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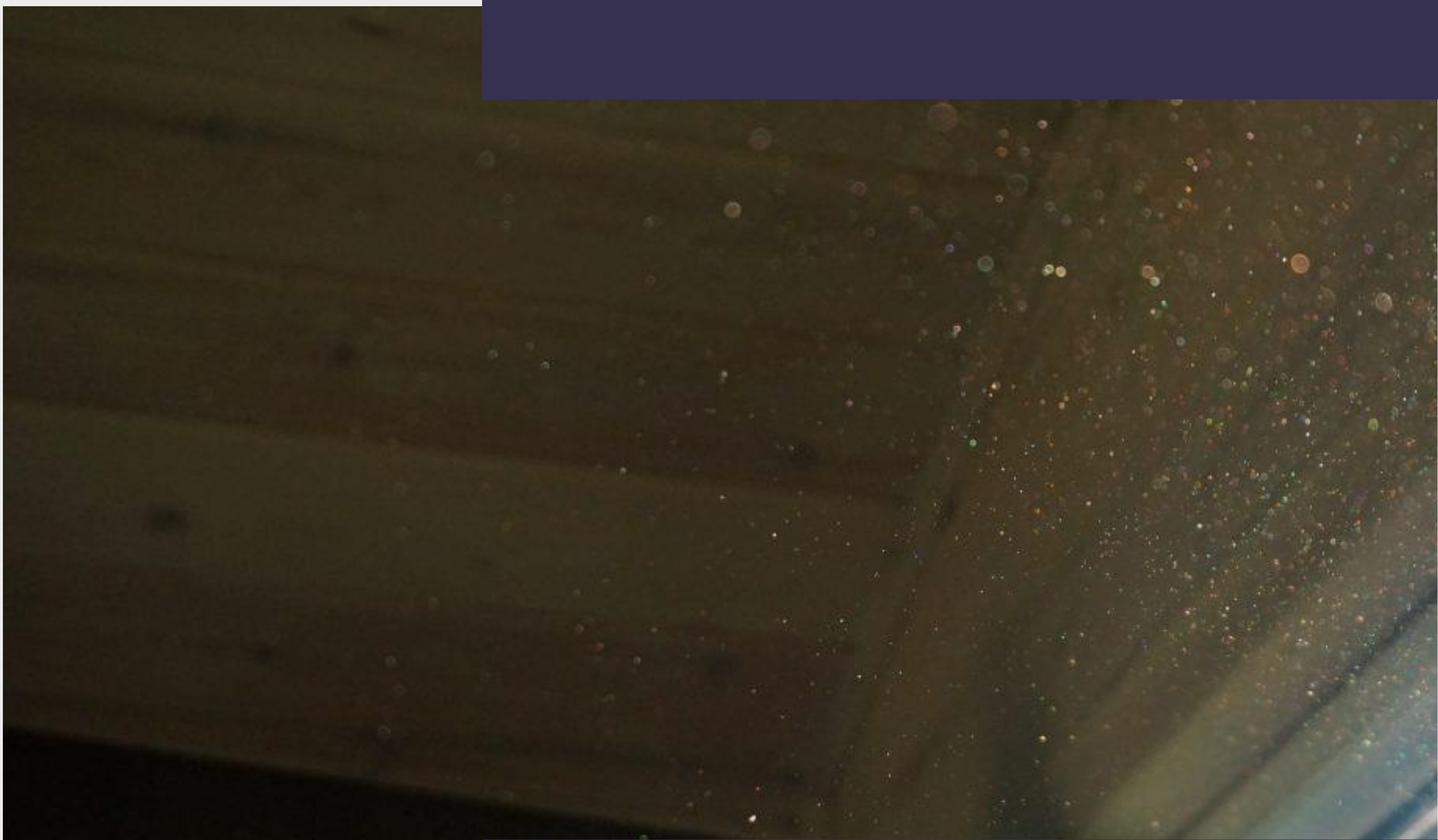
Indoor Air Quality



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Overview

People spend 80-90% of their time indoors (homes, schools, workplaces, other public spaces and on transport). The effects of poor indoor air quality on health are less well understood than those due to poor outdoor air quality.

The indoor environment is more complex and variable than outdoors. Sources and concentrations of pollutants can vary greatly between and within buildings. Several UK research projects are underway to address a range of knowledge gaps.

Indoor pollutant sources include building materials, cooking and heating appliances, consumer products, occupant activities, damp and mould, and the land on which buildings are sited. Concentrations of certain pollutants are higher indoors and can be exacerbated by poor ventilation. Indoor pollutant concentrations are also affected by the infiltration of air from outdoors.

There is strong evidence for associations between certain individual pollutants and overall poor air quality, with an increased risk of respiratory and cardiovascular illness, cognitive impairment and certain cancers.

There are inequalities in risk for some groups in the population. Vulnerable groups include those who are young, elderly or pregnant or those who have respiratory disease; other demographic characteristics associated with an increased health risk from poor air quality include socio-economic status and ethnicity.

Indoor air pollution can be tackled in several ways including removing pollutant sources, improving ventilation, air cleaning, increasing public awareness and legislative changes. There is a trade-off between improving ventilation and reducing the energy consumption of buildings.

The Government has established a cross-department working group and pledged to tackle aspects of indoor air quality in its 2019 Clean Air Strategy. The strategy included several commitments to reduce emissions in the home such as prohibiting the sale of the most polluting fuels and stoves, improving consumer awareness, and giving new powers to local authorities to take action to minimise air pollution.

1 Background

Poor air quality has negative health impacts. In 2022, the Chief Medical Officer published a report on air pollution. The report noted that as measures to reduce outdoor air pollution evolve, indoor air pollution is becoming a bigger proportion of the air quality problem and that action is needed to protect people's health, including in indoor public spaces over which they have no control.[1]

People spend around 80-90% of their time indoors, such as in the home, schools, workplaces, public places and when using public transport (enclosed buildings such as some train stations). The nature of indoor air pollution and health risks that arise from it are less well understood compared to poor outdoor air quality.[2]

The indoor air environment is more complex and variable compared to outdoors. The sources and concentrations of pollutants can vary greatly between buildings as well as between rooms within the same building.

Indoor air quality is affected by infiltrations of outdoor air, from internal sources of pollutants and indoor air chemical reactions through which primary pollutants are degraded and secondary pollutants are formed. In poorly ventilated buildings, indoor pollutants can often be concentrated.

Pollutants include a range of chemicals emitted from building materials, consumer products (such as furniture, paints and cleaning materials), combustion appliances (such as gas cookers and woodburning) and in some geographic areas, radon gas. Airborne particles of biological origin (bioaerosols) can be released into the environment (such as pollen, fungal spores, house dust mites and pet allergens), associated with buildings and their systems (such as mould), or produced by people (bacteria and viruses). People also produce carbon dioxide, which is itself not a pollutant but is used as an indicator of the level of ventilation.[1,3,4]

Air pollution and some individual pollutants are causally linked to several health conditions, including an increased risk of heart disease, stroke, respiratory illnesses, neurological illnesses and in some cases, cancer.[1]

People are mainly exposed to pollutants via inhalation, but they can also be ingested or absorbed through the skin.[5]

For some groups, the health risks from exposure to poor indoor air quality are greater. They include people with underlying health conditions, the young and elderly and pregnant women. Other characteristics may also be associated with an increased health risk from pollution. Examples include lower socio-economic status and ethnic background, due to overcrowded and poor quality housing, as well as housing location (next to busy roads).[1,3,5]

Interventions to tackle indoor air pollution and improve air quality include:

- controlling (moderation of use or removing) the sources of pollution (source control)
- using ventilation and other air cleaning technologies
- increasing public awareness
- behaviour change
- legislation.

It is relevant to note that while legislation has been put in place to improve outdoor air quality,[6] there are fewer legal controls on indoor air quality. Apart from workplace exposure limits for a small number of pollutants, there are typically no legally enforceable pollutant standards for indoor air quality. Legislation development is hampered by the limited evidence base, as most research relating air pollution to health impacts focuses on outdoor settings.[3]

The impact of air pollution has been highlighted in recent coroners' inquests.

