as O_3 and NO_x, which can potentially affect those with underlying health conditions such as asthma.[8, 30, 97, 98]

Unintended consequences of some photocatalytic paints

Some photocatalytic paints designed to improve air quality within indoor environments removed the targeted pollutant, but released other pollutants, such as formaldehyde and other VOCs, as a by-product.[99] Subsequent studies have shown that other pollutants, such as nitric acids and O_3, are also potential by-products of some of these types of paint.[100, 101]

Collaboration between disciplines and sectors

Workshop participants noted that indoor air quality research is a highly multidisciplinary topic, including physical sciences, engineering, social sciences, medical and life sciences. However, there are currently limited links between the disciplines involved in indoor air quality research. For example, researchers looking at a building's physics and airflow might engage physicists and engineers, but might not engage with chemists, social scientists, and health experts, and vice versa.

Several participants emphasised the opportunity for wider collaboration. For example, breaking down barriers between the various scientific and engineering disciplines, and between key groups operating in the indoor air quality space, such as policy makers, regulators, and the public.

Data sharing between three UKRI funded studies:

'INGENIOUS' (University of York), 'WellHome' (Imperial College London) and 'HIPTOX' (University of Manchester) are working to unify their house surveys and experimental methods so that they can compare their findings.[102] This will allow each study to build up significantly more data than it could alone, allowing them to better assess the key sources of air pollutants, the variability between homes, and how indoor air pollutants can affect the health of the people inhabiting them.

Communication with policy makers and the public

Some workshop participants felt that the impacts of indoor air pollution are sometimes underplayed in the UK, leading to a perception that people are more at risk from pollution outdoors.

Scientists need to engage with policy makers and the public to articulate where research is needed to underpin new policies and to inform messaging about how to manage and mitigate risks.

This could build on the Air Quality Information System Review initiated by Defra[103] and involve a wide range of stakeholders, including medical experts, scientific bodies, residents, landlords, building contractors, regulators, local and national authorities, and the wider public.

While some factors impacting indoor air quality will require government regulation or intervention, individuals can also take steps to protect themselves. It will be important to provide clear advice about how everyday activities carried out indoors, such as cooking, cleaning, DIY, and smoking, can impact indoor air quality depending on the methods, equipment or products used.

Given the complexity of indoor air quality, guidance will need to be tailored for different audiences and settings and kept simple enough for people to act on. It could build on some of the public health messaging from COVID-19, e.g., highlighting that good ventilation is important for protection from other biological and chemical airborne pollutants.

Messages relevant to the context

NICE (National Institute for Health and Care Excellence)[104, 105] has proposed structural and behavioural guidelines for indoor air quality in homes, and separate guidelines for local authorities, healthcare professionals and the building industry.

Engaging the public in research on indoor air quality.

A previous study in England on the effect of indoor air quality on childhood health was conducted by interviewers creating positive relationships with the inhabitants of homes and continuously conducting surveys. This approach led to 174 homes giving permission to be monitored for an entire year. [64, 106]

