A breath of fresh air

Responding to the health challenges of modern air pollution

Royal College of Physicians

The Royal College of Physicians

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Foreword

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Air pollution remains the most important environmental threat to health, with impacts throughout the lifecourse. It is an area of health where the UK has made substantial progress in the last three decades with concentrations of many of the main pollutants falling rapidly, but it remains a major cause of chronic ill health as well as premature mortality. Further progress in outdoor air pollution will occur if we decide to make it, but will not happen without practical and achievable changes to heating, transport and industry in particular. Air pollution is most important in the areas where people live, work and play.

As this report lays out, the negative impact of air pollution on health is very varied, and occurs both acutely due to very high peaks of air pollution, for example asthma attacks in children, and chronically due to prolonged exposure including heart disease, stroke, cancers and dementia. Outdoor air pollution should be seen as a societal problem: one polluting industry or road can lead to many thousands of people being affected without having any choice about the matter. We also need to understand indoor air pollution better to tackle it at source.

Historically steadily tightening regulation has spurred remarkable engineering improvements in cars and other transport, heavy industry and heating among other sectors which have reduced air pollution substantially whilst improving energy efficiency. Individuals and households also have a role – for example, the reduction in solid fuel burning in cities following smoke control areas significantly reduced air pollution in cities, although in some urban areas this is currently going backwards due to the popularity of wood burners.

The medical profession also has a role. We need to be able to advise patients, parents, carers and the public, especially on how risks can be reduced for those most vulnerable to the effects of air pollution, including children and those with chronic diseases. We also need to lay out to policymakers and the public the scientific links between air pollution and avoidable, premature disease, and possible solutions, as this report does.

Air pollution affects everybody, and is everybody's business. This report is an excellent resource, laying out the latest evidence. It also identifies some of the key practical steps that we can take to reduce air pollution, and therefore reduce a major cause of premature illness and mortality.

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Abbreviations and definitions

AAQD – Ambient Air Quality Directive
ABS – acrylonitrile butadiene styrene. A common thermoplastic polymer
ADHD – attention deficit hyperactivity disorder
AI – artificial intelligence
AOR – adjusted odds ratio
APOs – adverse pregnancy outcomes
AQEG – Air Quality Expert Group
AQIS – Air Quality Information System
ASD – autism spectrum disorder
AURN – Automatic Urban and Rural Network
BNZP – balanced net zero pathway
CAZ – clean air zone
CAFS2 – Cleaner Air for Scotland 2
CCC – Climate Change Committee
CCME – Canadian Council of Ministers of the Environment
CKD – chronic kidney disease
CI – confidence interval
CMO – chief medical officer
COMEAP – UK Committee on the Medical Effects of Air Pollutants
CO – carbon monoxide
CO_2 – carbon dioxide
COPD – chronic obstructive pulmonary disease
COSHH – Control of Substances Hazardous to Health
CSR – corporate social responsibility
DAERA – Department of Agriculture, Environment and Rural Affairs
DALY – disability adjusted life year
DAQI – Daily Air Quality Index
DL – deep learning
Defra – Department for Environment, Food & Rural Affairs
DfT – Department for Transport
DHSC – Department of Health and Social Care
DsPH – directors of public health
EEA – European Environment Agency
EMRs – electronic medical records
EPA – US Environmental Protection Agency
ESG – Environment, Social and Governance
EU – European Union
EV – electric vehicle
FEV1 – forced expiratory volume in 1 second
FVC – forced vital capacity
GMC – General Medical Council
GO-Science – Government Office for Science
H2ICE – hydrogen internal combustion engine
HFCs – hydrofluorocarbons
HiAP – health in all policies
HSE – Health and Safety Executive
ICS – integrated care system
IVF – *in vitro* fertilisation
IMD – Index of Multiple Deprivation
IMT – internal medicine training
JRCPTB – Joint Royal Colleges of Physicians Training Board
KPIs – key performance indicators
LAQM – Local Air Quality Management
LBW – low birth weight
LEZ – low emission zone
LSOA – Lower Super Output Area
LTNs – low traffic neighbourhoods
ML – machine learning
mVOCs – microbial volatile organic compounds
NAEI – National Atmospheric Emissions Inventory
NAQS – National Air Quality Strategy
NCDs – non-communicable diseases
NH_3 – ammonia
NICE – National Institute for Health and Care Excellence
NISRA – Northern Ireland Statistics and Research Agency
NO – nitric oxide
NO_2 – nitrogen dioxide
NO_x – nitrogen oxides. A group of reactive gases, primarily nitric oxide (NO) and nitrogen dioxide (NO_2) primarily formed during combustion processes, such as burning fossil fuels in vehicles and power plants. These gases are harmful to human health and contribute to the formation of smog and acid rain

NWP – numerical weather prediction

O_3 – ozone

OHP – Office for Health Improvement and Disparities

ONS – Office for National Statistics

PAH – polycyclic aromatic hydrocarbon

PM – particulate matter. A complex mixture of tiny particles of solids and liquids in the air made up from a huge variety of chemical compounds and materials, some of which are toxic

$PM_{2.5}$ – fine particulate matter; generally smaller than 2.5 μm diameter, measured by mass

PM_{10} – particulate matter; generally smaller than 10 μm diameter, measured by mass

PFD – prevention of future deaths (report). A tool used by coroners in inquests to draw attention to matters for which action could be taken to prevent future deaths

PTB – pre-term birth

QALY – quality-adjusted life year

RAC – Royal Automobile Club

RCP – Royal College of Physicians

RCPCH – Royal College of Paediatrics and Child Health

SAF – sustainable aviation fuel

SES – socio-economic status

SIGN – Scottish Intercollegiate Guidelines Network

SLCPs – short-lived climate pollutants

SO_2 – sulphur dioxide

UKHSA – UK Health Security Agency

ULEZ – Ultra Low Emission Zone

UFP – ultrafine particles

VOCs – volatile organic compounds

WELs – workplace exposure limits

WHO – World Health Organization

WI – widespread innovation

WPL – Workplace Parking Levy

ZEZ – zero emission zone

Introduction

Health harms of air pollution

Air pollution is the largest environmental health risk globally, causing loss of healthy years of life and premature death.

In 2016 the Royal College of Physicians (RCP), alongside the Royal College of Paediatrics and Child Health (RCPCH), launched a groundbreaking report, *Every breath we take: the lifelong impact of air pollution*,[1] which starkly pointed out the dangerous short- and long-term impact that air pollution is currently having on our nation's health.

Since that time the science has advanced, and wider awareness of the problem has been heightened by a number of tragic events.

In 2020, the second inquest of Ella Adoo-Kissi-Debrah concluded that air pollution played an important contributory role in her death.[2] Ella was a 9-year-old girl from south-east London who died from asthma in 2013 following 27 hospital admissions over 30 months. The UK has the highest prevalence of asthma in Europe;[3] in the 4 years to March 2023, 54 children and young people (aged up to 17 years) died from asthma, with deaths being four times higher in more deprived locations.[4] Additionally, in 2020 Awaab Ishak, a 2-year-old boy, died from a respiratory condition caused by exposure to mould in his Rochdale home.[5] These tragic events shine a light on the importance of air pollution as a driver of serious disease in children as well as in adults.

Large-scale epidemiological studies have established that adverse health effects of pollutants occur at concentrations below current air quality limit values, that air pollution is harming our children as they develop, and that it may be affecting our brain health, including dementia in later life.

While including a brief section on indoor air quality, most of the focus of the 2016 RCP/RCPCH report was on outdoor air pollution.[1] Recognising the growing importance of indoor spaces as a source of pollutant exposure, especially in the early years of a person's life, in 2020 the RCPCH/RCP published *The inside story: Health effects of indoor air quality on children and young people*.[6]

Air pollution is a dynamic process in place, time and chemical composition. The gases and particles that comprise the 'breathed environment' change in response to new sources of emissions from both outdoor and indoor sources. The principal pollutant emissions in the air are anthropogenic in origin, with combustion from domestic, transport and industry sources playing a prominent role. However, with interventions introduced to reduce carbon emissions, increasingly the particulate fraction comprises non-combustion sources (eg tyre, brake and road surface wear). It also comprises secondary particulates created by atmospheric chemical reactions involving nitrogen oxides (NO_x), sulphur oxides (from SO_2), volatile organic chemicals (VOCs) and ammonia (NH_3, largely from agriculture). Domestic wood burning, climate change, extreme temperatures and forest/heathland fires are also becoming problematic.[7]

According to PubMed, there are over 60,000 scientific studies that link air pollution to health outcomes involving multiple diseases and across a lifetime, with more than half of them published in the last decade. Epidemiological and mechanistic studies have provided overwhelming evidence for the pervasive effects of pollutants on almost all organs of the body. For combined outdoor and indoor pollution, this amounts to 8.1 million preventable deaths in 2021 worldwide, with 90% of them being attributable to non-communicable diseases (NCDs).[8]

At an individual level, exposure to air pollution shortens the average person's lifespan by 1.8 years, an impact that ranks just behind some of the leading causes of death and disease worldwide – cancer 2.5 years, tobacco smoking 2.1 years, malaria 0.3 years and inadequate water/sanitation/hygiene 0.6 years.[8] While low- and middle-income countries experience the greatest health burden of polluted air, the adverse health effects in countries with stronger economies such as the UK remain unacceptably high, with between 29,000 and 43,000 early deaths attributable to outdoor particulate and NO_2 pollution in 2019.[9] More than one in 19 deaths in UK cities and large towns are related to long-term exposure to air pollution.[10]

As highlighted in both the RCP/RCPCH 2016 and 2020 reports on air pollution and health,[1,6] these deaths are the 'tip of the iceberg', with substantial effects occurring on organ development in early life,[11] as well as initiating and accelerating NCDs,[12] increased risk of miscarriage and multiple health conditions across the lifecourse.[13] Because small particles can be absorbed into the circulation, they can reach every organ of the body. Here, they lead to oxidant cellular injury, inflammation, DNA damage and accelerated senescence,[14] the processes most likely to be responsible for initiating and driving progression of the many NCDs as well as impacting on organ development.[15] Indeed, recent research has indicated that long-term exposure to both fine $PM_{2.5}$ and NO_2 was positively associated with the onset of more than 700 health conditions, indicating a much more extensive impact on human health than previously appreciated.[16]

In addition to these long-term adverse health effects of air pollution, acute short-term exposures also trigger disease expression or exacerbation in those with established disease. This is most well documented in lung diseases such as asthma, chronic obstructive pulmonary disease (COPD) and lung infections, but air pollution episodes also precipitate acute cardiovascular events such as cardiac arrhythmias, myocardial infarction and stroke, with increased hospital admissions and use of emergency services. Short-term exposures also impact on seemingly healthy individuals, reducing both mental and physical performance.[17,18]

Outdoor air pollution

There are significant health harms associated with air pollution, but there are also effective interventions available to reduce them. In the UK, emissions of most outdoor air pollutants (except for ammonia) have decreased over recent decades, and there has been limited change in $PM_{2.5}$ and PM_{10} over recent years.[19] The decline in emissions can be attributed to a combination of changes to regulations, technology, urban planning, agricultural practices, and behavioural and broader societal changes. Some interventions to reduce air pollution emissions also have significant co-benefits. Active travel through walking, wheeling or cycling rather than using motorised transport reduces air pollution emissions and has direct health benefits through physical activity. Reducing the use of fossil fuels for energy has the co-benefit of reducing both air pollution and greenhouse gas emissions.

On account of the substantially expanded epidemiological and toxicological evidence base that causally links air pollution to diseases, in 2021 the World Health Organization (WHO) substantially revised downwards their health-related air quality limit value guidelines (levels and interim targets) for $PM_{2.5}$ and NO_2 to concentrations that translate to 99% of the UK population breathing toxic air (Table 1).[20,21] Evidence from mega-cohorts with several million participants from high-income countries with exposure to relatively low mean air pollutant concentrations show effects on health even at concentrations below the WHO air quality guideline values, with higher effect sizes at lower levels of exposure.[22] Put simply, there are no safe levels of air pollutants, so the more that we can do to try to improve our air, the better.