Following a 2020 inquest, Ella Adoo-Kissi-Debrah, a nine-year-old girl, was the first person to have air pollution listed as an associated cause of death, due to a severe fatal asthma attack.[7] In November 2022, a coroner ruled that the death of a two-year-old boy, Awaab Ishak, was due to prolonged exposure to black mould in a rented flat.[8]

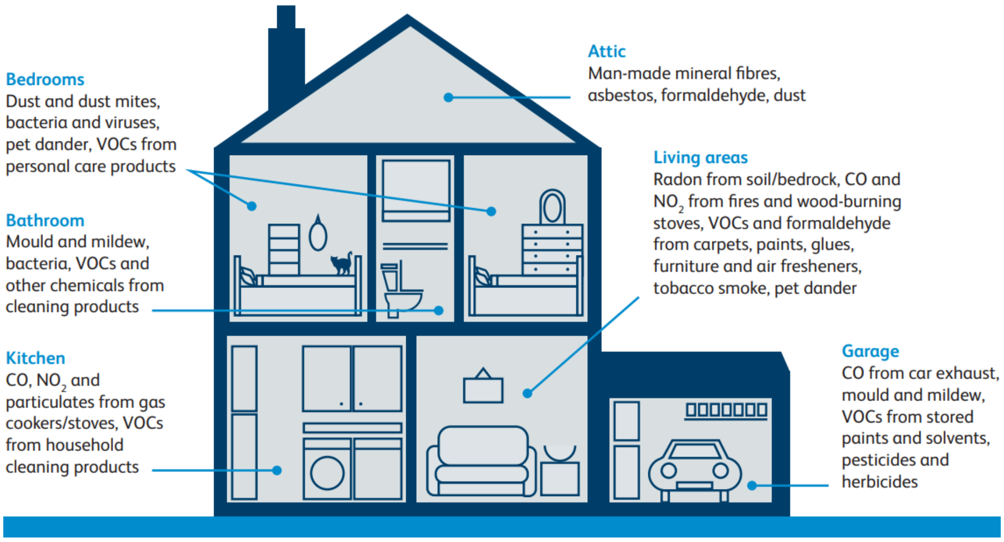
This briefing updates our previous report on indoor air quality from 2010 (PN 366[9]) and complements our 2023 report on urban outdoor air quality (PN 691[6]). Air quality targets (indoor and outdoor) are currently under inquiry by the House of Commons Environmental Audit Select Committee as part of their examination of the Government's approach to improving air quality. The Committee is expected to report later in 2023.[10]

2 Indoor air pollutants

Some air pollutants are common to both indoor and outdoor settings. However, their sources, composition and concentrations vary, with occupant behaviour and geographic location being important factors.[1,3] Particulate matter (PM), nitrogen dioxide (NO_2) and ozone (O_3) are also detailed in our POSTnote on urban outdoor air quality (PN 691[6]).

Indoor sources of air pollution can emit a wide range of pollutants. For example: combustion appliances can emit PM, NO_2, sulphur dioxide (SO_2), carbon monoxide (CO) and carbon dioxide (CO_2). A schematic of sources of indoor air pollutants in a typical domestic building is shown in Figure 1.

Figure 1. Sources of indoor pollution in a home.



Source: Royal College of Paediatrics and Child Health.[11] VOC: volatile organic compound, CO: carbon monoxide, NO_2: nitrogen dioxide.

2.1 Particulate matter (PM)

PM describes microscopic particles that originate from a range of human-made and natural sources. They are classified by size, named according to upper-limit diameter in micrometres, and comprise coarse particles (PM_{10}), fine particles ($PM_{2.5}$) and ultrafine particles ($PM_{0.1}$).[1,6] $PM_{0.1}$ makes up the majority of particles by number (typically >90%) but represents a relatively small proportion by mass.[12,13]

$PM_{2.5}$ and $PM_{0.1}$ pose a greater danger to health than PM_{10}, as they can penetrate deeper into the respiratory system and pass from the lungs into the blood and to other organs of the body.[14] Evidence also suggests that a small proportion of very small particles can cross the blood-brain barrier*. PM is linked to adverse long-term health impacts, such as an increased chance of developing some cancers and cognitive decline.[1,16]

Indoor PM is emitted from combustion (such as solid fuel burners, cookers, gas boilers and tobacco smoking) or formed through atmospheric chemical reactions between air pollutants (secondary PM).[17–22] PM from outdoor sources (such as industrial processes and road transport) can infiltrate indoors and contribute to poor indoor air quality.[3]

PM levels can vary with time within a building, typically resulting from the activities that produce them. One study suggested that, over a 12-hour period, $PM_{2.5}$ average concentrations were 14 $\mu g\, m^{-3}$, which increased while cooking up to peaks of 250 $\mu g\, m^{-3}$, and then slowly declined. Exposure during post-cooking decay was greater than that of the cooking period itself.[17] A UK-based study identified cooking as the primary source of $PM_{2.5}$ in English non-smoking households.[23]

Domestic burning (such as wood burning stoves) also emits PM, with large concentration spikes during refuelling,[24] and has been suggested to be the single largest source of outdoor primary $PM_{2.5}$ in the UK,[25] representing 27% of total $PM_{2.5}$ emissions in 2021.[26]

PM levels differ between non-residential indoor environments. Transport hubs (such as surface and underground train stations) can record very high PM levels.[27,28] Median $PM_{2.5}$ mass concentrations were found to be 28 $\mu g\, m^{-3}$ across London Underground lines compared to 14 $\mu g\, m^{-3}$ at ambient background locations,[29] with concentrations as high as 361 $\mu g\, m^{-3}$ on specific lines.[29] In 2022, an abundance of ultrafine metal-rich particles were identified on the London Underground which have the potential to pass from the lungs into the bloodstream.[30] PM concentrations inside vehicles can be high, for example, onboard trains.[31]

2.2 Volatile organic compounds (VOCs)

VOCs are chemicals that readily evaporate into the air at room temperature. They tend to be more concentrated indoors (consistently up to 10 times more than outdoors[32,33]), and 14% of all VOCs in outdoor (ambient) air are from indoor sources.[3,34] There are thousands of different VOCs present in indoor air, but not all are relevant to health at concentrations found in indoor environments.

A recent (2022) study identified 66 VOCs that are both relevant to health and are found frequently in European homes.[35] Some are better understood; for example formaldehyde is a well-known carcinogen (cancer-causing compound), and measures are currently taken to reduce worker exposure.[36]

** The blood-brain barrier is a protective lining that surrounds the brain. It prevents some substances, such as disease-causing organisms, from being transferred from the blood to brain tissue.[15]

However, most VOCs have not been assessed in terms of their indoor air quality impact on the general population.[37] Sources of VOCs indoors include building materials (such as paints, flooring, pressed wood products), plastics, dry-cleaned clothes, cleaning products, pesticides and fragrances (such as in candles, cosmetics, perfume and air fresheners).[33,38–45] Microbial VOCs (MVOCs) are produced from microorganisms found indoors (bacteria and fungi).[46] Some common VOCs in consumer products also act as precursor emissions that react to form secondary pollutants,[47] such as secondary organic aerosols (SOAs [a type of PM]) and secondary VOCs.[48,49]

A survey of 60 UK homes (over a 3-day period) found the most common VOC was *n*-butane, which is used as an aerosol propellent (in deodorants, cleaning products, fragrances and pesticides). Median concentrations of *n*-butane were 100 times greater than matched outdoor air samples.[3,50] In a study of European homes (including the UK), the most frequently measured pollutant at high concentrations was ethanol, followed by formaldehyde.[35]

VOCs can be trapped in household items (referred to as VOC sinks) such as carpets, and are subsequently released, resulting in chronic low-level exposure to VOCs.[51,52]

Health impacts associated with high concentrations of some VOCs include irritation of the eyes and respiratory tract, allergies (for example a study reported up to 28% of UK survey-respondents were chemically sensitive to fragrances[53]), asthma, damage to organs (liver, kidney and nervous system), as well as increased cancer risks.[1,35,45]

2.3 Bioaerosols

Bioaerosols are airborne particles of biological origin and can consist of whole organisms (such as bacteria, viruses and fungi) or material emitted from organisms (such as fungal spores, pollen, pet allergens and other proteins and metabolites).[54]

Sources of bioaerosols indoors include humans, pets, plants, mould, house dust mites, rodent or insect pests, building ventilation and water systems, and the ingress of outdoor air.[1,3]

Bioaerosols can have positive and negative health effects. Exposure to a diverse range of microbes is likely to be important during the early stages of childhood for the normal development of the immune system, and bioaerosols linked to livestock farming (especially cows) can be protective against developing allergies[55] and asthma.[56] Childhood allergy was described in POSTnote 467.[57]

Exposure to certain bioaerosols can lead to acute health effects, such as allergic rhinitis, coughing, triggering of asthma symptoms, skin conditions, chronic obstructive pulmonary disease (COPD) or the transmission of communicable disease, including respiratory infections (such as COVID-19, Legionnaires' disease and aspergillosis).[1,58–62] Bioaerosols can also lead to allergic sensitisation and an increased susceptibility to other indoor pollutants.[63]

Research has examined the impact on people of mould and damp issues in the home.[64] In addition to the physical health issues, mould can also impact occupants' wellbeing (due to property damage or inability to control the problem), which can lead to mental health impacts such as stress, anxiety and depression.[65–68]