References

1. Household air pollution, https://www.who.int/news-room/fact-sheets/detail/household-air-pollution-and-health, (accessed 3rd July, 2023).
2. R. M. Harrison and R. E. Hester, in *Indoor Air Pollution*, eds. R. M. Harrison and R. E. Hester, The Royal Society of Chemistry, 2019, DOI: 10.1039/9781788016179-fp007.
3. Introduction to Indoor Air Quality, https://www.epa.gov/indoor-air-quality-iaq/introduction-indoor-air-quality, (accessed 3 August, 2023).
4. B. L. Diffey, *British Journal of Dermatology*, 2011, **164**, 848-854.
5. H. K. Lai, M. Kendall, H. Ferrier, I. Lindup, S. Alm, O. Hänninen, M. Jantunen, P. Mathys, R. Colvile, M. R. Ashmore, P. Cullinan and M. J. Nieuwenhuijsen, *Atmospheric Environment*, 2004, **38**, 6399-6410.
6. N. Carslaw, in *Indoor Air Pollution*, The Royal Society of Chemistry, 2019, DOI: 10.1039/9781788016179-00105, pp. 105-126.
7. C. Whitty, K. Exley, S. Dimitroulopoulou, A. Gowers, T. Waite, A. Hansell, A. Mouatt, M. Ghalaieny, E. Martell, A. C. Lewis, S. Moller, A. Fraser, S. Sapsford, R. M. Harrison, B. Marner, S. Anderson, H. Cheng, H. Richardson, G. Erlendsson, B. Parry, D. Green, R. Martinez-Botas, N. Cumpsty, S. Rajoo, A. Walker, J. Relph, R. Deacon, C. Jones, J. Averley, E. Roaf, H. Larrington-Spencer, A. Clegg, T. Williamson, A. Giles, J. Robinson, B. Parish, B. Pearce, K. Langford, D. Fowler, M. Sutton, A. McGushin, O. Landeg, R. Simpson, Z. Preston, E. Blakey, A. Molloy, B. Akinwale, M. Hill, B. Owolabi, N. Watts, M. Thomson, C. Noakes, T. Sharpe, H. Freeman, M. Cook, A. Hathaway, H. Burridge, M. van Reeuwijk, D. Jenkins, G. Fuller, C. Pfrang, P. Agnew, Y. Clewlow, M. Hort, F. J. Kelly, J. C. Fussell, C. Baggot, C. Humphries, M. Orhewere, H. Sultan, J. Varney, R. McEachan, S. Jones, S. Muckle, J. Wright, K. Fenton, V. Hobart, K. Hunter, T. Ferguson, C. Culshaw, H. Birch, A. Hughes-Johnson, G. Campbell, K. O'Malley, S. Loader, N. Robinson, J. Parkinson, C. Hall, S. Brace, J. Newington, P. Coleman and I. Pantelidu, Chief Medical Officer's Report 2022, 2022.
8. A. C. Lewis, J. Allan, D. Carslaw, D. Carruthers, G. Fuller, R. M. Harrison, M. Heal, E. Nemitz, C. E. Reeves, N. Carslaw, A. Dengel, S. Dimitroulopoulou, R. Gupta, M. Fisher, D. Fowler, M. Loh, S. Moller, R. Maggs, T. Murrells, P. Quincey and P. Willis, *Indoor Air Quality*, DEFRA, 2022.
9. M. B. Áine Broderick, Sean Armstrong, Jerome Sheahan, Ann Marie Coggins, *Building and Environment*, 2017, **122**, 126-133.
10. Air pollution: applying All Our Health, https://www.gov.uk/government/publications/air-pollution-applying-all-our-health/air-pollution-applying-all-our-health, (accessed 30 August, 2023).
11. Public Health England publishes air pollution evidence review, https://www.gov.uk/government/news/public-health-england-publishes-air-pollution-evidence-review, (accessed 30 August, 2023).
12. R. L. Maynard, in *Indoor Air Pollution*, The Royal Society of Chemistry, 2019, DOI: 10.1039/9781788016179-00196, pp. 196-218.
13. F. J. Kelly, R. L. Maynard, J. Grigg, G. Shaddick, R. Carare, N. Fox, S. Love, I. Mudway, J. M. Delgado-Saborit, V. Guercio and A. Gowers, *Cognitive decline, dementia and air pollution*, COMEAP, UK Health Security Agency, https://www.gov.uk/government/publications/air-pollution-cognitive-decline-and-dementia, 2022.
14. A. Sommerlad and K. Y. Liu, *BMJ*, 2023, **381**, p655.
15. C. H. Halios, C. Landeg-Cox, S. D. Lowther, A. Middleton, T. Marczylo and S. Dimitroulopoulou, *Sci Total Environ*, 2022, **839**, 156201.
16. P. G. Tratnyek, E. Edwards, L. Carpenter and S. Blossom, *Environmental Science: Processes & Impacts*, 2020, **22**, 465-471.
17. *WHO Guidelines for Indoor Air Quality: Selected Pollutants*, World Health Organization, Geneva, 2010.
18. G. U. Brauer M, Brunekreef B, de Jongste J, Gerritsen J, Rovers M, Wichmann HE, Wijga A, Heinrich J., *Environ Health Perspect.*, 2006, **114**, 1414-1418.