Table 1. Current annual air quality limit values for $PM_{2.5}$ and NO_2 in the UK far exceed the guideline levels for health set by the WHO in 2021.[20]

Current UK air quality objectives compared with WHO guidelines

Pollutant µg/m³	WHO guidelines	England	Scotland	Wales	Northern Ireland
Annual mean $PM_{2.5}$	5	20	10	20	20
Annual mean NO_2	10	40	40	40	40

Indoor air pollution

In industrialised nations, people spend 80–90% of their time indoors and air quality therefore becomes important in homes, schools, workplaces, travel hubs and other public buildings. Air pollution can enter buildings from outside and also comes from a myriad of indoor sources, yet compared with ambient air pollution, there is still much to learn about the health effects of indoor pollution.[23] People are exposed to mixtures of both indoor and outdoor pollutants throughout the day, with specific locations and activities linked to peaks of exposure, eg transport, cooking. Thus, spatial and temporal variability in outdoor and indoor pollution concentrations and in individuals' time-activity patterns are key elements of personal exposure that drive adverse health across the lifecourse.[24]

Low- and middle-income countries are most severely affected by high levels of indoor pollution, mostly caused by biomass burning for heat and cooking in poorly ventilated homes.[25] In higher-income countries like the UK, the sources are more complex. Poor-quality and overcrowded housing, use of solid fuel combustion for cooking and heating, the increasing number of new chemical pollutants from products and inadequate ventilation, along with a paucity of health data, create causes of concern. The 154,000 deaths in the WHO European region attributed to household air pollution in 2019 are likely to be an underestimate.[26] The recent COVID-19 pandemic has shone a light on the importance of indoor environments and the crucial role that ventilation plays in creating healthy indoor air.[27]

Air pollution across the lifecourse and health inequalities

As we highlighted in the RCP/RCPCH *Every breath we take* report in 2016,[1] air pollution has harmful effects on health across the population, and at different stages of life (Fig 1).

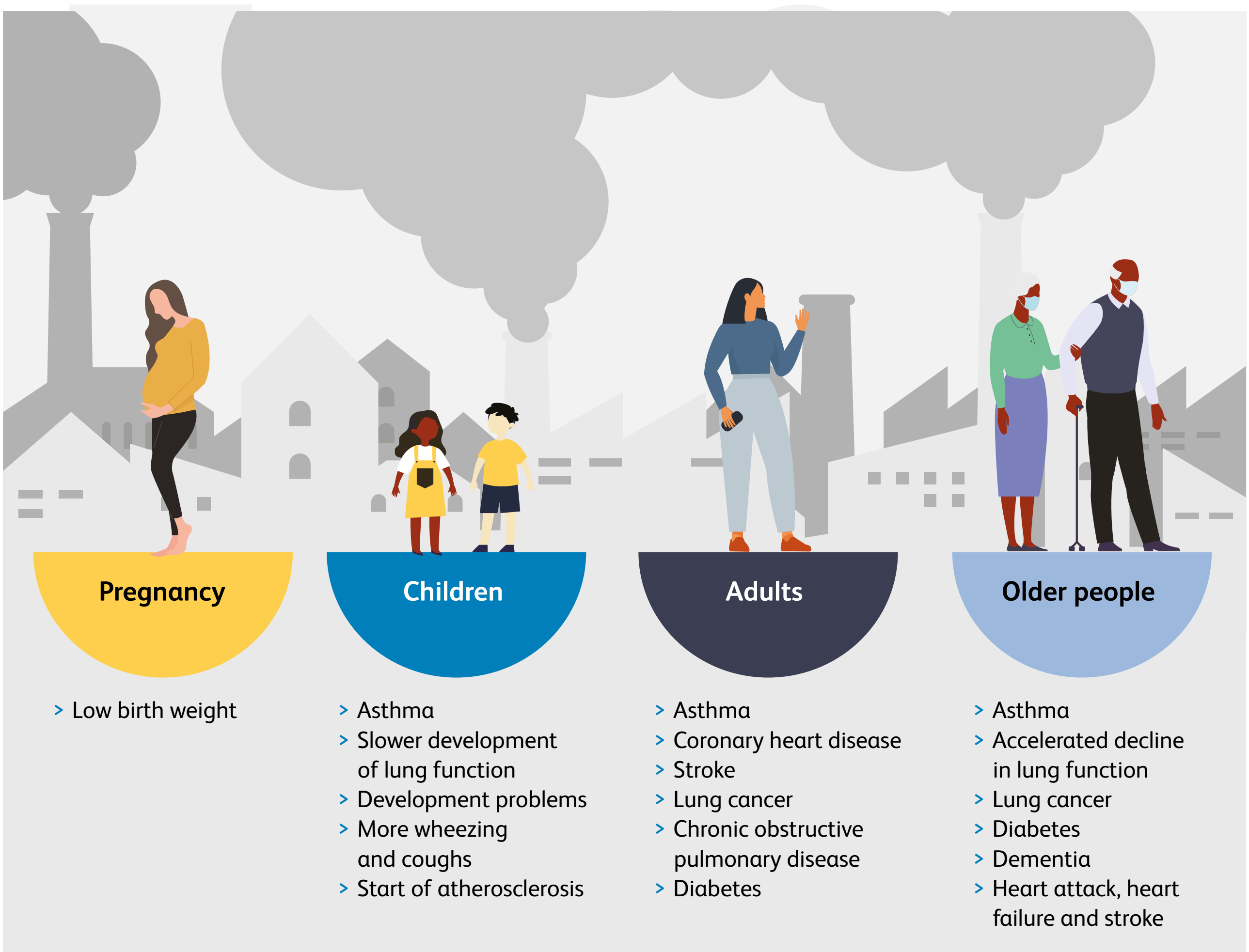

Fig 1. Health effects of air pollution throughout life (source: CMO's annual report 2022, adapted from PHE 2018).[28] Contains public sector information licensed under the Open Government Licence v3.0.

People can be exposed to air pollution where they live, play, study or work. This exposure is distributed unevenly in the UK; for example, urban areas tend to have higher concentrations of traffic-related air pollution, higher population density and more diverse ethnic groups than rural areas. Minoritised ethnic groups experience higher local NO_x and $PM_{2.5}$ emissions regardless of deprivation and these disparities exist across a range of settings, including suburban areas, small towns and rural areas. Changing patterns of air pollution are creating pockets of poor air quality in rural locations, often linked to specific activities, eg solid fuel burning (especially wood), agriculture, road transport, forest and heathland fires.

In addition to variation in exposure, some people are more susceptible to harm from air pollution, including the very young, older adults and people with existing respiratory conditions, cardiovascular disease and combinations of diseases (multimorbidity). Inequalities in exposure to air pollution and susceptibility to harm overlap and increase health harms – eg people living in areas of higher deprivation, including some ethnic minorities, may be exposed to high concentrations of air pollution from traffic or industrial processes, and they are also more likely to be living in poor health, with greater susceptibility to harm.[29,30]

The rationale behind this RCP update on air pollution and health

People are exposed to air pollution from multiple sources, and these are often outside an individual's control. Some pollutants, such as $PM_{2.5}$, can also travel considerable distances from their sources. Therefore, actions to reduce air pollution health harms require multiple interventions across different sectors. The chief medical officer for England's annual report 2022 on air pollution highlights the range of sectors involved in tackling air pollution, including transport, urban planning, the energy sector, industry, agriculture, the NHS, building design and use, and domestic heating.[28] Multiple stakeholders are involved across government, industry, academia, and the voluntary and community sector. The CMO's report also stresses the importance of indoor environments as sources of exposure.[28]

With the large increase in evidence linking air pollution to adverse health outcomes, in 2022 the EU recognised the need for:

- stricter thresholds for pollution, more closely aligned with new limits set by the WHO
- enhancing the right to clean air, and improved access to justice
- provisions for citizens to claim compensation for health damage due to air pollution
- strengthened rules for air quality monitoring to support preventive action and targeted measures
- requirements to improve air quality modelling, especially if and where air quality is poor
- better public information.[31]

For the UK, the magnitude of the adverse impact that breathing air pollutants has on health now requires more ambitious actions than those currently in place. With Brexit, our links to European air quality initiatives have been cut and the UK is now slipping behind.[32] For example, EU member states adopted the final text of the revised Ambient Air Quality Directive (AAQD – binding air quality limits and targets for countries to achieve by 2030 for all major pollutants and specifically for $PM_{2.5}$ and NO_2 – double the ambition of the previous limits). This landmark legislation puts all EU member states on a path towards meeting WHO air quality guidelines.[33] Similarly, on 7 February 2024, the US Environmental Protection Agency (EPA) strengthened the $PM_{2.5}$ standard to 9 µg/m^3.[34] These actions are more ambitious than the current targets for $PM_{2.5}$ laid out in the UK Environment Act 2021, which states that, by 2040, the annual average concentration of $PM_{2.5}$ must not exceed 10 µg/m^3.[32] Indeed, a recent study by the Institute for Fiscal Studies shows that, in 2023, almost everywhere in England is now below England's 2040 target for $PM_{2.5}$ air pollution,[35] but still falling short of the WHO's recommended limit.[20] In 2023, individuals living in the 20% most deprived areas experienced 8% higher average $PM_{2.5}$ concentrations than those in the 20% least deprived.

Historically, air pollution has been framed as predominantly an environmental issue in the UK, which explains why policy responsibility for this falls predominantly on Defra (the Department for Environment, Food & Rural Affairs) and equivalent bodies in local government with responsibility to deliver local air quality management.[36] With the overwhelming health evidence now connecting both acute and chronic exposure to air pollution to so many different diseases and health outcomes across the lifecourse, as well as intersections with other social determinants of health,[37] the RCP considers that the time has now come to take air pollution, both outdoors and indoors, much more seriously as an avoidable health risk, with an urgent need for much more ambitious action by the UK to improve the quality of the air that we all crucially depend upon for life.[38] In reframing this, improving human health must become central in a multi-pronged system approach to tackle this 'wicked problem'. The net result of air pollution is a sicker population with a huge economic burden that incorporates the cost of healthcare, productivity and utility at all stages of life.

This update provides new insights into why urgent action is needed, directed at those fields where there have been the greatest changes and where a renewed focus will provide a platform for further improvements. It also includes key cross-cutting issues such as inequalities, climate change, urban planning, education and economics, because many of these intersectoral factors are influencing the pollutant content of the air that we breathe and its adverse consequences on society, both in the short and, especially, in the long term. In the RCP/RCPCH's 2016 report,[1] we emphasised the impact that air pollution is having on the UK economy. Since then, much more information has become available, indicating a much greater economic impact than originally thought. In addition, inequalities and inequities, early-life exposures and brain health have come to the forefront and are covered in some detail in this update. We also recognise the importance of indoor environments where we spend most of our time, including occupational settings. However, while recognising the importance of occupational exposures in disease causation and the special issues involved, we have not covered this in our update, recognising that the oversight of this is principally by the Health and Safety Executive (HSE) in setting workplace exposure limits (WELs), as well as enforcing the Control of Substances Hazardous to Health (COSHH) regulations to ensure workplace air quality and protect workers from harm.

With the help of 30 experts, we have structured this report into three parts: 1) impacts of air pollution over the lifecourse; 2) health inequalities and economic impacts of outdoor and indoor air pollution; and 3) creating policies fit for the future. From this interdisciplinary approach, important new recommendations have emerged.
We request that government and other appropriate stakeholders respond to these recommendations in order to generate the much-needed joint further action and create new policy to clean up the air that we are all so dependent upon for our health and wellbeing. We also request that health professionals take greater ownership of this public health challenge, to help in prevention and management of the many diseases that air pollution is now known to cause, accelerate and exacerbate.

Recommendations

Some air quality legislation remains UK wide, while responsibility for other air quality policy is devolved to the national administrations in Scotland, Wales and Northern Ireland, with separate arrangements for England. Air pollution is also a transboundary issue that requires coordination and shared ambition across the four UK nations. The recommendations in this report are for all nations of the UK, with nation-specific recommendations as they apply.

Air quality as a public health issue

1 National, regional and local governments across the UK must recognise air pollution as a key public health issue and take increasingly ambitious action to reduce people's short- and long-term exposure to outdoor and indoor air pollution.

- Outdoor and indoor air pollution is recognised by the UK, EU and WHO as the greatest environmental risk to health.[9] Around 30,000 deaths are estimated to be attributable to long-term exposure to air pollution in the UK each year, with the health impacts of air pollution including dementia estimated to cost the UK £50 billion in 2019. With new and growing evidence of health harms,[39] including at low concentrations, air pollution must be recognised as a public health issue. Protecting human health needs to sit at the heart of air quality policy making so that interventions maximise public health gains for the population as a whole, and protect vulnerable groups in particular.

Limit values

2 Governments across the UK should work with stakeholders and citizens, including marginalised and vulnerable groups, children and young people, older people, minoritised ethnic groups and disabled people, to identify robust pathways towards the delivery of the World Health Organization's 2021 global air quality guideline levels.