2.4 Persistent organic pollutants (POPs)

POPs are a large group of different chemicals (including per- and polyfluoroalkyl substances (PFAS), polybrominated diphenyl ethers (PBDEs), phthalates, pesticides and fungicides), described as 'forever chemicals' due to their ability to resist degradation.[69–72] Persistent pollutants are detailed in POSTnote 579.[73]

POPs are commonly found indoors in fire-retardants, building materials, insulation materials, fungicidal products used to treat mould, carpets, cookware and repellents (such as water-resistant coatings on textiles), and can leach into the air.[74–76] Many POPs are described as endocrine disruptive compounds (that can disrupt hormone signalling), and have been linked to cancer, cardiovascular and reproductive health issues, due to their accumulation in the body.[77–80]

2.5 Ozone (O_3)

O_3 gas is formed in the air and is a powerful oxidising agent.[81,82] Ground level O_3 can be formed outdoors by photochemical reactions (driven by sunlight). Indoor O_3 can react with chemicals as well as components of the skin and hair to form secondary pollutants such as VOCs and SOAs.[83,84] O_3 is also generated from some air purifying and photocopying devices.[85,86] Short-term O_3 exposure is associated with respiratory illness.[1]

2.6 Nitrogen oxides (NO_x)

NO_x (nitric oxide (NO) together with NO_2) is formed indoors by combustion (typically gas cooking and gas heating)[3,81] NO_x concentrations are higher during the winter due to increased heating needs.[87] Ingress of outdoor air also contributes to indoor NO_x levels. NO_x has a short atmospheric lifespan of hours.[88] NO_2 has been associated with triggering and causing new asthma cases, wheezing, higher risk of heart attack and accelerated cognitive decline.[1,87,89] NO_2 has been described as the most harmful component of NO_x for human health.[6]

2.7 Carbon monoxide (CO)

CO is emitted as a product of the incomplete combustion of carbon-based fuels from cooking and heating appliances, especially gas boilers that are not correctly installed, maintained or ventilated, as well as tobacco smoking.[1,3,81,90] Exposure to CO causes cognitive impairment (low concentrations) and death (high concentrations).[91,92]

2.8 Carbon dioxide (CO_2)

Emissions of CO_2 are mainly from human and animal respiration, as well as combustion.[3] CO_2 concentration is used as a proxy for occupancy and to indicate ventilation indoors.[4] The Department for Education (DfE) has guidance on CO_2 levels in schools that can be used to indicate ventilation efficiency.[93]

A recent review concluded that at low CO_2 levels (<5,000 ppm), which are found in non-industrial environments, any reported health outcomes as a result of exposure to CO_2 may be due to the presence of human bio effluents and other indoor air pollutants related to inadequate ventilation.[4]

2.9 Sulphur dioxide (SO_2)

SO_2 is emitted primarily through the combustion of solid fuels (such as wood and coal), as well as tobacco smoke and gas appliances. In outdoor air it can react chemically to produce sulphates which remain in the air as secondary PM.[81,1] Outdoor SO_2 is considered the main source of indoor SO_2. Exposure can lead to irritation of the airways and exacerbation of asthma, and is associated with cardiovascular effects.[1]

2.10 Radon

Radon is a naturally occurring radioactive gas released from the decay of uranium within rocks and soil, through cracks and gaps.[94] Exposure can cause lung cancer; the risk increases with concentration and exposure period.[†] [95–97] Levels in outdoor air are low, but can be higher indoors. The areas of the UK that have higher levels of radon are well-documented,[98] and several effective measures can be used in buildings[99] in at-risk locations to reduce occupants' radon exposure to safe levels. The Government has established policies and guidance to limit the health impacts of radon, including regulations on buildings,[100] safety in workplaces,[101] conveyancing

[†] The risk of developing lung cancer due to radon exposure is highest in those people who smoke tobacco.

processes to identify risks[102] and general advice to the public.[94] However, there are an estimated 1,100 deaths from radon-related lung cancer every year.[94]

2.11 Environmental tobacco smoke (ETS) and vaping

Environmental tobacco smoke (ETS) has declined in public spaces (due to the 2007 ban[103]), but remains a source of indoor air pollution, particularly in the home. ETS consists of more than 5,000 chemical compounds (including CO, PM and VOCs), with at least 70 classified as carcinogens.[104,105] Smoking caused an estimated 125,000 deaths in the UK in 2019.[106,107] ETS can also accumulate in indoor environments (such as walls, flooring, furniture, clothes and dust), which recirculates and reacts to form secondary pollutants, leading to chronic exposure (termed third-hand smoke).[108–110]

E-cigarette or vape devices, originally designed for smoking cessation, have become increasingly common,[111] especially with young people[112,113] and those from lower socioeconomic backgrounds.[114] There is limited evidence regarding pollutants emitted during vaping, but studies have shown an increase in indoor $PM_{2.5}$ concentrations to over 150 µg/m^3.[115]

3 Health effects of poor indoor air quality

The health effects of ambient air pollution in general are well documented and were highlighted in the recent Chief Medical Officer's Report 2022[1] and a POSTnote on urban outdoor air quality (PN 691[6]).

Air pollution is causally associated as a risk factor for an increased risk of heart disease,[116] stroke,[117] some cancers,[118–120] dementia and cognitive decline,[15] impaired lung growth and some respiratory illnesses.[121,122] There is evidence of some negative health effects occurring even when pollutant levels are measured below the World Health Organisation (WHO) Global Air Quality Guidelines.[123,124]

However, people's typical exposure to the complex mixture of indoor air pollutants is less well characterised. Although there are pollutants common to indoor and outdoor settings, causal associations between indoor air quality and health effects are difficult to quantity for several reasons,[1,125] including:

- The differing composition of indoor air between buildings and rooms within the same building, due to different sources, ventilation rates, occupancy and occupant behaviour, weather and geographic location.[1,3]
- The wide range of exposures individuals are likely to experience due to spending time in multiple indoor environments, and thus experiencing different pollutant sources.
- The wide range of primary and secondary indoor pollutants, as well as infiltrations of outdoor air.[1,3]
- A lack of long-term indoor air quality monitoring and building ventilation data.[1,3]
- Variable concentrations of indoor air pollutants over time, for example there are large peaks of PM emitted during cooking or woodburning stove refuelling.[17,24] Acute and chronic exposure to indoor pollutants may lead to different health effects compared to outdoor air pollution.[1]

3.1 Health impacts of indoor air pollutants

The serious health risks from exposure to radon, tobacco smoke and asbestos are well established.[1] The impacts of other indoor pollutants are much less well understood and characterised for the reasons outlined above.[3,5] Research designed to identify strong trends has identified some links between pollutants and disease. Some studies may focus on a small number of indoor pollutants. Findings can be limited by a lack of data, small sample sizes, heterogeneity of emissions and exposures, data quality or confounding variables that may also contribute to a link.

Health effects identified in studies focused on high-income countries include:

- short term (acute) health effects associated with indoor pollutants:
  - **respiratory infection** – from mould[126] and from bacteria and viruses such as SARS-CoV-2.[1,60,127]
  - **respiratory infection symptoms -** from low level CO.[1]
  - **neurological symptoms and death –** from high level CO.[1]
  - **irritation of the upper airways –** from formaldehyde.[128]
- Long-term (chronic) health effects associated with indoor pollutants:
  - **asthma** – from some VOCs, [129] formaldehyde,[130] NO_2 and gas cooking,[131] mould[36] and bioaerosols.[132]
  - **allergic rhinitis** – from microbial aerosols[56] and mould.[133]
  - **coughing** – from mould.[134]
  - **wheezing** – from VOCs,[129] mould[134] and microbial aerosols.[56]
  - **cognitive impairment** – indicated by CO_2.[135]
  - **cancers** – lung and childhood leukaemia from radon,[136] mesothelioma from asbestos,[137] and multiple sites for ETS.[138]

Other studies have investigated indoor air quality health impacts, but these use data from developing countries (where many variables differ, including indoor activities, regulations, cooking and heating practices and climate), so findings may not be transferable to the UK population.[139–146]

3.2 Risk factors for health impacts from poor indoor air quality

Some people are more likely to be more vulnerable to the negative effects of indoor air pollution than others as a consequence of their health status as well as their exposure to poor quality air. Some of these risk factors overlap.