19. J. M. Kelso, *Pediatrics*, 2009, **124**, S116.

20. H. G. Brauer M, Smit HA, de Jongste JC, Gerritsen J, Postma DS, Kerkhof M, Brunekreef B. , *Eur Respir J.*, 2007, **29**, 879-888.

21. A. Baccarelli, A. Zanobetti, I. Martinelli, P. Grillo, l. Hou, A. Giacomini, M. Bonzini, G. Lanzani, P. M. Mannucci, P. A. Bertazzi and J. Schwartz, *Journal of Thrombosis and Haemostasis*, 2007, **5**, 252-260.

22. S. Gaihre, S. Semple, J. Miller, S. Fielding and S. Turner, *Journal of School Health*, 2014, **84**, 569-574.

23. J. G. Allen, P. MacNaughton, U. Satish, S. Santanam, J. Vallarino and J. D. Spengler, *Environmental Health Perspectives*, 2016, **124**, 805-812.

24. P. Monks, H. ApSimon, D. Carruthers, D. Carslaw, D. Derwent, R. M. Harrison, D. Laxen, J. Stedman, R. Maggs, T. Murrells, P. Quincey, P. Willis, R. Hunter, B. McCauley, A. Taylor, A. Gowers, C. Bayley and T. Williamson, *Fine Particulate Matter (PM2.5) in the United Kingdom*, 2012.

25. J. G. Ayres, H. R. Anderson, B. Armstrong, R. G. Derwent, K. Donaldson, R. M. Harrison, S. Holgate, T. King, D. Laxen, P. Poole-Wilson, V. Stone, D. Strachan, D. Walters, R. L. Maynard, H. Walton, J. Cumberlidge, I. Mills, I. Myers, J. F. Hurley, R. Atkinson, P. G. Burney, J. Stedman and M. L. Williams, *Long term exposure to air pollution: effect on mortality*, 2009.

26. K. Straif, T. Fletcher, A. Cohen, D. S. Greenbaum, J. Samet, U. Heinrich, E. Dybing, K. Husgafvel-Pursiainen, K. Katsouyanni, K. R. Smith, D. Krewski, B. Turpin, J. Mauderly, J. J. Vandenberg, I. Romieu, P. Vineis, A. Russell, K. Ziegler-Skylakakis, R. A. Baam, P. Boffetta, P. Brennan, V. J. Cogliano, F. El Ghissassi, B. Secretan, A. Ullrich, C. Demetriou, M. Dherani, P. Nafstad, H. Adair-Rohani, T. M. Penning, N. Bruce, D. Pope, I. Choudhury, A. Schilmann, P. E. Schwarze and K. Victorin, *Air Pollution and Cancer*, International Agency for Research on Cancer, World Health Organisation, 2013.

27. J. Chen and G. Hoek, *Environment International*, 2020, **143**, 105974.

28. M. Pilling, H. ApSimon, D. Carruthers, D. Carslaw, R. Colvile, R. Derwent, S. Dorling, B. Fisher, R. M. Harrison, M. Heal, D. Laxen, S. Lindley, I. McCrae, J. Stedman, M. Ashmore, M. E. Jenkin, P. Woods, S. Moorcroft, T. Murrells, P. Quincey and K. Stevenson, *Particulate Matter in the United Kingdom: Summary*, Air Quality Expert Group (AQEG), 2005.

29. Particulate Matter (PM) Basics, https://www.epa.gov/pm-pollution/particulate-matter-pm-basics#PM, (accessed 3 August, 2023).

30. Health Effects of Ozone in Patients with Asthma and Other Chronic Respiratory Disease, https://www.epa.gov/ozone-pollution-and-your-patients-health/health-effects-ozone-patients-asthma-and-other-chronic, (accessed 28 June, 2023).

31. L. Ferguson, J. Taylor, M. Davies, C. Shrubsole, P. Symonds and S. Dimitroulopoulou, *Environment International*, 2020, **143**, 105748.