- National governments across the UK must ensure that there are defined policy pathways towards achieving the WHO global air quality guidelines. In England, the annual mean $PM_{2.5}$ target to be reached by 2040 is now recognised by WHO as 'Interim target 4' – with most of the country on track to meet it by 2030. There is clear opportunity for increased ambition to achieve greater public health gains with a pathway(s) towards the 2021 WHO global air quality guidelines for all air pollutants. The Environment (Air Quality and Soundscapes) (Wales) Act 2024 must be implemented to meet the WHO guidelines on air quality. Air Quality Standards (Scotland) Regulations 2010 should align new limit values with the 2021 WHO guidelines and a new Act should be created in Northern Ireland to enshrine WHO limit values in law.

3 Governments across the UK must take increasingly ambitious action on air pollution as our knowledge about its role in causing and accelerating disease and impairing fetal and child developmental processes continues to develop. The UK must become an international leader in creating cleaner air through increased ambition and technical innovation.

- While the UK has historically led the world in tackling toxic air, in recent years other economically developed regions such as Europe, Canada, New Zealand and the USA have either already achieved, or are moving rapidly towards achieving, the 2021 WHO global air quality guideline levels for both particulate and gaseous pollutants. Continuous action to tackle air pollution is required. Maximising the public health gains from improved air pollution will require strong ambition and leadership, as well as cross-government support and action. The UK must create bold and bespoke air pollution policies to ensure that it leads again and does not trail behind other comparable high-income nations.

4 The UK government must regularly review the effectiveness of the air quality limit values and population exposure reduction targets as public health measures, including assessing whether more stringent limit values, legally binding interim targets or other tools and approaches would be more effective at continuously driving down air pollution and yielding the best possible public health outcomes, including a dedicated focus on populations with high levels of pollution and vulnerability to health harms.

> There is no evidence of a safe threshold for many pollutants. Research shows that levels of air pollution that are considered to be below current regulatory standards still have significant negative health impacts. For the UK to deliver the greatest possible health gains from its clean air policies, government needs to regularly review the best tools and approaches to reduce air pollution, and how actions can focus on areas and populations with high levels of pollution and vulnerability to health harms. These include people who are pregnant, children, older people and those with medical conditions, as well as those living in deprived urban and rural communities. Responsibility to identify and implement the most effective approaches to tackle air pollution should be held jointly by between government departments responsible for health and the environment. They need to be supported by those with responsibility for transport, net zero and energy, and housing and local communities.

Action on air pollution at source

5 National and local governments must take greater action to tackle all sources of air pollution, increasing action where progress is already being made and tackling areas that have been overlooked or lightly regulated, such as agriculture, indoor and domestic emissions.

> Tackling air pollution at source is the best way to deliver improved air quality. Some sectors, such as industry and transport, have seen effective and welcome emission reductions, while other sectors, such as agriculture and air pollution from buildings and indoor environments, lag behind. There is an urgent need to address air pollution from residential buildings, particularly focusing on the management of moisture, emissions from wood burning and other solid fuels used for heating, volatile organic compounds (VOCs) and other pollutants from household, cleaning and personal care products, and promoting use of low-emission alternatives across all these categories, through education, policy changes and product standards. Efforts must continue to be made in agriculture and transport, which remain significant emitters – for example, improving manure management by implementing proper storage and handling of livestock manures and slurries to reduce ammonia emissions.

Public health campaign

6 Government should fund and deliver a coordinated, UK-wide public health clean air campaign to provide accurate and trusted information about the health impacts of short- and long-term air pollution exposure, the sources of indoor and outdoor air pollution, and practical advice to reduce personal exposure. The campaign should use accessible and tailored messaging across multiple platforms to ensure relevance and reach target audiences, including vulnerable population groups and individuals.

> Drawing on the success of campaigns such as Better Health Smoke Free,[40] UK government and the devolved nations should deliver a mass media campaign with accessible information about the main sources of outdoor air pollution, such as vehicle use and solid fuel burning, and the sources and impacts of indoor air pollution. Action and advice on how to reduce individual exposure should also be included, with a focus on vulnerable groups whose health and wellbeing are disproportionately impacted by air pollution. This campaign should be provided across multiple platforms, including daily pollution information on weather reports by broadcast media (TV, radio and online), text message and smartphone applications, and easy access to information. At times of particularly high pollution levels, governments across the UK should issue alerts, including recommended actions to reduce harmful exposure. Blame for the problem must not be transferred to those who suffer the impacts – a public health campaign must be accompanied by coordinated and systemic actions to reduce air pollution.

7 National and local governments should ensure that the public are fully engaged in the development of air quality policies through actively listening to their concerns and creating a shared, evidence-based vision of better health through better air.

- Governments must actively engage with the public affected by poor air quality and by measures to tackle it, by designing and implementing policy interventions that improve air quality. This needs to be supported by access to evidence-based, trustworthy information that establishes a health-based rationale for action to counter misinformation and maximises support for interventions.

Planning and the built environment

8 National and local governments must take a health in all policies (HiAP) approach to the built environment and delivery of local services in urban and rural areas, including evidence-based policies covering transport, planning and development, active travel and the provision of green and blue spaces. To maximise health gain, government should introduce a statutory duty to require the integration of health in all environment and planning policies, including the proposed large increase in providing new homes across the UK.

- Air pollution, health and wellbeing must be placed at heart of place-based design and in local government services. Initiatives addressing inequalities and inequities such as Marmot Places[41] – with improved housing quality, public transport, access to green spaces and active travel – will improve health and air quality. The involvement of public health professionals and practitioners is vital to ensure that action to improve air quality is joined up across all levels of government and working towards the same goal of improving health. Specialist public health resources must be increased in local authorities, with directors of public health given more influence.

9 National and local governments need to deliver improvements in the provision of public transport to reduce emissions from personal vehicle travel and ensure that the infrastructure needed for increased active travel is in place, with the goal of achieving 50% of urban journeys being made on foot or by bike by 2030.

- A shift to low-carbon and healthier urban and transport planning is essential. Electric vehicles have often been proposed as the panacea, but these only go some way to reducing emissions and do not address important issues such as healthy use of public space, congestion, urban heat islands, and lack of physical activity in the population that is essential for good physical and mental health. Providing infrastructure and enabling adoption of walking and cycling ('active travel') and public transport use will reduce the need for private vehicle use, with added air quality and public health co-benefits. Road space reallocation away from private car use and to active travel and public transport will be required, and the government must provide strong messaging and leadership on the necessity of this.

Indoor air quality

10 National governments across the UK should work with the research community, industry, third sector and regulators to develop a cross-departmental indoor air quality strategy. This needs to address the health harms from exposures to air pollution, such as from wood-burning stoves or from damp and mould in homes, workplaces, transport, healthcare settings, and indoor public and retail spaces. It should include ongoing representative measurements and opportunities for action through net zero design and retrofit, enforcing current regulations and developing 'fit-for-purpose' revised product and building regulations, as well as improving indoor ventilation and setting standards for healthy indoor air quality.

- Despite society spending a significant proportion of time in buildings, indoor air quality has received much less attention and research than outdoor air. Yet, we know that in our homes and other buildings is where we are exposed to pollution from outdoor air, as well as from chemical and biological substances generated indoors. Net zero policies and climate adaptation will require many changes to old and new buildings that will, in turn, change our indoor environments. A dedicated strategy, held jointly across government departments responsible for health, the environment and net zero, would deliver a coordinated approach that recognises the interconnection across the health and sustainability agendas and delivers technical, regulatory and behaviour co-benefits.

Inequalities and inequities

11 All air quality policy developed by national and local governments across the UK must consider the disproportionate impacts of air pollution on certain groups, including recognised ethnicity- and deprivation-based disparities. It should focus action on areas and populations with high levels of air pollution and greatest vulnerability to health harms from pollution.

- The impacts of air pollution are disproportionately experienced by vulnerable populations and marginalised communities at risk of poorer health outcomes. Of the groups that are more exposed, many will also be more vulnerable to the exposure – including children, older people and those living with existing chronic health conditions. All policy developed at a national, regional and local level across the UK to tackle poor air quality must recognise and actively consider where interventions are most needed and the benefits of taking action to reduce inequalities, including how interventions can be targeted and tailored to benefit socially disadvantaged and marginalised groups. As has been learnt from the COVID-19 pandemic, local communities should be involved in decision making and co-development to promote uptake and sustainability of initiatives.

12 A whole-systems approach is needed to join up public sector bodies and agencies with responsibilities for air quality, public health, education, social care and healthcare services, to pool resources and deliver coordinated action. These actions must be evidence-based and tackle air pollution as a wider determinant of health and contributor to inequalities, thereby reducing the gap in healthy life expectancy and health outcomes experienced across the UK.

- Improving air quality will reduce health inequalities as fewer people are affected by its health impacts, including those whose health is more susceptible to its impacts. This will, in turn, reduce NHS and social care costs and productivity losses. Joining up the many and varied public sector bodies with responsibility for air quality, public health and healthcare services will enable joint action. Currently, these can be fragmented and wide-ranging, involving multiple bodies across government, the NHS and the third sector. The need for strong national action, leadership and incentives – as well as measurement and enforcement at hyperlocal level – is critical here to success.

Net zero

13 The Department for Energy Security and Net Zero should ensure that air quality co-benefits are maximised and integrated within the UK's mitigation and adaptation actions for climate change and net zero. It should act on opportunities to close the persistent inequalities in air pollution impacts through targeting investments to reduce greenhouse gas emissions for families living in fuel poverty, social housing and the private rented sector, and in those living in areas with the greatest deprivation.

- From the transition to low-carbon, 'clean' energy to delivery of net zero housing and clean transport, many of the actions for transition to net zero will bring large air quality co-benefits. The WHO COP26 special report on climate change and health highlighted the health benefits of coordinated action on mitigation through benefits from improved air quality, finding that benefits outweighed costs by two to one.[42] Developers in England and the devolved administrations must demonstrate how they will minimise local air quality impacts during the construction (and demolition) phase of new developments. The current state of damp and mould in UK housing shows that it is crucial that adequate attention is given to ventilation of homes and buildings as part of energy insulation.

14 Air quality needs to be included in organisations' corporate social responsibility (CSR) initiatives as part of their 'green' and sustainable action plans.

- Many businesses and organisations have CSR initiatives with a big focus on reducing their carbon footprint and improving the sustainability of their practices. Air quality should be included in CSR initiatives, with equal weight and importance to carbon footprint, with dedicated KPIs and reporting.

Health professions

15 The NHS in England, Wales and Scotland, and Health and Social Care (Northern Ireland), need to reduce air pollution from all sources. The NHS in each nation should facilitate air quality action by commit to sharing data and evidence for supporting actions to improve air quality, integrating and analysing both central and local data sources to enable tracking of progress towards measurable air quality targets.

- A dedicated national framework is needed to consistently assess and share data on air quality and its associated health benefits. This will help to ensure a standardised approach to evaluating and communicating these co-benefits across the NHS and integrated care service providers. In England, this will help maximise the positive impact on health from the NHS in England's net zero ambitions and Green Plan delivery.

16 Medical royal colleges, faculties, and professional and membership bodies need to incorporate education on air quality into undergraduate and postgraduate training programmes, continuing professional development, assessments and clinical guidelines, to enable health professionals to take account of air pollution in the prevention, diagnosis and management of diseases and conditions.

- New science has established that serious harm from air pollution extends beyond the lungs and cardiovascular system as a driver of many different diseases, such as brain disorders, cancer in non-smokers, and childhood disorders. While research continues to grow, the link between air pollution and mental health remains understudied and often overlooked, even though evidence indicates that air pollution significantly affects brain health and cognitive function. Clinicians must be aware of these developments so that they can take account of them in their practice.

17 Health professionals and practitioners have a responsibility to speak to and educate their patients about the health effects of air pollution and to advocate for cleaner air.

- Patients should be empowered to understand how air quality may be affecting their health and/or health conditions. It is key that doctors, and all healthcare professionals, understand that they have a responsibility to talk to patients about air pollution, its health risks, and how to avoid it or reduce its impacts. The advocacy of clinicians talking about the health impacts of air quality that they see in their work is vital to make the case that air pollution is a health issue, just as tobacco smoking is.

Research

18 Air pollution researchers and policy makers should routinely make use of co-produced tools and methodologies from complexity science and participatory research to inform policy development.