Sociodemographic characteristics like age, education, gender and where someone lives, are factors in determining people’s living conditions and their exposure to poor air quality. It has been estimated that other societal issues, coupled with events (notably the COVID-19 pandemic) can also have a considerable impact, possibly reinforcing or exacerbating patterns of inequality, exclusion and exposure to indoor air pollution.[147]

Vulnerability factors linked to health status include having a compromised immune system, pre-existing respiratory conditions (asthma, chronic obstructive pulmonary disease), and being young, elderly, or pregnant. Existing conditions make these identified groups more vulnerable even if their exposure to pollutants is the same as other groups.[1]

Settings:

- **Housing –** inequalities in exposure are linked to housing quality and its location (such as near busy roads). Indoor activities that generate pollutants such as cooking, smoking and drying clothes indoors, can increase with the number of occupants.[148] People in lower socio-economic groups may also live in more overcrowded housing and be less able to afford to live in higher quality housing with adequate ventilation. They also can be exposed to other building characteristics that affect overall indoor air quality, or have limited or no choice to change or to be able to access solutions to mitigate issues arising from air pollution, such as that caused by damp and mould.[148,149] Damp problems were found to be more common in private rented homes (11%) than owner-occupied homes (2%).[64]

- **Institutional settings** - those living or spending long periods in institutional settings – such as care homes, hospitals, prisons and schools – may also be at greater risk from indoor air pollution. This results from their biological vulnerabilities as well as the impact of the building location, age and quality. A 2022 report by the Department for Environment, Food and Rural Affairs (Defra) Air Quality Expert Group on indoor air quality,[3] noted the following:

    - **care homes** – specific concerns about ventilation, which can be limited by restricted window openings (to keep residents safe) and overheating.[150–152] This increases the risk of spread of infections transmitted by bioaerosols (such as COVID-19) and the build-up of indoor pollutants.

    - **nurseries and schools** – children spend up to 30% of their time at school, accounting for a large proportion of their exposure to indoor air pollutants. Ventilation may be limited to preserve heat, with research indicating that these settings can have high levels of CO, CO_2 $PM_{2.5}$, VOCs and other pollutants of indoor and outdoor origin. Those located in urban or high traffic areas have poorer indoor air quality.[153]

    - **hospitals** – overheating is a concern, with specialised ventilation measures needed to maximise optimal temperatures, whilst minimising the spread of airborne infections, odour, and managing risks associated with medical gases.

Some people are subject to risks related to their occupation and workplace. Workplace settings are diverse and vary according to sector. This includes working with substances such as asbestos, particulates or VOCs. Typical sectors affected include manufacturing and construction.[154] Employers must provide risk assessments to manage these risks.

Demographic characteristics

- **Children** are particularly vulnerable as a consequence of having less developed organ systems, particularly the lungs,[5] increased breathing rates and thus a greater intake of air and pollution into the lung. One modelling study reported that one-third of schools in England were located in areas with outdoor $PM_{2.5}$ levels exceeding the 2005 WHO Global Air Quality Guidelines.[155] These schools tended to be more ethnically diverse, and claimed more Free School Meals.[1] Major cities in the UK are exceeding the stricter WHO $PM_{2.5}$ limits set out in 2021, meaning most schools in these areas are subject to high pollutant levels.[156] A more recent study found that every London borough exceeds the latest WHO limits for a separate pollutant, NO_2.[157]

- **Pregnant women and babies** are affected by air pollution, with data showing that PM exposure is linked to increased risk of maternal cardiovascular effects in pregnancy,[158] low birthweight, and reduced lung function in childhood.[1,159]

There is an association between some other demographics and geographical factors and exposure. Most data examine the link to outdoor air quality, with limited research specific to indoor air.

- **Socio-economic status** – in general, those living in deprived areas are more likely to live in areas with high outdoor air pollution concentrations that infiltrates inside. One large review study found that households in more deprived areas had higher levels of indoor PM, NO_2, VOCs and environmental tobacco smoke.[148] Low income households classified as living in poverty were more likely to have damp issues in the home (7%) than those not in poverty (3.5%).[64] On the other hand, wood burning stoves are mostly associated with higher-income homes, although some may use them because of the rising costs of energy.[160] One academic expert stated that this could be expected to increase due to the recent cost of living crisis.[161]

- **Ethnicity** – the data exploring this link is complex, but one large 2015 study examined the exposure to air pollution in the most deprived 20% of neighbourhoods in England; the highest levels were seen in ethnically diverse neighbourhoods. A similar 2019 study in London also found that communities with higher levels of deprivation or a higher proportion of people from a non-white ethnic background, were more likely to live with poorer air quality.[1] Minority ethnic groups are also more likely to have damp problems in their home.[64]

3.3 Impact on the NHS and economy

Measuring indoor air quality is complex, and it is challenging to attribute cause (pollutants) to effects (a direct health impact), and to disentangle the negative impacts of poor air from other factors that lead to health inequalities. Some analyses have sought to estimate an overall population health impact of poor air quality in general, and to assess the economic consequences on the NHS and society more broadly. However, there is limited research that specifically examines indoor air or the impacts of specific indoor pollutants on health services and wider economy.

The Royal College of Physicians and Royal College of Paediatrics and Child Health estimated in a 2016 report that that 40,000 deaths are attributable to outdoor air pollution in the UK every year, placing a burden on NHS and social care services,[11] while deaths attributable to indoor air pollution are unknown. According to a report from the UK Health Security Agency (UKHSA, previously Public Health England), the total NHS and social care cost of air pollution ($PM_{2.5}$ and NO_2 only) is estimated to be £1.5-5.5 billion in England over the period between 2017 and 2025, increasing to £5.5 -18.6 billion up to 2035.[162] The total societal costs of air pollution are estimated at £22.6 billion per year.[163]

One study estimated that the indoor air pollutants most associated with loss of disability adjusted life years (DALYs[‡] – a metric used to estimate disease burden across a population[164]) were (in order of DALYs lost): PM_{10} and $PM_{2.5}$, followed by formaldehyde and NO_2, then radon, ozone and finally, SO_2.[165]

The first study applied in UK housing estimated that exposure to formaldehyde was associated with approximately 4,000 cases of childhood asthma (800 DALYs lost) in 2019, whereas exposure to damp and/or mould was associated with approximately 5,000 cases of asthma (~2,200 DALYs) and approximately 8,500 lower respiratory infections (~600 DALYs) among children and adults in 2019. Alternative data sources suggest that the percentage of dwellings affected by damp and/or mould may even be higher, resulting in a possible 3-8-fold greater number of cases.[36]

Poor indoor air quality and ventilation rates have been linked with more sick days in schools and workplaces, resulting in lower economic productivity and attainment in school due to absence.[166–170] The European Public Health Alliance (EPHA) estimates the total health related social costs (including loss of work and hospital admissions) due to heating and cooking in the UK to be £2.2 billion per year, of which 40% is from wood burning.[171] In addition, specific public health costs related to cooking with gas are estimated to be at least £1.4 billion per year.[172]

A 2022 report by the Royal Academy of Engineering’s National Engineering Policy Centre (NEPC) highlighted the importance of good ventilation as a measure to mitigate the impacts of disease mediated by airborne mechanisms and prevent potential high economic and societal costs of a future pandemic.[173] The COVID-19 pandemic highlighted the importance of good indoor air quality and ventilation to promote infection-resilient environments.[174,175] Ventilating indoor spaces is a key public health action to improve indoor air quality to reduce the risk of exposure to bioaerosols, such as the SARS-CoV-2 virus.[176,177]

‡ Disability Adjusted Life Years (DALY) is the sum of the years of life lost to due to premature death and the years lived with a disability. One DALY represents the loss of the equivalent of one year of full health.

4 Monitoring indoor air quality

High quality systematic outdoor air quality monitoring data has been recorded in the UK for decades,[34] but there is very limited data available regarding indoor air quality, which is rarely actively managed.[3] Active monitoring of an indoor space is usually only performed when:

- Complaints are made by building occupants and risks to health and wellbeing require assessment (such as via private indoor air quality consulting companies).[3]
- Building owners or developers are seeking credits for voluntary environmental assessment schemes, including BREEAM,[178] LEED,[179] WELL,[180] and Passivhaus,[181] which lead to building certifications.[3] However, these schemes can accrue significant additional costs to building projects.[182,183]
- Experimental monitoring as part of academic research studies, which are often limited in scope and short-term (discussed later).

The DfE provided CO_2 monitors to every state funded school and childcare provider in a recent scheme (as a proxy for ventilation).[184] Where good ventilation was not possible, HEPA air cleaning units were provided. However, no other pollutants were considered.

4.1 Monitoring technologies

Methods used to monitor and assess indoor pollutants are outlined in the Defra Air Quality Expert Group report on indoor air quality and the 2022 technical guidance TM68 published by The Chartered Institution of Building Services Engineers (CIBSE).[3,185] Pollutants are measured by different means, such as a filter-based approach for PM, electrochemical sensors for gases (CO, CO_2, NO_2 and O_3) and air sampling for VOCs.[3] A variety of methods are used to sample and characterise bioaerosols (traditionally by culture based methods but increasingly by novel high throughput molecular (DNA) based methods),[186] with most being labour intensive.