32. *WHO guidelines for indoor air quality: dampness and mould*, World Health Organization, 2009.

33. S. Walker, How inequality leads to poor asthma outcomes, https://www.openaccessgovernment.org/inequality-poor-asthma-outcomes/55407/, (accessed 28th June, 2023).

34. A. C. Lewis, D. Jenkins and C. J. M. Whitty, *Nature*, 2023, **614**, 220-223.

35. L. Ferguson, J. Taylor, K. Zhou, C. Shrubsole, P. Symonds, M. Davies and S. Dimitroulopoulou, *Buildings and Cities*, 2021, DOI: 10.5334/bc.100.

36. C. Shrubsole, S. Dimitroulopoulou, K. Foxall, B. Gadeberg and A. Doutsi, *Building and Environment*, 2019, **165**, 106382.

37. S. Dimitroulopoulou, C. Shrubsole, K. Foxall, B. Gadeberg and A. Doutsi, *Air quality: UK guidelines for volatile organic compounds in indoor spaces*, 2019.

38. *The Building Regulations*, Ministry of Housing, Communities and Local Government, 2021.

39. Control of Substances Hazardous to Health (COSHH), https://www.hse.gov.uk/coshh/, (accessed 17 July, 2023).

40. *EH40/2005 Workplace exposure limits*, Health and Safety Executive, 2020.

41. G. Settimo, M. Manigrasso and P. Avino, *Atmosphere*, 2020, **11**, 370.

42. German Committee on Indoor Air Guide Values, https://www.umweltbundesamt.de/en/topics/health/commissions-working-groups/german-committee-on-indoor-air-guide-values#indoor-air-guide-values, (accessed 31st March, 2023).

43. Labelling of building and decoration products with respect to VOC emissions, https://www.anses.fr/en/content/labelling-building-and-decoration-products-respect-voc-emissions, (accessed 30 August, 2023).

44. Legal Requirements on VOC emissions, https://www.eurofins.com/consumer-product-testing/services/certifications-international-approvals/voc/legal-requirements/, (accessed 30 August, 2023).

45. *Hygienic guide values from the German Committee on Indoor Air Guide Values*, German Environment Agency, 2022.

46. UKRI, https://www.ukcleanair.org/, (accessed 18 July, 2023).

47. Clean Air, https://www.ukri.org/what-we-do/our-main-funds-and-areas-of-support/browse-our-areas-of-investment-and-support/clean-air/, (accessed 30 August, 2023).

48. GDPR guidance for researchers and study coordinators, https://www.hra.nhs.uk/planning-and-improving-research/policies-standards-legislation/data-protection-and-information-governance/gdpr-guidance/, (accessed 30 August, 2023).

49. Using data about people in research, https://www.ukri.org/councils/mrc/facilities-and-resources/find-an-mrc-facility-or-resource/mrc-regulatory-support-centre/using-data-about-people-in-research/, (accessed 30 August, 2023).

50. F. X. Mueller, L. Loeb and W. H. Mapes, *Environmental Science & Technology*, 1973, **7**, 342-346.

51. E. D. Lebel, C. J. Finnegan, Z. Ouyang and R. B. Jackson, *Environmental Science & Technology*, 2022, **56**, 2529-2539.

52. D. Fowler, O. Wild, A. C. Lewis, D. Carslaw, W. Bloss, S. Beevers, W. Collins, A. Flore, R. M. Harrison, D. Joffee, C. Le Quéré, J. Pyle, D. Reay, C. E. Reeves, I. Boyd, G. Brasseur, K. Shine, P. Coleman, A. Gowers, H. Macintyre, J. Newington, H. Margue, L. Marloni, E. Surkovic, G. Park, T. Andrew, N. Hewitt, B. Hoskins, S. Turnock and D. Vigar, *Effects of net zero policies and climate change on air quality*, The Royal Society, https://royalsociety.org/topics-policy/projects/air-quality-climate-change/, 2021.