- Air pollution is a 'wicked problem' due to its ever-changing complexity, meaning that it is impossible to solve in a way that is simple or final. The impacts of air quality policy initiatives cannot be considered separately from their physical, geographical, social, cultural, political and economic contexts. Utilising tools from complexity science would achieve a multitude of benefits, including enabling representation of both the positive and negative potential impacts of policy options across priority areas such as health, economy, clean energy and climate change. Adopting these methods in the policy-making process can identify paths of causal interaction with broader outcomes, to enable beneficial outcomes to be optimised and unintended negative consequences to be mitigated. This approach leverages the insights of diverse stakeholders, including affected communities, to create more relevant and effective solutions as recently demonstrated in the Defra Air Quality Information System (AQIS) review.[43]

19 UK Research and Innovation (UKRI) and its research councils, the National Institute for Health and Care Research (NIHR) and charitable funders should support studies on the effects of air pollution through the lifecourse to address priority research questions identified by the UK Committee on the Medical Effects of Air Pollutants (COMEAP). Key areas for future research include identifying and understanding links between exposure and susceptibility throughout the lifecourse, the lag periods between exposure and short- and long-term health impacts, including multiple indoor and ambient environmental exposures and multimorbidity outcomes, and identifying opportunities for effective (and cost-effective) early intervention. The negative impact of air pollution on mental and behavioural disorders, reduced cognition, impaired childhood learning and dementia also mandates further research.

> Having sufficient research and evidence covering the span of air quality issues will lead to a more comprehensive understanding of the problem and better solutions to inform policy development and drive innovation. Principles of co-design should be embedded throughout the research process, from inception to delivery and impact. The research community should adopt best practice in public involvement to incorporate the perspectives, knowledge and lived experiences of patients, carers, advocates, service users and communities in the research process. They should also utilise public engagement activities, such as citizen science and community outreach, to share research findings with affected communities. This will deliver studies that address the concerns and needs of those most impacted by air pollution and will also support buy-in for potential mitigation strategies.

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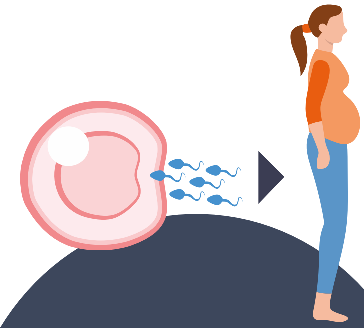
01

Impacts of air pollution over the lifecourse

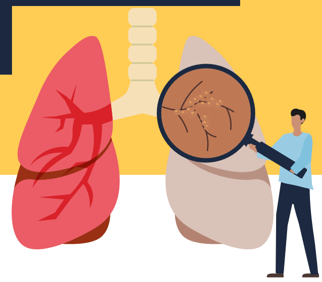
The equivalent of around **30,000 deaths a year** in the UK are estimated to be attributed to air pollution.

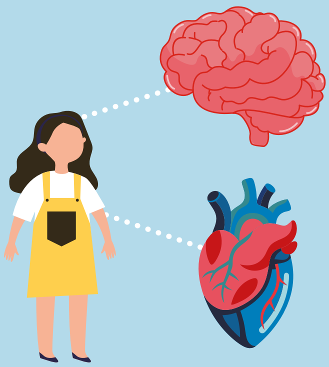
Air pollution negatively impacts health at all stages of life and early exposure can lead to ill health later in life.



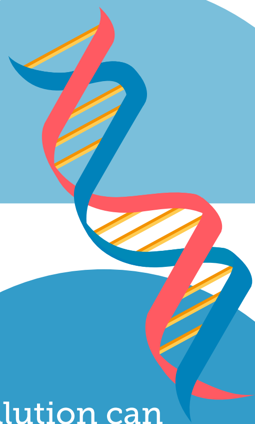
Impacts begin before conception and continue throughout pregnancy. Globally **around 2.7 million low-birth-weight babies and 5.8 million** pre-term babies each year are linked to $PM_{2.5}$ exposure.

Air pollution **affects almost every organ in the body, including the brain, lungs, heart, liver and kidneys** and the diseases linked to them.





Children are vulnerable as they are developing their key protective systems. Effects include reduced lung growth, weakened immune systems, and reduced brain development.



Air pollution can cause or worsen health conditions in adults and is associated with cancers as **air pollutants can damage DNA.**

Exposure throughout life can substantially increase the risk of dementia.

Key points

- Air pollution is present everywhere in our lives, both outdoors and indoors. Emissions of many outdoor pollutants have improved since the 1970s, with some notable exceptions including ammonia from agriculture. Although the indoor environment offers some protection from outdoor air pollution, it is also a place where we are exposed to pollution from indoor sources. Exposure from indoor sources is likely to increase as buildings are made more airtight.
- Over the past 10 years we have gained new evidence of the harmful impacts of air pollution that occur, even at low air pollution concentrations. These harms may take decades before they fully manifest. Exposure to air pollution in one part of our lives may go on to impact our health as we grow and age.[1]
- The latest government estimates of the mortality burden of air pollution in the UK (for 2019) are equivalent to a range of 29,000–43,000 deaths per year for $PM_{2.5}$ and NO_2 combined,[1a] giving a central estimate of 36,000 deaths. Reductions in pollutant levels since 2019 will have reduced impacts further, perhaps towards a central estimate of around 30,000 deaths per year. This is a welcome decrease from the 40,000 estimated in the 2016 RCP report,[2] but still a large impact on population health. New estimates are now available on morbidity impacts. These include 3,010 new cases of lung cancer in adults and 9,750 new cases of asthma in children in 2019. Around 315,000 days of school absence in 2019 were attributed to illness from $PM_{2.5}$.
- The harmful effects of air pollution begin before conception and continue through pregnancy. It has long been acknowledged that air pollution exposure during pregnancy can affect birth outcomes. Globally, around 2.7 million low-birth-weight babies (around 5.8 million pre-term each year) have been attributed to ambient and household $PM_{2.5}$ exposure. New evidence is emerging of negative impacts on childhood development and on maternal health too. Health inequalities, particularly those starting in early life, tend to persist throughout a person's life. Reducing air pollution, especially during the prenatal period and childhood, can significantly impact on this trend, leading to fewer long-term health disparities.
- Childhood and adolescence are a time of marked vulnerability due to the development of key protective systems. This means that adverse exposures during childhood and adolescence can have significant and long-term impacts on health. The impacts of air pollution exposure on children are multiple. Examples include reduced lung growth of children, with around 5% loss of forced vital capacity (FVC) over a 5-year period found in one study of London schoolchildren. More positively, recent evidence has also shown that interventions to remove or reverse these impacts are also possible.
- For a long time, it was thought that air pollution health impact in adults was mainly through respiratory health. In recent years, scientists have found links between almost every organ system in the body and the major diseases that affect them. These include the lungs, cardiovascular systems, metabolism, renal, liver, gastrointestinal, bone, skin and cancers. For example, ischaemic heart disease and stroke are estimated to account for approximately 11,200 and 3,100 respectively of the UK's premature deaths from ambient air pollution. Given the prevalence of cardiovascular disease and severe impact on life and wellbeing, it follows that, if reductions in air quality can be realised, significant health gains from improved cardiovascular health would follow.
- The impact of indoor and outdoor air pollution on mental health is under-researched and poorly recognised. Evidence implicates outdoor air pollutants as risk factors for a variety of mental health problems, including depression, anxiety, personality disorder and schizophrenia. Recent analysis using UK data has found that exposure to multiple air pollutants substantially increases the risk of dementia, especially among those individuals with high genetic susceptibility.

1.1 Introduction

The sheer volume of evidence on air pollution and health is overwhelming, and it grows by the week. To date there have been over 60,000 peer-reviewed studies. Over 6,000 publications were added to this evidence base during 2023, and over 30,000 studies have been added since the publication of the RCP's report *Every breath we take: the lifelong impact of air pollution* in 2016.[2]

From the efforts of researchers around the globe, we now know about the impacts of air pollution on more health conditions and on the progression of disease. Many of these impacts have been found in studies conducted in the UK. Most significant has been the new knowledge of the impacts of air pollution in the earliest period of life and on our brain health, including child and adult mental health, and dementia.

These studies also offer a way forward. There is increasing evidence that improving air quality leads to improvements in health. This allows us to reframe the evidence as an opportunity to improve our health and to reduce the individual and societal burdens that ill health creates.

Part 1 provides a synthesis of the evidence on air pollution and health, with a focus on the new knowledge that has emerged from research since the publication of our last report.[2] It charts changes in the air that we breathe, as well as advances in the understanding of its impacts from the earliest stage of life, through childhood development and into our lives as adults.

1.2 The changing nature of air pollution

1.2.1 Which pollutants harm our health?

The air pollutants with the greatest effect on the health of the UK population are particulate matter, nitrogen dioxide (NO_2) and ozone. The greatest effects are attributable to particulate matter, measured in the UK's atmosphere as $PM_{2.5}$ (fine particles; generally smaller than 2.5 μm diameter, measured by mass) and PM_{10} (particles smaller than 10 μm diameter, measured by mass). $PM_{2.5}$ is contained within PM_{10}, the difference being made up of coarse particles, or $PM_{2.5–10}$. The major proportion of the $PM_{2.5}$ and NO_2 concentration in the UK atmosphere is not the result of direct (or primary) emissions to the atmosphere, but results from chemical reactions in the atmosphere, and is termed secondary, while ozone is entirely a secondary pollutant. Because of this, studies of emissions must take account of compounds that are precursors of these pollutants, as well as emissions of the pollutants themselves. In this context, emissions of sulphur dioxide, ammonia, volatile organic compounds (VOCs) and nitric oxide (NO, which together with NO_2 is part of NO_X) are important.

1.2.2 The outdoor environment

Emissions of these pollutants in the UK between 1970 and 2022 are shown in Fig 1.1.[3] This shows a steady reduction in UK emissions for all pollutants other than ammonia, for which progress has been painfully slow.

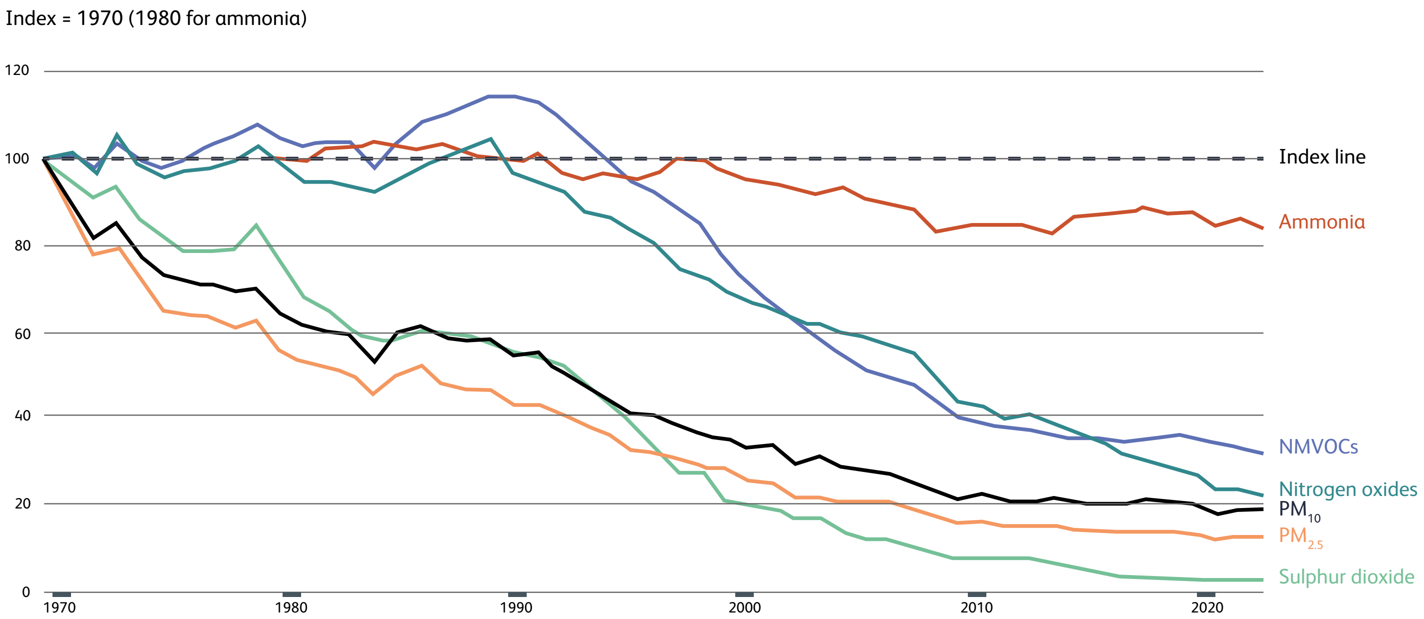


Fig 1.1. Trends in annual UK emissions of particulate matter (PM_{10} and $PM_{2.5}$), nitrogen oxides, ammonia, non-methane volatile organic compounds and sulphur dioxide, 1970–2022 (1980–2022 for ammonia).[3] Contains public sector information licensed under the Open Government Licence v3.0.