Measurement technologies have varying costs and capabilities.[187,188] Higher-cost sensors used to monitor pollutant concentrations are accurate but expensive. Lower-cost alternatives are more accessible to the public and for wide-scale monitoring studies, but typically have larger margins of error.[1,189] There are typically no standardised testing procedures, methodologies or regulations covering indoor pollutant sensors, other than for smoke and carbon monoxide alarms.[190] Sensors optimised and calibrated for outdoor use might not be suitable for indoor settings[3].

4.2 Recent and current UK research projects examining indoor air quality

Funding for indoor air quality research has historically been low, although this is increasing, with UK Research and Innovation (UKRI) recently awarding £9 million for indoor air projects,[191] which are part of its £42.5 million Clean Air Programme.[192] The Government also allocated £10.7 million for local authorities to improve air quality in 2023, although only a small number are indoor air projects.[193] For 2024, £6 million has been allocated for projects.[194]

Indoor air quality research and monitoring is often limited to small short-term research studies in specific environments. Projects in the UK include:

- **Schools air quality monitoring for health and education (SAMHE)**[195] – a research project between 5 UK universities and the UKHSA, and funded by the DfE and Engineering and Physical Sciences Research Council (EPSRC), which aims to monitor indoor air quality (CO_2, VOCs and PM) in up to 2,000 schools.

- **Tackling air pollution at school (TAPAS)**[196] – a UKRI funded network between UK universities and the charity Global Action Plan, aiming to recommend how best to monitor indoor air pollutants in schools, assess potential interventions and take an integrated approach with city planning.

- **Identifying determinants for indoor air quality and their health impact in environments for children (InChildHealth)**[197] – a UKRI funded project which will investigate and link indoor air quality (chemical and particle concentrations, as well as bioaerosols) with health impacts and interventions in schools across 7 countries.

- **Understanding the sources, transformations and fates of indoor air pollutants (INGENIOUS)**[198] – a UKRI funded project between 4 UK universities and the Born In Bradford (BiB) study, which aims to monitor indoor air quality linked to health impacts in 300 Bradford homes, as well as understand how indoor air chemistry and occupant behaviour impact indoor air.

- **West London healthy home and environment study (WellHome)**[199] – a UKRI funded project between 3 UK universities, which will monitor air quality in 100 West London homes of children with asthma and explore the link between pollutants and symptoms.

- **Impacts of cooking and cleaning on indoor air quality: towards healthy buildings for the future (IMPeCCABLE)**[200] – an EPSRC funded project between 3 UK universities looking at the impact of cooking and cleaning activities on indoor air quality, focussing on VOCs, PM and secondary pollutants produced.

- **Indoor air quality emissions and modelling system (IAQ-EMS)**[201] – a UKRI funded project aiming to develop software and data tools to allow modelling for the estimation of indoor air pollutant emissions and exposure.

Many other projects and networks of the UKRI Clean Air Programme also have indoor air quality aspects,[192] such as: BioAirNet[202] (bioaerosols), CleanAir4V[203] (vulnerable groups), HEICCAM[204] (impact of climate change), FUVN[205] (urban ventilation), TRANSITION[206] (transport microenvironments) and HIPTox[207] (ranking and linking pollutants with health outcomes).

5 Indoor air quality legislation and guidance

This section describes legislation and regulations, and guidance from a range of organisations, and discusses the Government's wider approach to tackling air quality.

Several pieces of devolved legislation address air quality, and are outlined in a House of Commons Library briefing (CBP-9600[208]). The legislation focuses on ambient air quality (the air surrounding us outdoors), transboundary air quality (cross-border air) and legal limits for key pollutants (Box 1). There are typically no legally enforceable pollutant standards, regulations, or compliance monitoring focussing on indoor air quality, other than some regulations that apply to workplaces. Improving outdoor air quality will in turn improve indoor air quality, due to infiltration of outdoor air into indoor settings.[1]

Box 1: UK outdoor air quality standards

Ambient air quality

Ambient air quality legislation derives from EU law. It sets limits for PM, NO_2, O_3, cadmium, arsenic, nickel, mercury and polycyclic aromatic hydrocarbons (PAHs).[209,210] These were implemented in England by Air Quality Standards Regulations 2010 and separate legislation by each devolved nation.[211,212]

Transboundary air quality

Transboundary air quality legislation derives from international and national agreements. The Gothenburg Protocol[213] and EU directives (2016/2284/EU[214]) set emissions ceilings for sulphur, nitrogen oxides, VOCs and ammonia. These laws are implemented in the UK through the National Emission Ceilings Regulations 2018 (NECR). However, parts of the NECR are set to be deleted with the implementation of The Retained EU Law (Revocation and Reform) Act 2023.[215]

Government targets

The Environment Act 2021[216] required the Government to introduce targets for ambient air quality in England. The Government has set two targets for $PM_{2.5}$ only: an annual mean concentration limit of 10 µg/m^3 and a population exposure reduction target of 35% from a 2018 baseline, both to be met by 2040. These are set out in The Environmental Targets (Fine Particulate Matter) Regulations 2023.[217] Interim targets are outlined for 2028 in the Environment Improvement Plan 2023.[218]

5.1 Indoor air quality legislation

There is no overarching legislation on indoor air quality, but some separate Acts and other regulations cover specific issues and products:

- **Air Quality (Domestic Solid Fuels Standards) Regulations 2020**[219] – in order to meet its international obligations on transboundary pollutants,[208] the Government developed a policy to restrict the use of the most polluting solid fuels used in homes.[§] Small quantities of wood and manufactured solid fuels must be certified as 'Ready to Burn' (indicating less than 20% moisture content for wood and low sulphur and smoke emissions for solid fuels). Wood sold in larger volumes is subject to information on correct use (such as storage, checking moisture levels) being provided to the customer.

- **Clean Air Act 1993**[220] - This Act gives local authorities the power to designate smoke control areas.[221] Smoke control areas ban smoke emissions from household chimneys unless using designated fuels (dry wood) or exempt appliances (Defra-exempt stoves). It also controls emissions of dark smoke (that tends to be more polluting) from industrial or trade premises.

- **Workplace exposure limits**[222] - The Health and Safety Executive (HSE) imposes limits to control exposure to certain pollutants and hazardous substances in the workplace. They are calibrated for a healthy working-age adult, and so might not be suitable for a wider population that includes vulnerable groups, such as people with underlying health conditions.[3]

- **Building Regulations** – These do not cover all existing buildings, they apply when constructing new homes or buildings, and in some cases, renovations.

  – **Part F – Ventilation**[223,224] – Sets the requirement for adequate ventilation in dwellings and other buildings, via measures such as minimum airflow rates and air changes per hour, as well as the monitoring of indoor air quality in certain limited non-domestic settings. The regulations also cover the installation and commissioning of ventilation systems. However, correct installation is not enforceable. Regulation 47 of the Building Regulations describes which sections are not subject to penalties for contravening the legislation, of which Regulation 42, mechanical ventilation air flow rate testing, is listed.[225,226]

  – **Part L – Conservation of fuel and power**[227,228] – Sets the requirements for adequate airtightness and air permeability testing in dwellings and other buildings.

[§] The regulations made it illegal to sell house coal (May 2023) and restricted the sale of wet wood (2021).

- **Part C – Site preparation and resistance to contaminants and moisture**[229] – Gives guidance on the protection from radon, such as flooring resistance to prevent passage of radon into buildings.

- **Housing Act 2004**[230] – Implemented the Housing Health and Safety Rating System (HHSRS), which gives responsibility for assessing health and safety risks to the owners or landlords of buildings, and enforcement to local authorities. The HHSRS aims to minimise housing hazards and covers ventilation, mould, CO, combustion products and VOCs.[231]

- **The Volatile Organic Compounds in Paints, Varnishes and Vehicle Refinishing Products Regulations 2012**[232] – Places limits on VOC content in paints, varnishes and refinishing products and ensures relevant products carry a label detailing the product sub-category, VOC limit values and maximum product VOC content.

- **Furnishing and Fire (Fire) (Safety) Regulations 1988**[233] – These regulations require household items that need to be fire resistant pass the open flame ignition test – flame retardants (a source of indoor air pollution) are used to prevent ignition and pass testing.

5.2 Strategies examining indoor air quality

The Government produced the Clean Air Strategy in 2019, which set out actions to improve air quality in England. Apart from Northern Ireland, each devolved nation in the UK has its own version of this strategy.[234] The Government stated it would raise awareness of air pollution at home, reduce the impact of domestic burning and reduce VOC exposure.