53. A. J. Curtis, D. Helmig, C. Baroch, R. Daly and S. Davis, *Atmospheric Environment*, 2014, **95**, 634-643.

54. P. Monks, J. Allan, D. Carruthers, D. Carslaw, C. Dore, G. Fuller, R. M. Harrison, M. Heal, A. C. Lewis, A. Tomlin, M. Williams, D. Fowler, B. Marner, R. Maggs, T. Murrells, P. Quincey, P. Willis, S. Baldwin, B. McCauley, A. Taylor, A. Gowers, S. Moller and A. Stroud, *Impacts of Vegetation on Urban Air Pollution*, Air Quality Expert Group, DEFRA, 2018.

55. V. R. J. H. Timmers and P. A. J. Achten, *Atmospheric Environment*, 2016, **134**, 10-17.

56. C. M. Wang, B. Barratt, N. Carslaw, A. Doutsi, R. E. Dunmore, M. W. Ward and A. C. Lewis, *Environmental Science: Processes & Impacts*, 2017, **19**, 528-537.

57. Y. S. Kashtan, M. Nicholson, C. Finnegan, Z. Ouyang, E. D. Lebel, D. R. Michanowicz, S. B. C. Shonkoff and R. B. Jackson, *Environmental Science & Technology*, 2023, **57**, 9653-9663.

58. E. D. Vicente, A. M. Vicente, M. Evtyugina, A. I. Calvo, F. Oduber, C. Blanco Alegre, A. Castro, R. Fraile, T. Nunes, F. Lucarelli, G. Calzolai, S. Nava and C. A. Alves, *Building and Environment*, 2020, **180**, 107059.

59. I. Rivas, J. C. Fussell, F. J. Kelly and X. Querol, in *Indoor Air Pollution*, The Royal Society of Chemistry, 2019, DOI: 10.1039/9781788016179-00001, pp. 1-34.

60. National Atmospheric Emissions Inventory, https://naei.beis.gov.uk/, (accessed 20 July, 2023).

61. Indoor Air Quality Guidelines (IAQGs): Presentation and work by ANSES, https://www.anses.fr/en/content/indoor-air-quality-guidelines-iaqgs, (accessed 20 July, 2023).

62. Guideline for the assessment of indoor air quality, https://www.bmk.gv.at/themen/klima_umwelt/luft/innenraum/rl_luftqualitaet.html, (accessed 30 August, 2023).

63. D. K. Farmer, M. E. Vance, J. P. D. Abbatt, A. Abeleira, M. R. Alves, C. Arata, E. Boedicker, S. Bourne, F. Cardoso-Saldaña, R. Corsi, P. F. DeCarlo, A. H. Goldstein, V. H. Grassian, L. Hildebrandt Ruiz, J. L. Jimenez, T. F. Kahan, E. F. Katz, J. M. Mattila, W. W. Nazaroff, A. Novoselac, R. E. O'Brien, V. W. Or, S. Patel, S. Sankhyan, P. S. Stevens, Y. Tian, M. Wade, C. Wang, S. Zhou and Y. Zhou, *Environmental Science: Processes & Impacts*, 2019, **21**, 1280-1300.

64. D. Crump, S. Dimitroulopoulou, R. Squire, D. Ross, B. Pierce, M. White, V. Brown and S. Coward, *Pollution Atmospherique*, 2005, 71-76.

65. S. Coward, J. Llewellyn, G. Raw, V. Brown, D. Crump and D. Ross, *Indoor air quality in homes in England*., Building Research Establishment, 2001.

66. S. Coward, V. Brown, D. Crump, G. Raw and J. Llewellyn, *Indoor air quality in homes in England: Volatile organic compounds*., Building Research Establishment, 2002.

67. ANSES changes its method of developing indoor air guideline values (IAGVs), https://www.anses.fr/en/content/anses-changes-its-method-developing-indoor-air-guideline-values-iagvs, (accessed 30 August, 2023).