Both the height and distance from a source are important in determining airborne concentrations, since pollutants become more dilute as the wind carries them away from their source. Hence, while emissions from a tall industrial chimney will far exceed those from a domestic chimney, a person close to the domestic chimney is likely to receive a far greater exposure from this source. Traffic pollutants close to a busy highway are highly elevated but decline to very low concentrations within about 100 m of a road in open country.

Airborne concentrations have not necessarily improved as fast as emissions. There are two main reasons for this. Firstly, the UK imports and exports air pollution and thus we are affected by changes in other countries. Fortunately, Europe has legal requirements which try to ensure that all countries are adopting similar steps to reduce emissions. More important for secondary pollutants is that the relationship between the emissions of precursors and the secondary constituent may not be proportional (referred to as non-linear), and the concentration of nitrate in air, for example, is not falling as rapidly as emissions of precursor NO_x. As nitrate is a major component of $PM_{2.5}$, this is partially responsible for a rather slow decline in $PM_{2.5}$ concentrations in recent years. Ozone is wholly secondary, and its concentrations are determined by a complex inter-relationship between NO_x, VOCs, sunshine, and loss by deposition to the ground surface. Third, and generally less significant, is that weather conditions also affect airborne concentrations, and a systematic change in the weather over time is likely to lead to a change in pollutant concentrations, even if emissions remain constant. Climate change will worsen air quality by increasing the frequency of wildfires and heatwaves, which release pollutants, and by shifting precipitation patterns, leading to more frequent and intense droughts and floods, which can increase dust and pollutants in the air.

As well as being formed by chemical reactions, pollutants are also removed from the atmosphere by chemical processes, and airborne particles undergo both chemical changes and physical transformations that can change their sizes. Airborne particulate matter is the pollutant affecting public health the most, and one that can readily undergo transformations, both in its formation and during its atmospheric existence.[4] Particles in the $PM_{2.5}$ size range are mostly capable of remaining airborne from a week to as long as a month, so have plenty of time to change. The major component chemical composition varies quite modestly between the cities of London, Beijing and Delhi (Fig 1.2), despite widely varying sources and airborne concentrations.

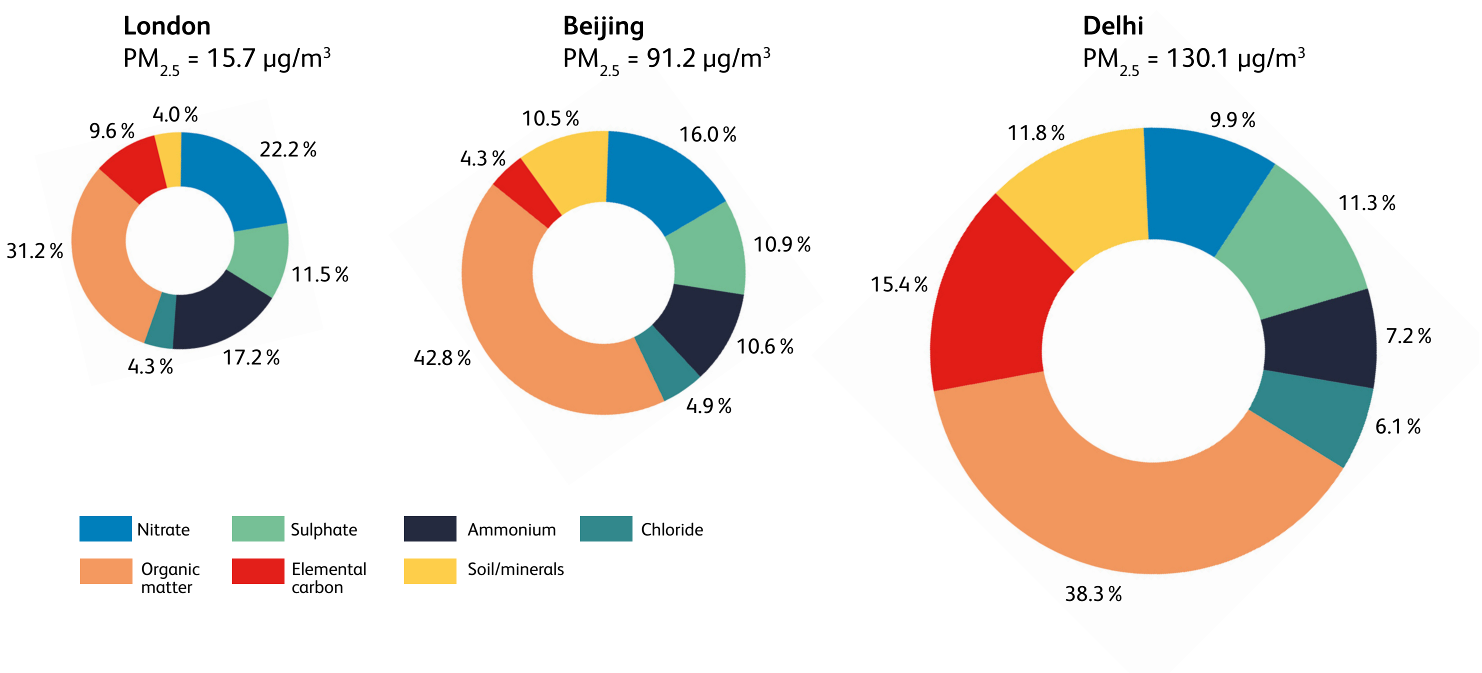


Fig 1.2. Major component composition of $PM_{2.5}$ sampled during winter campaigns in London, Beijing and Delhi. Adapted from Harrison (2020).[5]

Among the major components are typically secondary ammonium sulphate and nitrate, arising from oxidation of SO_2 and NO_x respectively in the atmosphere, followed by neutralisation by ammonia, which in the UK arises primarily from breakdown of animal waste. The SO_2 arises mainly from combustion of sulphur-containing fossil fuels, such as coal and oil, and has reduced hugely in previous decades due to the emission control and subsequent closure of coal-fired power stations, and desulphurisation of motor fuels. NO_x comes from all high-temperature combustion processes, with automotive diesels playing a major role, especially in the urban atmosphere, and its emissions have not fallen as quickly as those of SO_2. Another large contributor to airborne particles is organic matter (organic carbon), which may arise from oxidation of VOCs, or from primary emissions from sources such as diesel vehicles and wood burning. While the diesel source has declined substantially due to the requirement for diesel particle filters to be fitted to new cars, the wood-burning source has been increasing in the UK due to recreational burning of wood in the home, and a perception of wood burning as a low-cost heating option. Diesel particle filters have not only reduced emissions of organic carbon; they have also reduced emissions of particles rich in elemental (black) carbon, and concentrations of this pollutant have consequently declined appreciably in recent years.

Ozone is unusual in being a wholly secondary pollutant and behaves very differently from other pollutants in the UK atmosphere.[6] It has a high concentration in the north Atlantic atmosphere (probably double that in pre-industrial times) and, in most circumstances, reduces in concentration as air masses transit across the UK, due to uptake on ground surfaces and chemical reaction with NO from combustion sources. As a consequence of the latter process, ozone concentrations are typically lower in cities than in the surrounding rural areas, and lower still close to road traffic. Easterly air masses, especially during summer anticyclonic conditions, can bring high concentrations of ozone from mainland Europe to the UK for short periods.

1.2.3 The indoor environment

Surveys of personal activity show that most people spend 80–90% of their time indoors, hence indoor air is an important source of air pollutant exposure.[7]

Some indoor air pollutants arise substantially by infiltration from outdoors, but for others, indoor sources are important. For example, cooking is a major source of airborne particles, and un-flued heaters and gas cookers can be a major source of NO_x in the indoor atmosphere. For some pollutants, indoor sources can be predominant. This is frequently the case for some VOCs, released from building materials (eg formaldehyde) and many furnishings (eg toluene and xylenes), and biological particles such as bacteria and spores, including important aeroallergens which can exacerbate respiratory disease. Carbon monoxide from inefficient combustion appliances and carbon dioxide, largely from human respiration in crowded environments, can also be a health risk. The balance between indoor and outdoor sources is dependent upon ventilation levels, and the modern trend towards more tightly sealed buildings leads to a greater impact of indoor sources of pollution.

The indoor environment has a much larger surface-to-volume ratio compared with outdoors. This leads to higher rates of pollutant loss to surfaces, and a greater potential for chemical reactions on surfaces, which can be an important source of some chemicals such as nitrous acid. For most pollutants, the high indoor loss rates lead to lower concentrations than outdoors in the absence of indoor source emissions. Surfaces can also act as a reservoir for semi-volatile compounds, such as many components of tobacco smoke, which can adsorb onto surfaces, and then be released slowly over subsequent days. Since personal activities (cooking, smoking etc) strongly influence indoor sources, there is greater variability between indoor than outdoor environments, which tend to be more homogeneous. Even within the home, there can be strong gradients in concentration between different parts of the house, caused by localised pollutant releases. There is less scope for photochemistry due to the lower indoor light levels, but this is not entirely absent and can act as both a source and a sink of pollutants indoors.

1.3 New insights from air pollution epidemiology

1.3.1 Advances and understanding

Air pollution epidemiology has been critical in identifying associations between air pollution and health, and in quantifying the impact. Over the years, our ability to understand how air pollution affects our health has significantly improved, with enhancements in air pollution exposure methodologies, innovative data linkage and statistical techniques. These improvements have advanced our understanding of, among others, the concentrations at which effects occur and the latency periods between exposure and health effects.

1.3.2 Effects from low levels of air pollution

Although it is regularly noted that emissions of air pollution have reduced significantly over the past 100, 50 and even 10 years, advances in exposure assessment, modelling and health studies are showing that current lower levels of air pollution continue to affect our health. The evidence has been sufficient for the World Health Organization to revise its air quality guidelines in 2021.[8]

The United States (US) Environmental Protection Agency has also strengthened the National Ambient Air Quality Standard for $PM_{2.5}$.[9] Evidence contributing to this change included that from studies funded by the US Health Effects Institute in the USA, Canada and Europe, which used cutting-edge epidemiological approaches to better understand the relationship between long-term exposures to pollutants and effects on mortality and morbidity.

Of these, the ELAPSE study of European cohorts used fine spatial modelling of just 100 m × 100 m in 11 European countries and found an increased risk for mortality, even at the lowest observed concentrations for $PM_{2.5}$, black carbon and NO_2.[10] The US study used a large national health cohort (68.5 million Americans), high-resolution annual mean exposures and novel modelling approaches, and showed that mortality is associated with long-term concentrations below the annual US National Ambient Air Quality Standard for $PM_{2.5}$ at the time (12 μg/m^3).[11] Based on evidence such as this, in February 2024 the US Environmental Protection Agency strengthened[9] the annual standard to 9 μg/m^3.

There are challenges in measuring pollutants at low levels, but continuous improvements in methodologies and use of personal exposure measurements are also helping to improve assessments, and further demonstrate health effects from exposure to air pollution at much lower levels than previously thought possible. While thresholds at which effects occur will vary between individuals, the consensus is that there is no evidence of a threshold below which no effects are expected to occur at a population level, and so further reductions in air pollution will continue to have a public health benefit.

1.3.3 Delayed effects from exposure to air pollution

Cohort studies following large groups of people over extended periods (10–15 years) have shown associations between long-term air pollution and mortality and morbidity. However, since the RCP's 2016 report,[2] studies have been published that have much longer follow-ups (over 25 years) of people. These show how exposure from decades ago influences morbidity and mortality throughout life.

A study comparing early life exposures to the 1952 smog in London with other cities in the UK found that almost 20% of children *in utero* or under 1 year old during the smog later developed asthma, compared with 11% in other cities.[12] A 2016 study using population data from the Office for National Statistics (ONS) longitudinal cohort study in England and Wales found mortality risks associated with exposures from the previous decade, but also that exposure to black smoke (approximating to $PM_{2.5}$) in the 1970s was linked to all-cause, cardiovascular and respiratory mortality in 2002–9.[13] Furthermore, a Scottish study considered exposure and effect over a 75-year period and noted that higher early-life $PM_{2.5}$ exposure increased risk of all-cause mortality and lung cancer mortality in late adulthood.[14]

We also know that short-term elevations in air pollution, known as episodes, can increase morbidity, particularly from respiratory and cardiovascular effects, increasing hospital admissions and mortality within hours or days of the exposures. For example, for particulate matter, studies indicate that acute health effects occur after episodes that last at least 24 hours. For nitrogen dioxide, effects in people with asthma have been shown within an hour of exposure.[15]

However, current thinking around timing of effects continues to develop, as the evidence suggests that even acute effects such as asthma attacks might not occur immediately, but in the week following an episode. The UK Committee on the Medical Effects of Air Pollutants (COMEAP) has found evidence that there are persistent effects extending beyond 24 hours post-exposure (up to at least 5 days) for a range of cardiovascular endpoints. For respiratory diseases, morbidity effects have been reported up to 1 week or more after exposure. This is important to consider when we develop advice for the public, particularly susceptible groups such as those with pre-existing disease.[16]

1.4 Health impacts of air pollution in the UK

The latest published estimates of the mortality burden of air pollution in the UK are equivalent to a range of 29,000–43,000 deaths per year[1a] for $PM_{2.5}$ and NO_2 combined, giving a central estimate of around 36,000 deaths based on pollution levels in 2019. Reductions in pollutant levels since 2019 (Fig 1.3) will have reduced impacts further, perhaps towards a central estimate of around 30,000 deaths per year. This is a welcome reduction from the 40,000 estimated in the 2016 RCP report,[2] but still a large impact on population health. Ozone levels have in contrast risen, linked at least in part to the reduction in NO_2 levels.