In April 2023 Defra published the Air Quality Strategy, which sets out actions it expects local authorities in England to take to meet long-term air quality limits, such as the $PM_{2.5}$ target of 10 ug/m^3 by 2040, as well as actions to improve indoor air quality (distributing guidance and best practice around ventilation).[235]

5.3 Indoor air quality guidance

Several public health bodies and organisations with technical expertise have issued guidance on achieving improved indoor air quality.

Public health organisations and health services

The WHO Global Air Quality Guidelines released in 2021 apply to outdoors and indoors.[236] The guidelines set targets and interim targets for $PM_{2.5}$, PM_{10}, O_3, NO_2, SO_2 and CO. The $PM_{2.5}$ target of 5 μg/m^3 as an annual mean is stricter than the Government limit level of 10 μg/m^3, and a NO_2 limit of 10 μg/m^3 is below the Government limit of 40 μg/m^3 as an annual mean. The

WHO also released Indoor Air Quality guidelines for selected pollutants in 2010,[237] and guidelines for Household fuel combustion in 2014.[238]

The National Institute for Health and Care Excellence (NICE) 2020 Indoor air quality at home guidance aims to raise awareness, with recommendations to achieve good indoor air quality for the public, local authorities, architects and builders, among others.[159]

The NHS released updated guidance on specialised ventilation for healthcare buildings in 2023 (HTM 03-01[239]).

Government Departments and Agencies

The UKHSA published guidelines in 2019 covering Indoor Air Quality Guidelines for selected VOCs in the UK, which details exposure limit values for select VOCs (such as benzene and formaldehyde).[45]

The Education & Skills Funding Agency released guidance in 2018 on ventilation, thermal comfort, and indoor air quality in schools (BB101[93]).

In response to the Coroner's Prevention of Future Deaths report following the death of Awaab Ishak from prolonged exposure to damp and mould in his home, the Office for Health Improvement and Disparities (OHID)/Department of Health and Social Care (DHSC) in partnership with Department for Levelling Up Housing and Communities (DLUHC) and UKHSA, recently (September 2023) published new guidance for the housing sector on damp and mould.[240] The guidance re-emphasises landlords' responsibilities in promptly responding to damp and mould issues and follows the Government's commitment to improving renting conditions. The guidance is aimed at social and private rented housing landlords of all accommodation types in England, and their workforce where applicable. It can also be referred to by owner occupiers.

The DLUHC recently (September 2023) published a review of the HHSRS,[241] which previously remained unchanged since its introduction in 2006. The review proposes several key changes, including improved access to the system, improving the system itself for local authorities and property professionals, and to ensure alignment with other legislative standards such as the newly implemented (2022) Building Safety Act. New regulations are required to bring these recommendations into force.

Professional bodies

The Royal College of Physicians and Royal College of Paediatrics and Child Health have released two major reports that cover indoor air quality. Every breath we take: the lifelong impact of air pollution in 2016[11] (which is being updated in 2024), and The inside story: Health effects of indoor air quality on children and young people in 2020.[5]

CIBSE released guidance in 2019 (TM40) that encourages indoor air quality, health-based metrics and pollutants to be used in building performance evaluation, rather than the current approach, whereby 'air quality' is used to refer to building design choices (such as ventilation rates) or occupant perceptions (such as smells or health effects typically associated with sick building syndrome).[242]

The Institute of Air Quality Management (IAQM) released Indoor Air Quality Guidance in 2021 covering the assessment, monitoring, modelling and mitigation of indoor pollutants to assist its membership and qualified practitioners with indoor air quality.[243]

The Building Engineering Services Association (BESA) has produced several guidance documents on the topic of indoor air quality, including a beginners guide, good practice and building management.[244]

The International Society of Indoor Air Quality and Climate (ISIAQ) develops and maintains a database that collates indoor air and environmental quality guidelines, regulations and standards from around the world.[147,245]

5.4 Recent legislative proposals

In response to the recent coroners' inquests, parliamentarians have responded by developing legislation to address and improve air quality. They include:

- **Social Housing (Regulation) Act (Awaab's Law)**[246] – A recent amendment passed in July 2023 makes landlords responsible for addressing damp and mould in their properties within strict time limits.
- **Clean Air (Human Rights) Bill (Ella's Law)**[247] – This Private Members' Bill starting in the House of Lords proposed to set new emissions limits for many pollutants (in England and Wales), and align the government target for $PM_{2.5}$ with stricter WHO guidelines[**], both in outdoor and indoor settings. The Government has stated that meeting these improved targets would be impossible in many locations due to natural and imported $PM_{2.5}$.[248] The Bill completed its Lords stages but at the time of writing had not progressed in the Commons.

[**] The WHO sets a limit of $PM_{2.5}$ at 5 μg/m^3 instead of the current limit used by the Government of 10 μg/m^3.

6 Interventions to improve indoor air quality

6.1 Challenges managing indoor air quality

The 'joined-up approach'

Due to the complexity and variability of indoor environments (homes, public transport, hospitals and schools), many stakeholders note that it can be difficult for one group, charity, research study or Government department to consider all the contributing variables. For example, some groups' focus may be on a discrete area, such as on ventilation and CO_2 (as a proxy marker for air pollution) rather than considering the full picture. The 'joined-up approach' can be considered in three areas:

- **Government responsibility** – No one Government department has overall responsibility for indoor air quality. A Cross Government Working Level Group on indoor air quality was established in 2021 and has members from several government departments.[3] The Royal Academy of Engineering recommended greater government coordination in its report on infection resilient environments.[173] The Royal College of Paediatrics and Child Health and NICE recommended that local authorities should have increased oversight and powers, and should offer advice and integrate indoor air quality into local planning.[5,159] However, stakeholders highlighted that local authorities have limited funding.[249–251]

- **Multi-level stakeholder engagement –** Building facilities management, building owners, developers, operators, air quality practitioners, residents, policymakers, engineers, scientists, architects and healthcare professionals (among others) may have differing levels of understanding or priorities regarding indoor air quality. Greater awareness and investment in indoor air quality will allow improvements.

- **A holistic approach to healthy indoor environments** – The Chief Medical Officer's Report states that it is important to consider how indoor air solutions affect other variables in the indoor environment, such as lighting, temperature, humidity, noise and the impact on outdoor air. Changing one of these factors can negatively affect another. Climate change, its effects and mitigation strategies are other important factors to consider.[1,252–254]

Strengthening the indoor air quality evidence base

As outdoor air quality improves, the focus is switching to indoor air pollution. There are gaps in indoor air quality research, such as air flow and pollutant accumulation dynamics in buildings, the composition of indoor air pollution from different sources (external, internal and the materials buildings are constructed with), as well as concentrations over time and how different pollutants react (indoor air chemistry).[2,3,255] Specific pollutants also need attention (for example, understanding which bioaerosols under what circumstances benefit or adversely impact health).[256] No systematic long-term monitoring studies of indoor air quality exist, in part due to the complex and variable nature of indoor environments.[3] Large-scale data sources on health impacts mostly come from developing countries, due to the lack of data obtained in developed countries. The sources of pollution differ in these two groups of countries.

Large-scale indoor air quality monitoring programmes are taking place in other countries such as France (indoor air quality observatory)[257] and the US (real time monitoring in schools).[258] In the UK, the role of an indoor air quality observatory was played by BRE (Building Research Establishment) a former government research laboratory. Since then, there is no systematic and large-scale monitoring in the UK, although there are calls to establish such capacity.[205]

Randomised controlled trials (RCTs) are considered the highest level of primary evidence to establish causal associations in research.[259,260] RCTs of indoor air quality interventions, coupled with a systematic national indoor air quality monitoring scheme that produces high-quality and long-term baseline data linked to health outcomes and inequalities,[125,153] can better inform health economics and cost-benefit analysis. This could inform policymakers, legislation (such as Regulatory Impact Assessments (RIAs)[261]) and local authority planning (such as Health Impact Assessments (HIAs)[262]). Although some RCTs assessing indoor air quality interventions have been carried out,[263] trials in this field generally may not be realistic, as they are challenging to carry out and often cannot be designed to minimise or disentangle the complex and large number of confounding variables involved.

Public awareness of indoor air quality

Social practices and technical systems (such as whole energy systems, buildings and arrangements for ventilation) are interlinked and develop in parallel. This makes it difficult to single out particular variables (such as individual behaviours) that can be modified by providing more or better information. The extent to which sharing information can be effective in changing behaviours is debated; social practices are influenced by a range of factors, some of which are structural and outside individual control.