68. OQAI and indoor air quality website, https://www.oqai.fr/fr, (accessed 30 August, 2023).

69. C. J. Weschler and N. Carslaw, *Environmental Science & Technology*, 2018, **52**, 2419-2428.

70. H. Wang and G. Morrison, *Indoor Air*, 2010, **20**, 224-234.

71. C. J. Weschler and W. W. Nazaroff, *Environmental Science: Atmospheres*, 2023, **3**, 640-661.

72. A. P. Ault, V. H. Grassian, N. Carslaw, D. B. Collins, H. Destaillats, D. J. Donaldson, D. K. Farmer, J. L. Jimenez, V. F. McNeill, G. C. Morrison, R. E. O'Brien, M. Shiraiwa, M. E. Vance, J. R. Wells and W. Xiong, *Chem*, 2020, **6**, 3203-3218.

73. S. Patel, S. Sankhyan, E. K. Boedicker, P. F. DeCarlo, D. K. Farmer, A. H. Goldstein, E. F. Katz, W. W. Nazaroff, Y. Tian, J. Vanhanen and M. E. Vance, *Environmental Science & Technology*, 2020, **54**, 7107-7116.

74. *Methods for monitoring indoor air quality in schools: report of a meeting, Bonn, Germany*, 4-5 April 2011, World Health Organization. Regional Office for Europe, 2011.

75. H. Edwards, A. Whitehouse and J. Grigg, *The Toxic School Run: UK Children at Daily Risk from Air Pollution*, https://www.unicef.org.uk/wp-content/uploads/2018/09/UUK-research-briefing-The-toxic-school-run-September-2018.pdf, 2018.

76. A. Lewis and P. Edwards, *Nature*, 2016, **535**, 29-31.

77. A. C. Rai, P. Kumar, F. Pilla, A. N. Skouloudis, S. Di Sabatino, C. Ratti, A. Yasar and D. Rickerby, *Science of The Total Environment*, 2017, **607-608**, 691-705.

78. N. Castell, F. R. Dauge, P. Schneider, M. Vogt, U. Lerner, B. Fishbain, D. Broday and A. Bartonova, *Environment International*, 2017, **99**, 293-302.

79. International Organisation for standardisation, 2019, **ISO 16000-1:2004**.

80. INGENIOUS Understanding Air Pollution in Homes, https://ingenious.york.ac.uk/home, (accessed 28 June, 2023).

81. WellHomeStudy, https://linktr.ee/WellHomeStudy, (accessed 28 June, 2023).

82. C. Chen, Y. Zhao and B. Zhao, *Environmental Science & Technology*, 2018, **52**, 1081-1087.

83. F. Klein, N. J. Farren, C. Bozzetti, K. R. Daellenbach, D. Kilic, N. K. Kumar, S. M. Pieber, J. G. Slowik, R. N. Tuthill, J. F. Hamilton, U. Baltensperger, A. S. H. Prévôt and I. El Haddad, *Scientific Reports*, 2016, **6**, 36623.

84. Z Xiang, H. Wang, S. Stevanovic, S. Jing, S. Lou, S. Tao, L. Li, J. Liu, M. Yu and L. Wang, *Building and Environment*, 2017, **125**, 348-355.

85. T. Liu, Q. Liu, Z. Li, L. Huo, M. Chan, X. Li, Z. Zhou and C. K. Chan, *Science of The Total Environment*, 2017, **599-600**, 1614-1621.

86. S. Yun, S. Zhong, H. S. Alavi, A. Alahi and D. Licina, *J Expo Sci Environ Epidemiol*, 2023, **33**, 396-406.

87. L. Chatzidiakou, D. Mumovic and A. Summerfield, *Building Services Engineering Research and Technology*, 2015, **36**, 129-161.

88. E. Chatzidiakou, PhD, University College London, 2014.

89. V. V. Tran, D. Park and Y. C. Lee, *Int J Environ Res Public Health*, 2020, **17**, 2927.

90. W. W. Nazaroff and C. J. Weschler, *Atmospheric Environment*, 2004, **38**, 2841-2865.

91. G. C. Morrison and W. W. Nazaroff, *Environ Sci Technol*, 2002, **36**, 2185-2192.

92. T. Salthammer, *Int J Hyg Environ Health*, 2020, **224**, 113423.

93. T. Vera, F. Villanueva, L. Wimmerová and E. I. Tolis, *Applied Spectroscopy Reviews*, 2022, **57**, 625-674.

94. Carbon dioxide, https://en.wikipedia.org/wiki/Carbon_dioxide.

95. J. González-Martín, N. J. R. Kraakman, C. Pérez, R. Lebrero and R. Muñoz, *Chemosphere*, 2021, **262**, 128376.

96. N. Carslaw, To clean, or not to clean? That is the question., https://www.ukcleanair.org/2022/05/10/to-clean-or-not-to-clean-that-is-the-question/, (accessed 28 June, 2023).