Research by expert groups in the UK[18] (COMEAP, reporting to the Department of Health and Social Care and the Department for Environment, Food & Rural Affairs), and internationally through the World Health Organization (WHO),[19] provides detailed reviews of the large literature on air pollution epidemiology that has amassed over recent decades and recommends response functions for a variety of health effects. These views have been synthesised in a recent study led by the Environmental Research Group at Imperial College London.[20,21] Table 1.1 shows estimated impacts covering the UK in the years 2019 and 2040 under a 'business as usual' scenario that follows emission controls under current legislation. Impacts are quantified for most effects for concentrations in excess of the WHO Global Air Quality Guidelines (5 μg/m^3 for $PM_{2.5}$, 10 μg/m^3 for NO_2 and 60 μg/m^3 for ozone). For mortality associated with $PM_{2.5}$, impacts are quantified against total exposure, as there is growing evidence for effects below the WHO guideline.

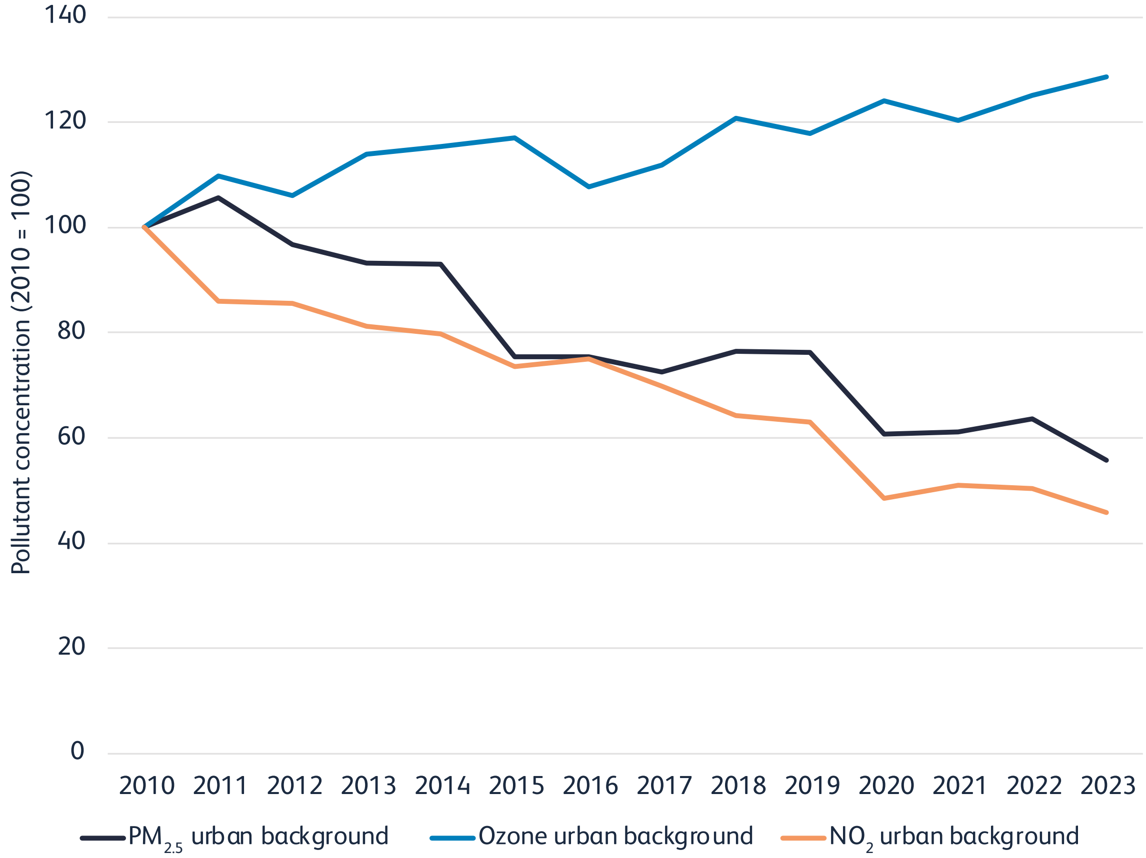


Fig 1.3. Pollutant concentration trends at urban background sites in the UK, 2010–23.[17] Contains public sector information licensed under the Open Government Licence v3.0.

Table 1.1. Estimated annual impacts as change in life years lost for mortality and change in incidence for morbidity for exposure to air pollutants in excess of the WHO guidelines. Data adapted from studies by Walton *et al* and Beevers *et al*.[20,21]

Pollutant	Effect (new cases unless otherwise noted)	Age group	Impacts in 2019	Impacts in 2040
Core effects*				
$PM_{2.5}$†	Mortality (as life years lost)	Over 30 years	413,000	331,000
$PM_{2.5}$	Acute myocardial infarction	Over 30 years	4,410	2,140
NO_2	Asthma (adults)	Over 19 years	5,740	1,350
$PM_{2.5}$	Asthma (children)	0–18 years	9,750	4,890
NO_2	Cardiovascular hospital admissions	All ages	3,040	710
$PM_{2.5}$	Chronic obstructive pulmonary disease (COPD)	Over 30 years	11,300	5,390
$PM_{2.5}$	Lung cancer	Over 30 years	3,010	1,830
NO_2	Respiratory hospital admissions	All ages	4,100	950
O_3	Respiratory hospital admissions	All ages	49,100	49,500
$PM_{2.5}$	Stroke	Over 30 years	5,940	2,860
Sensitivity effects*				
NO_2	Acute lower respiratory infections	0–12 years	95,100	22,600
O_3	Cardiovascular hospital admissions	All ages	4,680	4,720
$PM_{2.5}$	Dementia	Over 60 years	39,900	19,300
$PM_{2.5}$	Diabetes	Over 30 years	18,500	8,620
$PM_{2.5}$	School absences (days)	5–12 years	315,000	154,000

*Core effects in the table are those considered quantifiable with the highest confidence. Sensitivity effects are those quantifiable with lower confidence, but still based on the results of high-quality epidemiological research and systematic reviews.

The effects shown in Table 1.1 are likely to be conservative, given that they largely do not include exposure to concentrations below WHO guidelines and take steps to exclude effects with possible overlapping or double counting. Many effects with emerging data are not included.

1.4.1 Impacts of short-term changes in air pollution

The information provided above shows links between long-term exposure to air pollution and chronic health conditions. Research has also established links between short-term exposure and a variety of health and other effects. These include:

- cardiovascular and respiratory hospital admissions (reviewed by COMEAP)[23]
- acute bronchitis in children[24]
- asthma episodes[25]
- days of restricted activity, including attendance at both school and work (reviewed by Orellano *et al*)[26]
- times for marathon runners,[27] leading to slower times for men by 32 seconds and for women by 25 seconds per 1 μg/m³ change in $PM_{2.5}$ concentrations, aggregating to slower times overall by a few minutes at typical ambient $PM_{2.5}$ concentrations
- decision making by chess players,[28] for whom a 10 μg/m³ change in $PM_{2.5}$ concentrations caused a 26% increase in erroneous moves
- decision making by baseball umpires,[29] for whom a 10 μg/m³ change in $PM_{2.5}$ concentrations caused a 2.6% increase in incorrect calls.

The analysis of marathon runners, chess players and baseball umpires demonstrates the impacts of day-to-day changes in exposure on individuals who would not be thought of as belonging to vulnerable groups.

1.5 Health impacts through the lifecourse

The following sections describe how air pollution affects health throughout the lifecourse, from before conception to death. Numerous impacts have been identified, including birth outcomes (eg pre-term birth and low birth weight), impacts on children (lung health and asthma, risk of obesity, brain health and development etc) and impacts on adults via the respiratory, cardiovascular, metabolic and other systems. The range of impacts identified is supported by recent research in Denmark,[30] which found an association between both $PM_{2.5}$ and NO_2 pollution and more than 700 health conditions. Information from epidemiological studies enables the incremental contribution of air pollution to be assessed for some effects, for example mortality, ischaemic heart disease, COPD, dementia, asthma and lung cancer.[20]

1.6 From conception to birth

The health impacts of air pollution on pregnant women and unborn children are felt at numerous stages in the journey from before conception to birth and beyond (Fig 1.4).

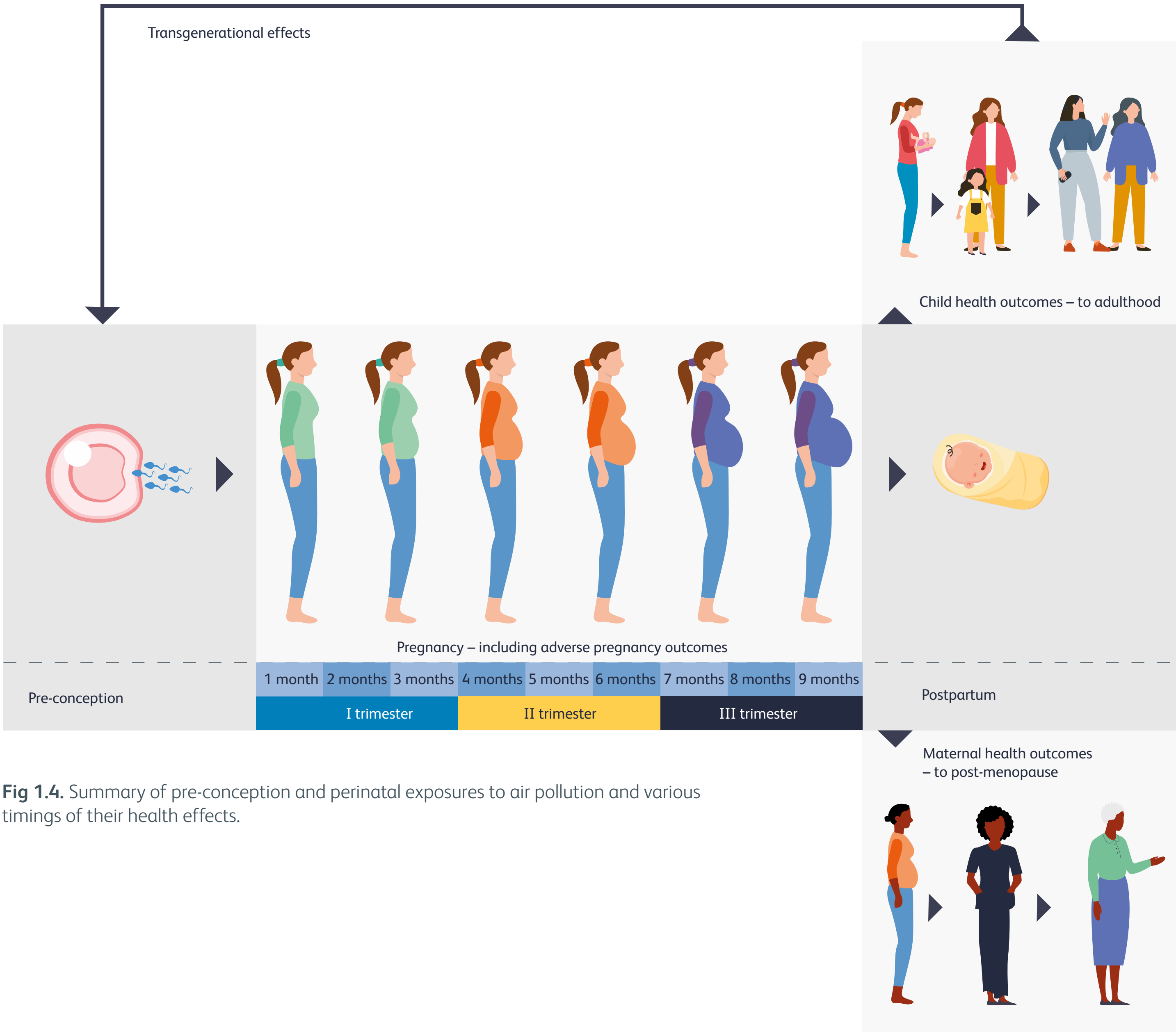


Fig 1.4. Summary of pre-conception and perinatal exposures to air pollution and various timings of their health effects.