There is limited data that has evaluated the public's awareness of indoor air pollutants and sources.[1] One 2020 survey by Global Action Plan in the UK reported that 72% of respondents thought that indoor air quality impacted their health.[264] Several stakeholders noted the 'home halo' effect, whereby residents often overestimate the quality of the air inside their home.[265,266] Research shows that the public may be receptive to information that can inform behaviour change, such as switching products or changing lifestyles to improve air quality. A recent survey (March 2023) found that 65% and 61% of respondents opened a window when cooking and when cleaning respectively.[264] Another found that 32% of gas cooking appliance users would be motivated to switch to electric if there was a financial incentive.[267]

Climate change and net-zero

Climate change, and adaption and mitigation policy measures to address it, can both affect indoor air quality. The aim to reach net-zero and subsequent move to more renewable forms of solid fuels, heating and cooking will improve indoor air quality. However, increasing temperatures, heavy rainfall and sea levels rises due to climate change could worsen indoor air quality, through an increased risk of development of mould and damp.[62]

Climate change mitigation strategies, such as the move to carbon neutral buildings (PB 44[268]) to reach net-zero targets (via new builds and retrofitting [PN 650[269]]), will also have significant detrimental effects on indoor air quality, as a consequence of affecting airtightness, temperature and humidity.[3,270] Increasing energy efficiency (via insulation) and airtightness reduces ventilation, sealing in and increasing the concentration of indoor pollutants.[3,271,272] New build homes have been shown to have higher formaldehyde concentrations than older buildings.[273] Due to the poor thermal integrity of most UK buildings,[274] retrofitting of existing housing stock is part of the Government's plan to reach net-zero targets.[275–277] However, analysis of housing stock found that up to 79% of current English housing requires additional ventilation measures to limit negative effects on health.[278] Retrofitted buildings can have an increased concentration of pollutants during and following the work, due to increased airtightness and the introduction of pollutant emitting building materials.[279–281] A review of the impact of climate change adaptation mitigation policies on indoor environmental quality is included in the HECC report (Health Effects of Climate Change), which will be published by the UKHSA in late 2023.

Woodland or green space creation in pursuit of net-zero could lead to infiltrations of new allergens and MVOCs that people have not been exposed to before.[282] Species selection is often considered during green infrastructure creation (PB 26[283]), which is important to minimize potential allergy related health effects.[284] Woodland creation is detailed in a POSTnote (PN 636[285]).

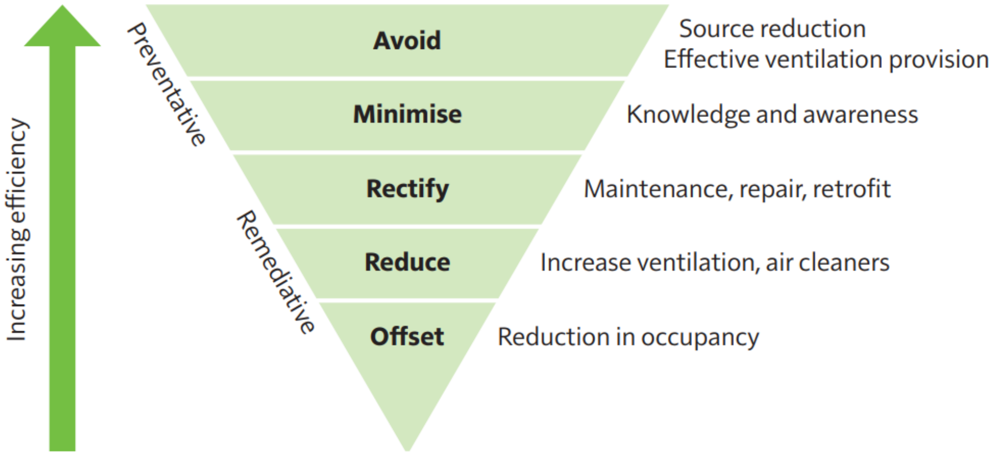
Alignment between climate change, net-zero and air quality policies, regulations and actions can reduce unintended negative impacts on indoor air quality.[286]

6.2 Specific interventions

Controlling the sources of pollutants

Source control (removal or moderation of use of common pollutant emitting products or activities) is widely agreed as an important step to improve indoor air quality, as other interventions (ventilation and air cleaning devices) do not fix the root cause of indoor pollution, and may move the problem to outdoor air.[3,287] A proposed hierarchy of interventions for indoor air quality is shown in Figure 2.

Figure 2: Hierarchy of indoor air quality interventions



Source: Chief Medical Officer's Report, 2022[1]

Source control involves removing or limiting sources of indoor pollution, which can be linked to occupant behaviour (such as cooking, air fresheners, cleaning or personal care products), given that emissions from the surroundings, (including building materials, and gas cookers/heating if living in rented residences), are much harder to control. The Government controls the use of chemicals through REACH regulations and offer users information through labelling schemes.[288]

Occupant behaviour can be informed via dissemination of information and an increase in awareness of indoor air quality (see below). Improving awareness (by product labelling for example), as well as controlling sources of emissions where no control lies with the occupant, (such as pollutants associated with the building fabric) can be addressed via legislative changes.

Ventilation

Ventilation improves airflow and removes indoor air pollutants to the outside,[289] but can also bring outdoor air pollutants indoors (for example, if situated by a main road or if nearby building occupants burn wood), which can be a major barrier (in terms of effectiveness and occupant choice) to ventilating.[1] Methods of ventilation involve simple measures such as opening windows, and more complex and expensive technologies such as mechanical systems.[3] The impetus to achieve net-zero could lead to changes that will result in indoor air pollutants being sealed inside the home. There is consensus among stakeholders that a careful balance needs to be struck between adequate ventilation and energy efficiency. Buildings with mechanical ventilation systems with heat recovery, combined with good airtightness, can be more energy efficient than naturally ventilated buildings, in part due to their uncontrolled heat loss in colder weather.[3,173,290]

Ventilation systems need to be installed, commissioned and maintained correctly to prevent future retrofitting. However, under the Building Regulations (discussed above) there is no penalty for incorrect installation, and once installed, ventilation rates are often not monitored in buildings.[125] A government study in 2019 showed that nearly all new build homes measured

(96.4% of naturally ventilated and 96% of mechanically ventilated homes) did not meet the required ventilation rates (for both trickle ventilator provision and extract flow rates) set out in the Building Regulations, Part F – Ventilation.[291]

Air-cleaning devices

Air cleaning devices (also referred to as air purifiers) are becoming more widespread and commonly used in homes, hospitals and schools.[292–294] Air cleaners vary in cost from low-cost consumer products to high-cost medical grade devices used in care settings. The strongest evidence for effectiveness is for devices fitted with fine grade filters (such as high-efficiency particulate air (HEPA) filters), due to their ability to remove fine particulates and bioaerosols (such as viruses) from the air.[1,295]

Portable air cleaners were shown to decrease $PM_{2.5}$ by between 23-92%.[296] Another study found a 42-51% reduction in PM.[297] The reduction in PM concentration has an impact on health, with reductions in blood pressure observed, but these results have limited significance,[297,298] and it is unknown if these short-term benefits would translate into long-term health improvement. Further research and clinical trials could enable long-term health benefits to be identified.

The impact of some air cleaners with specific characteristics have been scrutinised. A large review (covering 59 academic articles) and an update from the US Environment Protection Agency (EPA), identified a variety of pollutants actually emitted by some air cleaners into the indoor environment through their operation (including ozone (O_3), formaldehyde, NO_x, secondary reactants [from VOC interaction]).[3,299,300] There are limited regulations or guidance covering air cleaner use, testing or standards in the UK, but the NHS and DfE have published guidance regarding HEPA and UV-based air cleaners, as well as recommended specifications for particular indoor settings.[301–303]

Dissemination of information and guidance

Dissemination of accessible and clear educational materials can raise public awareness of indoor air pollutants and mitigation measures.[1,3,304,305] Citizen science projects, such as the SAMHE research project, which was designed with and for schools to monitor indoor air pollution (see above), couples research with educational materials, making teachers and pupils more aware of indoor air quality.[195]

Charities also produce high quality, accessible resources about indoor air. The British Heart Foundation,[306] Asthma and Lung UK,[307] and Global Action Plan[308] have easily accessible information regarding indoor pollutants and simple mitigation measures.

Information regarding simple source control measures, or ventilation if necessary, can increase awareness and improve air quality.[1] Substituting electric for gas appliances is an option, although some people are less able to make these choices (due to cost or their occupancy status [tenants]). A Defra funded study showed that some wood burners use household and garden waste materials as fuel[160] that may emit more pollutants than cleaner fuels. Alongside the new fuel restriction legislation, Defra released an information campaign called 'Burn Better'.[309]

The COVID-19 pandemic raised public awareness of the importance of ventilation. In a DHSC funded study, 75% of survey respondents recognised the importance of ventilation.[310] Advice on the proper use of ventilation systems can further improve indoor air quality. For example, extractor fans capture many pollutants emitted during cooking.[311,312] However, people may be unaware of how to use or maintain them effectively (e.g. replacing filters and keeping the fan operating for 10 mins after cooking).[1,3,23] There is a consensus among experts that air pollution (outdoor and indoor) should be included in medical education, so that doctors have more information about the health impacts of air pollution.[5,313] OHID has advice on air quality for frontline health and care professionals.[314]

Stakeholder perspectives on policy options

Stakeholders (academics, industry professionals, charities, and researchers from government agencies) highlighted several policy areas where there are opportunities to improve indoor air quality. Legislation can limit exposure sources, but stakeholders agree that a careful balance needs to be made between legislative changes and individuals' freedom of choice in relation to choices they make about their own homes.[315] Other options relate to changes that could be made to improve air in public indoor settings over which individuals have no control.