97. *RESIDENTIAL AIR CLEANERS A Technical Summary*, Environmental Protection Agency, 2018.

98. H. Claus, *Photochemistry and Photobiology*, 2021, **97**, 471-476.

99. A. Gandolfo, S. Marque, B. Temime-Roussel, R. Gemayel, H. Wortham, D. Truffier-Boutry, V. Bartolomei and S. Gligorovski, *Environmental Science & Technology*, 2018, **52**, 11328-11337.

100. A. Gandolfo, V. Bartolomei, D. Truffier-Boutry, B. Temime-Roussel, G. Brochard, V. Bergé, H. Wortham and S. Gligorovski, *Physical Chemistry Chemical Physics*, 2020, **22**, 589-598.

101. J. Auvinen and L. Wirtanen, *Atmospheric Environment*, 2008, **42**, 4101-4112.

102. Exploring how air pollution in indoor spaces affects human health, https://www.ukri.org/news/exploring-how-air-pollution-in-indoor-spaces-affects-human-health/, (accessed 23 June, 2023).

103. Air Quality Information System Review, https://uk-air.defra.gov.uk/research/aq-system-review, (accessed 30 August, 2023).

104. *Indoor air qualtiy at home*, NICE, 2020.

105. *Improving Indoor Air Quality*, NICE, 2020.

106. R. Berry, V. Brown, S. Coward, D. Crump, M. Gavin, C. Grimes, D. Higham, A. Hull, C. Hunter, I. Jeffrey, R. Lea, J. Llewellyn and G. Raw, *Indoor Air Quality in Homes*, Building Research Estabilishment, 1996.

Acknowledgements

This workshop summary has been written by RSC staff and represents the views of a group of experts brought together by the RSC's Environment, Sustainability and Energy Community (ESEC), Analytical Science Community (ASC), and the Faraday Community for Physical Chemistry (FCPC) on 9 November 2022. It does not necessarily reflect the views of individual participants, their institutions, or groups. We are grateful to the following people who attended the workshop and contributed their views:

- Prof. Dwayne Heard (University of Leeds, President of the FCPC, 2021-2024)
- Dr Stephen Mudge (President of ESEC, 2020-2023)
- Dr Diane Turner (Anthias Consulting Ltd., President of the ASC, 2020-2023)
- Prof. Sani Dimitroulopoulou (UK Health Security Agency)
- Dr Vicky Hilborne (University College London)
- Prof. Christian Pfrang (University of Birmingham)
- Dr Silvia Alcove Clave (Johnson Matthey)
- Dr Leon Barron (Imperial College London)
- Dr Sean Beevers (Imperial College London)
- Dr Heather Birch (NERC)
- Mr Shaun Brace (Defra)
- Prof. Nicola Carslaw (University of York)
- Dr Lia Chatzidiakou (University of Cambridge)
- Dr Roger Coulston (Aqdot)
- Dr Derrick Crump (Indoor Air Quality Consulting)
- Prof. Anna Hansell (University of Leicester)
- Prof. Gordon McFiggans (University of Manchester)
- Dr Sanja Potgieter-Vermaak (Manchester Metropolitan University)
- Mr Chetas Rana, Building Research Establishment
- Miss Suzie Wallace (EPSRC)
- Dr Stephanie Wright (Imperial College London)

The report draws on desk research and the expert workshop.

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Communications support was provided by: Ms Elisabeth Ratcliffe (Communications Campaign Manager) and Siobhan Godwood (Creative Campaign Manager).

The RSC is grateful to Sarah O'Reilly (Sarah O'Reilly Speeches) and Chris Gooch (Open Design Agency) for copywriting and design support.

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