1.6.1 Prior to conception

While pregnancy itself is a much-studied critical period for the effects of air pollution and other environmental factors on mother and child, maternal and paternal pre-conception effects also contribute. Infertility rates are increasing globally, with both active decision making about personal childbearing choices and biological impediments to conception having a role. Air pollution is one such biological impediment, contributing to declining human fecundity. Measured as expected time to pregnancy and 12-month infertility rate, exposure to ambient fine particles is estimated to account for 2.25% of all couples affected by infertility – some 660,000 couples worldwide.[31] How air pollution affects fertility remains unknown, but effects on male and female infertility are clear.

Sexually mature males produce sperm daily and air pollution negatively affects sperm quantity and quality, meaning reduced sperm concentration and total count and decreased total and/or progressive motility,[32] all of which affect fertility. Air pollution exposures also alter sperm DNA, affecting the expression of genes in the placenta and umbilical cord blood of the baby that are, for example, involved in neurodevelopment and associated with health outcomes for the child.[33]

In contrast to daily sperm production in sexually mature males, females are born with a full complement of oocytes generated during fetal development. Once puberty begins, an oocyte matures into an egg within an ovarian follicle and is released as part of each menstrual cycle. A study of leftover ovarian follicular fluid collected during egg harvest from women undergoing *in vitro* fertilisation (IVF) revealed ambient black carbon particles in all 20 samples, while the five samples of ovarian tissue collected during another study also all contained these particles.[34] This means that air pollution reaches the ovary, with such exposures shown to negatively affect oocyte quality, ovulation and thereby fertility by disrupting metabolism and hormone synthesis.[35]

1.6.2 Pregnancy outcomes

A wide variety of adverse pregnancy outcomes (APOs) have now been attributed to maternal air pollution exposures. The most frequently and consistently reported adverse effects of air pollution exposures in pregnancy are pre-term birth (PTB; birth before 37 weeks of gestation) and low birth weight (LBW). These have been described in many countries and in association with different particulate and gaseous components of air pollution. A meta-regression analysis across 204 countries and territories focusing on ambient and household $PM_{2.5}$ attributed nearly 16% of LBW babies (around 2.7 million babies) and 36% of all pre-term babies (around 5.8 million babies) each year globally to total $PM_{2.5}$.[36] PTB and LBW underpin a huge global health burden, with around 13 million years lost to disability attributed to PTB of all causes.[37] Effects of PTB and LBW are wide-ranging, from immediate effects on the baby including the gastrointestinal and respiratory tracts and the central nervous system, to longer-term neurodevelopmental effects that include behavioural, motor and visual impacts. PTB is a one of the main risk factors for mortality in children aged <5 years and PTB rates appear to be worsening.[38]

Increasingly, air pollution exposures prior to and during pregnancy are associated negatively with other APOs. While air pollution has not been linked to stillbirths, at least in the UK,[39] the risk of missed abortion or incomplete miscarriage becomes more severe as pollutant concentrations increase,[40] and PM_{10} exposures across the course of pregnancy are associated with an 11% increase in pre-eclampsia.[41] Concerns have also been raised about the effects of air pollution exposure prior to and during pregnancy on maternal mental health.[42]

1.6.3 Fetal programming and implications for child health

The effects of prenatal air pollution exposures extend beyond APOs to long-term health outcomes for the child. Maternal environmental exposures are well recognised to affect fetal development and the long-term function of multiple tissues and organs, resulting in clinical symptoms and disease in childhood and/or adulthood. Initial studies focused on the effects of air pollution on childhood respiratory outcomes, such as wheezing and asthma, linked to prenatal exposures to NO_2, SO_2 and PM_{10}.[43] It is now recognised that maternal air pollution exposures during pregnancy are associated with a much broader range of child health impacts, including immune function, brain development and cardiometabolic health.[44] Prenatal air pollution exposures are linked to changes in immune cells in blood and tissue up to 6 months of age, with these changes underpinning the increased likelihood of developing allergic rhinitis and asthma at 6 years of age.[45] From a neurodevelopmental perspective, pregnancy and postnatal average exposures to $PM_{2.5}$ have been linked to autism spectrum disorder.[46] Pregnancy exposures to $PM_{2.5}$ are also associated with depression in adulthood and, alongside childhood exposures, with elevated odds of psychotic experiences.[47]

While numerous studies have sought to identify critical gestational windows for the adverse effects of prenatal air pollution exposures, there is no clear trimester of susceptibility. This likely reflects the different developmental trajectories of different organs. For example, cardiogenesis is completed in the first half of pregnancy, but maturation of the lungs is dependent on extrauterine exposures and so continues postnatally. Air pollution disproportionately impacts vulnerable populations, especially pregnant women and children, leading to a widening of health inequalities. These populations are often already at higher risk due to socio-economic factors such as poverty and limited access to healthcare, and exposure to poor air quality further exacerbates these vulnerabilities, affecting fetal and child development.

1.6.4 Pregnancy exposures and long-term health of women

While the lifelong impacts of the pregnancy environment on offspring have been recognised for decades, it is only recently that long-term health effects for the mother have been recognised. APOs, such as the development of various hypertensive disorders of pregnancy that increase with air pollution exposures,[41,48] are included increasingly in cardiovascular disease risk assessments for women. Such APOs – alongside gestational diabetes and cardiovascular events in labour that are also linked to maternal air pollution exposures – have been associated with later cardiovascular and cardiometabolic disease, such as type 2 diabetes.[48] Air pollution exposures might provide additional physiological stress during pregnancy that exacerbates latent risk factors or causes new dysregulation of normal adaptive responses within various tissues. These will interact with ongoing longer-term air pollution exposures known to increase the risk of cardiovascular events in women.[49]

1.6.5 Biological mechanisms of perinatal air pollution exposures and health outcomes

Much of the evidence for the short- and long-term effects of maternal air pollution exposures on pregnancy outcomes and the ongoing health of the child are from epidemiological studies in various populations worldwide. These adverse effects relate to functional effects on the placenta and developing fetal organs. This might include translocation of particles, especially ultrafine particles, across the air–tissue barrier of the lungs for distribution via the mother's circulation to and across the placenta. This could also be via the release of mediators from the airways in response to particulates and gaseous and chemical air pollutants that then act on the placenta and fetal organs (Fig 1.5).

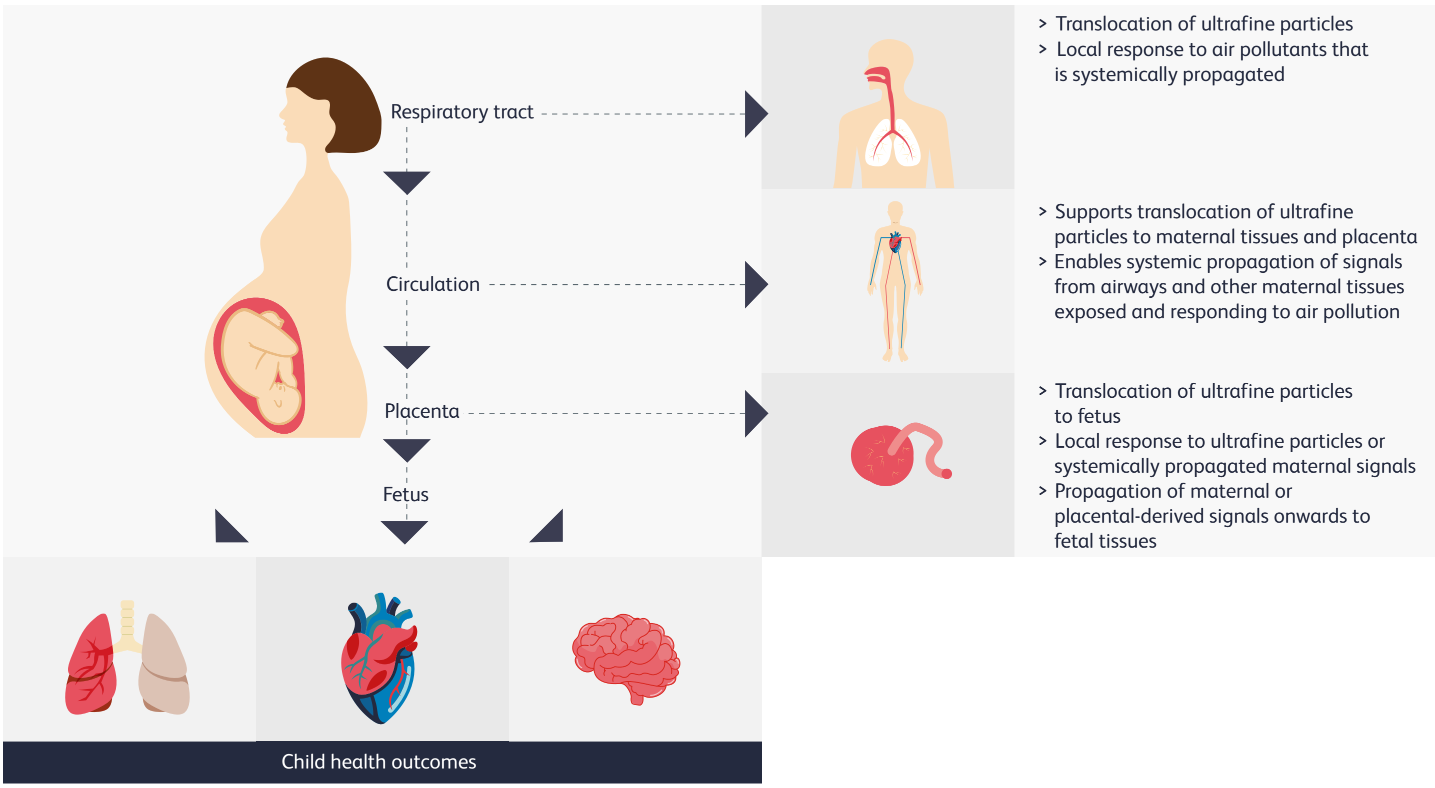


Fig 1.5. Summary of pathways from transmission of maternal air pollution exposures and responses during pregnancy and effects on placental, fetal and child health.

Black nanosized carbon particles with composition and appearance consistent with traffic sources (friction and fossil fuel combustion) have been found in the human term and pre-term placenta.[50,51] In the placenta, while carbon particles can be taken up by certain cells like maternal endothelial cells, the primary function of the placenta is not to transport carbon but to facilitate gas exchange between the mother and fetus. Fine carbon particles are also detectable in both the maternal and fetal (umbilical cord blood) circulation, and there is evidence of transmission to fetal tissues including lungs, brain and liver.[52] A positive correlation with maternal residential load[50] highlights that the burden in placenta and fetal tissues will be greatest where air pollution burden is greatest. Black carbon particles have also been found in breast milk, with all samples studied containing black carbon particles at levels that correlated positively with maternal residential exposure.[53] Metals have also been found in breast milk and infant formula[54] and metal-based nanosized pollutants also penetrate the amniotic fluid,[55] so that the fetal skin, airways (via aspiration of amniotic fluid) and gastrointestinal tract (via swallowing of amniotic fluid) will be exposed to these contaminants. This means that the developing fetus and newborn are exposed directly to various air pollutants.