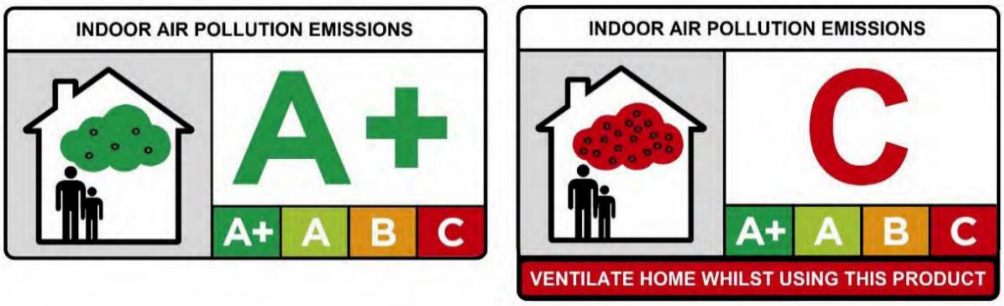
Opportunities to enable healthier occupant choices

Legislation can drive healthier occupant choices via regulations that provide the consumer with pollutant information (such as labelling schemes or warnings at the point of sale). A limited range of products such as paints, varnishes and vehicle refinishing products are regulated by VOC limits, but VOC sources in other consumer products are not.[232]

The Government's 2019 Clean Air Strategy highlighted labelling of VOC-emitting products in a 'traffic light' system as a potential intervention (Figure 3).[234] Limits to pollutants present in products, or incentives to produce low-emitting products by changing their formulation, could improve indoor air quality and provide consumers with healthier options.[316] EU countries have guidelines and/or labelling schemes for pollutant-emitting products and construction materials.[3]

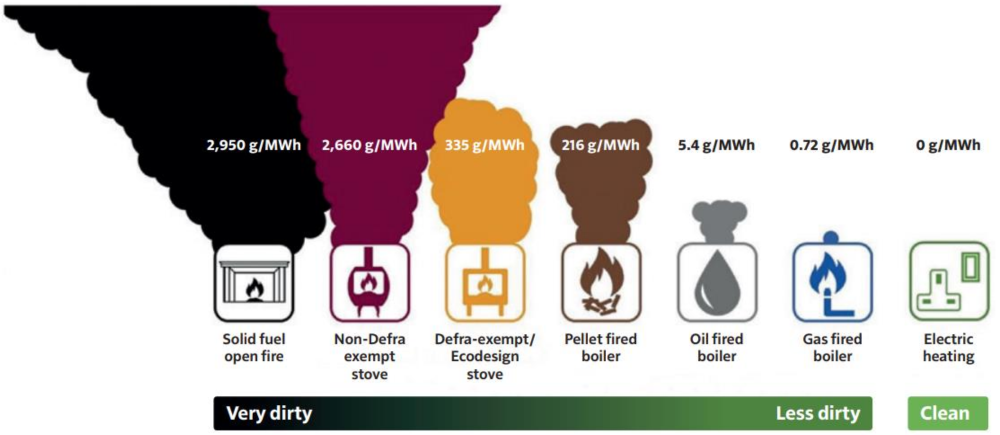
Domestic burning has been suggested to be the largest source of $PM_{2.5}$ in the UK.[25,26] Defra have developed standards that label less-polluting stoves as Defra Smoke Exempt Appliances or eco-designed. However, the 2022 Chief Medical Officer's Report highlighted that these produce higher pollutant levels compared with gas or electric heating (Figure 4). Not using stoves, using cleaner stoves or electric heating can improve outdoor and indoor air quality. Depending on how electricity is generated, electric heating can be considered clean only from the point at which it is used.

Figure 3. Mock-up of potential VOC product labels - adapted from a French system.



Source: Government Clean Air Strategy, 2019[234]

Figure 4. $PM_{2.5}$ emissions of domestic heating methods.



Source: Chief Medical Officer's Report, 2022[1]

Opportunities to reduce indoor air pollutants that are outside of occupant control

Indoor air pollution arises from occupant behaviour and product choice, but also due to sources the exposed person cannot control or access. Priority areas to target strategies to improve air quality in these situations involve:

- **Exposure in public spaces and social housing** - Several stakeholders raised the point that public spaces and social housing can provide a good opportunity for legislative changes to improve indoor air quality for the whole population (as well as vulnerable groups in care settings and schools) and set an example for other sectors of what good indoor air quality looks like. Changes are easier to implement in these spaces due to Government or local authority control.[125,317]

  For example, the installation of mechanical ventilation systems at Birmingham New Street train station in 2016 (which due to its enclosed nature, recorded very high pollutant levels[318]), reduced daily concentrations of NO_2 by 23-42% and of $PM_{2.5}$ by 62-81%.[319] Electrification can also reduce pollutant levels in train stations.[27]

- **Exposure in the workplace** – While there are no workplace exposure limits specific to vulnerable people, there is existing regulation to protect people at work, and preventive measures can be put in place by employers to limit pollutant exposure to vulnerable groups (such as those with underlying health conditions).[1,222,320,321] In addition, not all pollutants are covered or assigned a limit in the workplace exposure limit regulations.[3]

- **Internal sources of pollutants** - Several stakeholders suggest that fire-resistance laws in the UK are strict compared to other nations. The UK has some of the highest use of flame retardants in the world, in turn leading to poorer air quality.[322] A report from the Environmental Audit Committee report identified flame retardants as a source of toxic chemicals and highlighted potential mitigation measures.[323]

  Many stakeholders agree that gas appliances and domestic burning are important sources of indoor air pollution.[315] The UK has one of the highest numbers of homes (50%) cooking with gas in the EU.[172] Gas boilers are expected to be phased out in new builds as part of plans to reach net-zero, with low emission alternatives including electric boilers and heat pumps (PN 699).[324] However, this does not cover gas cooking. Gas cooking has been linked with adverse health effects – the WHO and a separate meta-analysis study found that children in homes with gas cooking appliances are at increased risk of asthma and respiratory symptoms such as wheezing.[131,237]

  Domestic burning is a large source of $PM_{2.5}$ in the UK, impacting indoor and outdoor air quality. Stakeholders highlighted that some countries (parts of the EU and US) restrict or ban burning on days of high outdoor pollution, which significantly reduced pollutant concentrations and hospital admissions.[1] An academic study is trialling a pollution alert system for wood burners in the UK.[325] Some countries also use stove replacement schemes to replace old stoves with new low emission alternatives, which also reduced pollution and the number of children experiencing respiratory symptoms.[1]

  In smoke control areas, domestic burning is allowed with authorised fuel and stoves. However, if non-compliance is detected, local authorities find it difficult to enforce the legislation, due to difficulty evidencing non-compliance, difficulty understanding the number of stoves in their area, and a lack of resources.[251,326]

- **Exposure from buildings** – Stakeholders highlight that home, commercial and public building developers (and retrofitters) are incentivised by net-zero aims to make homes and other buildings as energy efficient as possible,[5,125,315,327] mostly without consideration for the potential impacts on indoor air quality.

  Ventilation rates in new-builds are poor,[291] which can lead to mould and a build-up of pollutants inside buildings.[64] Correct installation and maintenance of ventilation systems is not enforceable under the Building Regulations, and ventilation rates are not monitored thereafter.

Building materials used in construction or retrofitting (such as in insulation) can release toxic chemical pollutants into the air (such as VOCs (including formaldehyde), PFAS and a wider range of chemicals [44,328–330]). In addition, fungicides are added to building materials and paints to tackle mould issues, which are toxic.[331] Materials are available that can prevent mould (breathable construction materials that prevent moisture build-up[332]) as well as emit fewer pollutants into the home,[333] although their use is not common or regulated.

Some non-domestic buildings are required to monitor indoor air in the updated Building Regulations. 'Smart homes', whereby indoor air quality sensors are installed in new-build homes, could provide residents with more information regarding indoor air quality.[334]

Several stakeholders state that with the newly established (2022) Building Safety Regulator,[335] there is a greater opportunity to put a focus on ensuring compliance and improving indoor air quality in existing buildings.[125]

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