The mechanisms of effect of air pollution exposures within the fetoplacental unit are likely to be similar to those at other tissue sites. These relate to oxidative stress and inflammation and a multitude of downstream effects, from DNA damage to mitochondrial dysfunction and epigenetic changes. In pregnancy, these are centred on the placenta, where unfavourable maternal environmental exposures manifest as altered function of the placenta, with detrimental effects on the growth and health of the fetus. There are now many studies reporting changes in measures of the biological effects of pollutants on the placenta, in relation to either maternal air pollution exposure and/or later health outcomes for the child. Most studies of the relationship between air pollution and pregnancy and child health outcomes are of ambient air pollution, although indoor household air pollution is now being considered.[36] Irrespective of the source of the polluting particles, gases or chemicals, the biological and thereby functional effects on the placenta and fetal tissues are likely to be broadly the same. There is also evidence that these detrimental effects on the placenta occur even when, for example, maternal $PM_{2.5}$ exposures during the pre-conception period and throughout pregnancy are relatively low.[56]

Various pregnancy and child health outcomes from common air pollution exposures are explained by differential effects on the expression of genes that contribute to the function and development of specific cells and tissues.[57] These effects on gene expression also contribute to the reported transgenerational effects of air pollution exposures, including effects on neurodevelopment and neurobehavioural disorders transmitted across the generations.[58]

1.7 Through childhood and adolescence

1.7.1 Childhood as a time of vulnerability

Childhood and adolescence are a time of marked vulnerability due to the development of key protective systems. It is also a key time for flexibility and change within the immune system and plasticity of the brain. This means that adverse exposures during childhood and adolescence can have significant and long-term impacts on health. Indeed, there is a strong link between deprivation and both worse health outcomes in children and poor air quality, which can exacerbate existing inequalities. Deprived areas tend to have higher concentrations of air pollution with residents more likely to experience poor health outcomes thereby adding to the inequalities caused by deprivation. More positively, recent evidence has also shown that interventions to remove or reverse the impact are also possible.

Since the RCP's 2016 report,[2] there has been increasing evidence on the mechanisms that happen at key times in life and also that these mechanisms now cross and work in some way across multiple body systems. For example, the innate vulnerabilities of developing bodies and systems result in longer exposures, greater exposures, an inability to respond to exposures (such as clearance of toxins) as effectively, and the body's possible over-reaction to exposures (such as that by the immune system). All of these factors lead to the risk of developing direct exposure-related conditions and also the body altering its way of dealing with toxins and pollutants.

1.7.2 Respiratory health in children

The respiratory system has the most direct contact with pollutants, making the journey of exposure easier to define from a mechanistic perspective.

Direct inhalation takes the pollutants into the lungs and potentially into the systemic blood supply. Key mechanisms in childhood include inflammation and oxidative stress, alongside direct impacts on lung function development, resulting in the development of long-term chronic respiratory illness such as asthma and wheezing in childhood, and COPD and fibrosis later in life.[59–61] The London Low Emission Zone (LEZ) study quantified the potential risk to lung volumes, demonstrating a loss in forced vital capacity (FVC) of between 4.8 and 5.3% (89–99.6 mL) over a 5-year period due to NO_2 exposure.[62] The Children's Health study cohort in California provided evidence of both the negative impact on lung function, but also the potential to turn this around if improvements are made in pollution levels. Over the period of the study, NO_2 levels reduced by 33% and the percentage of children with clinically low lung function (FEV_1 <80%) reduced from 7.9% to 3.6%.[59] Garcia *et al* showed that both NO_2 and particulate matter exposure in childhood correlated with the bronchitic symptoms reported in 25% of the cohort on review in adulthood.[63]

Evidence that exposure to traffic-related air pollution is a cause of asthma has greatly strengthened since 2016. In 2019, Achakulwisut and colleagues estimated that, globally, 4 million (95% uncertainty interval, 1.8–5.2 million) new asthma cases in children are attributable to traffic-derived NO_2 pollution per year – with 64% of these cases in urban centres.[64] There is also emerging evidence that short-term exposure to pollution is associated not only with worsening asthma symptoms, but also with asthma deaths. A 2023 case-crossover study of asthma deaths of children in North Carolina found that the odds of a fatal exacerbation of asthma in the highest-exposed tertile were more than twice those in the lowest tertile of $PM_{2.5}$ exposure over the previous 3–5 days.[65]

Normal lung function (how much air one can forcibly breathe out, and how quickly) has been increasingly regarded as an important indicator of lung health. Lung function in absolute terms increases as children grow (lung function growth), and studies by Melén and colleagues concluded that environmental factors that reduce lung function during childhood are associated with poorer health outcomes throughout the lifecourse.[66] Since the RCP's 2016 report,[2] evidence that long-term exposure to outdoor air pollution suppresses lung function potential during childhood continues to strengthen, such as recent data from a Dutch birth cohort.[67] The most convincing data to support that air pollution directly suppresses lung function and that decreasing pollution improves lung function are from a Swedish birth cohort, which measured lung function repeatedly during childhood.[68] During the period of the cohort, air pollution levels at participants' home addresses decreased progressively, and this reduction resulted in an increase in lung function. These, and similar data from the southern California study,[61] strongly suggest that the association between increased exposure to air pollution and reduced lung function growth is causal. How exactly air pollution impairs lung function growth is unclear; one potential explanation is that inhaled particulate matter retained within lung tissue (Fig 1.6) chronically disturbs lung cell function.

The respiratory impacts of air pollution on children are also closely linked to the impacts on the immune system. With a developing immune system, all exposures to external stimuli have significant impacts. Zhou *et al* demonstrated the increase in incidence of chronic upper respiratory infections, which is likely due to disruption of the normal development of the immune system alongside genetic factors.[69] There is alteration to the normal T-cell pathway, increasing the risk of allergies and asthma.[70]

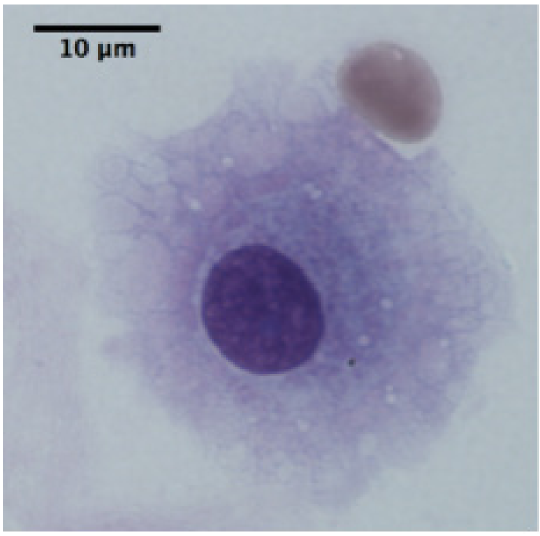


Fig 1.6. Carbonaceous particulate matter (the black spot) in a human placental phagocytic cell. Image courtesy of Professor Jonathan Grigg on behalf of Dr Norrice Liu.

1.7.3 Brain health and development in children

More evidence is emerging that links air pollution to impacts on the brain and development. During childhood, the brain is highly sensitive to environmental insults (including pollutants), due to it undergoing rapid growth and development. Key developmental processes such as neuronal differentiation, synaptogenesis and myelination are occurring, making the brain more vulnerable to disruptions. The blood–brain barrier is not yet fully developed, which allows more pollutants to cross into the brain, leading to neuroinflammation and oxidative stress. Developing brains are not as good at detoxification or repair as mature brains, which can lead to toxin accumulation and longer exposure to pollutants. Increased exposures make developing brains more susceptible to oxidative stress and neuroinflammation. Developing neurons are particularly sensitive to oxidative damage, which can impair neurodevelopment and increase the risk of neurodegenerative diseases later in life. Pollutants can also trigger inflammatory responses in the brain. Since the developing brain has a different immune response profile from the mature brain, it may be more susceptible to inflammation caused by pollutants, which can disrupt normal brain development and function.[71]

Air pollution can cause epigenetic changes such as DNA methylation and histone modification, which can affect gene expression and brain development.[72] These changes can have long-lasting effects on neurological function and increase susceptibility to neurological disorders such as Alzheimer's disease. Early sustained exposure to particulate matter, and in particular ultrafine particulate matter, in childhood has been found to be a significant risk factor for developing both Alzheimer's and Parkinson's diseases later in life.[73]

Impacts within childhood include risk of neurodevelopmental disorders such as autism spectrum disorder (ASD) and attention deficit hyperactivity disorder (ADHD), and other cognitive and behavioural disorders later in life.[74] Studies have shown that children exposed to high levels of air pollution may exhibit behavioural issues such as increased aggression, anxiety and depression, with longitudinal data from the ALSPAC (Avon Longitudinal Study of Parents and Children) cohort showing increased risk of some psychiatric disorders in adolescence and beyond. $PM_{2.5}$ levels during pregnancy and during childhood were associated with elevated odds for psychotic experiences ((adjusted odds ratio (AOR), 1.11 (95% confidence interval (CI), 1.04–1.19); *P* = 0.002) and AOR, 1.09 (95% CI, 1.00–1.10); *P* = 0.04). There was also an association between pregnancy $PM_{2.5}$ exposure and depression (AOR, 1.10 (95% CI, 1.02–1.18)).[47]

1.7.4 Obesity and skin

Newer evidence has emerged from combining the cohort studies that have been done across Europe, such as HELIX, which has provided exposome data (environmental exposures that an individual encounters throughout life) from multiple cohort studies and strengthened the mechanistic information that we have. They demonstrated that the risk of obesity is increased by both prenatal (or maternal) exposure and early childhood exposures.[75]

A final key area of exposure and vulnerability in childhood and adolescence is seen within the largest organ in the body: the skin. There is now a large body of evidence regarding the impact that pollutants are having. A key mechanism is that of oxidative stress and inflammation alongside interruption of the key function of the skin as a barrier.[76] Air pollution exposure is a risk for atopic dermatitis and eczema in children, which in turn will damage skin as a barrier for later life and leave those affected at risk of increased infections.[77,78]

1.7.5 Air pollution and lifecourse health trajectories

As outlined, the impacts of air pollution exposure on children are multiple. However, more impactful than these is the impact on the trajectory for health. This is most obviously seen within lung function. We now know that everyone has a predictable trajectory for their lung growth, and this is set by genetic predisposition. It is possible at age 6 to predict the likely lung growth of that individual in adulthood (much like we can often predict height, based on centiles). Any early life insult, such as pollution exposure or severe infection, would send an individual off their predicted line to a lower one, as demonstrated in a report by Melén *et al*.[66] It is likely that this concept of a predictable trajectory can be applied to many different aspects of health and disease, and so limiting exposure to preventable insults by reducing pollution exposure would in turn improve the adult health of today's children and reduce inequalities.

1.8 Impacts on organ systems in adulthood

For a long time, it was thought that air pollution health impacts in adults occurred mainly through respiratory health. We now know that the impacts are far wider.

In the early 1990s, observations began to emerge that air pollution was causing hospitalisation and deaths from cardiorespiratory disease – not just from respiratory conditions, but from those of the cardiovascular system as well. The realisation that air pollution could have effects on organs beyond the lung (termed 'systemic effects') was a turning point in air pollution research, and in recent years scientists have found links between air pollution and almost every organ system in the body, and the major diseases that affect them (Table 1.2). A number of biological mechanisms account for how inhaled air pollutants can exert effects on systemic organs (Box 1.1).

Table 1.2. Overview of ways in which air pollution affects our bodies, grouped by organ system. Several key aspects are highlighted here, and more details can be found in the review by Schraufnagel *et al*.[79]

	Impacts of air pollution
Lungs	Acute respiratory effects include reductions in lung function, pulmonary inflammation and exacerbation of respiratory conditions such as wheezing and asthma. Chronic exposure is associated with COPD and progression of emphysema.
Cardiovascular system	Acute effects include changes to heart rhythm, loss of blood vessels' ability to control blood flow, high blood pressure and an increased tendency for the blood to clot. Chronic exposure is linked to many cardiovascular conditions.
Metabolism	The incidence of diabetes continues to increase in the UK, most notably in terms of type 2 diabetes, for which obesity is a major risk factor. Air pollution has been linked to both metabolic syndrome (which has a number of risk factors for diabetes) and type 2 diabetes. There is also a suggestion that obesity may be a susceptibility factor for air pollution, ie air pollution has greater detrimental effects on the body in people with obesity than in those with a normal weight. Having diabetes increases the risk of developing other conditions such as heart and kidney disease, which are also exacerbated by air pollution.
Renal	Both short- and long-term exposure to air pollution can impair kidney function, through decreasing the rate by which blood is filtered by the kidney or an imbalance in the substances that pass into the urine. Long-term exposure to air pollution is linked to chronic kidney disease (CKD; a substantial loss of renal function characterised by damage to the kidney) and progression of the disease, leading to kidney failure. CKD is common (around 10% of people in the UK have CKD), with severe CKD linked to around 40,000 deaths in the UK. Thus, while the renal effects of air pollution are not fully established, the burden on health could be considerable.
Liver	Emerging evidence suggests that exposure to air pollution causes inflammation of the liver and leads to the release of markers of liver injury into the blood. Associations are also emerging with non-alcoholic fatty liver disease, the most common chronic liver disease in Western countries.
Gastrointestinal system	Air pollution is associated with changes to the microbiome of the gut, ulcers and gastritis, as well as inflammatory bowel disease and Crohn's disease.
Bone	Air pollution has been linked to a weakening of the bones through osteoporosis, which makes the bones more prone to fracture.
Skin	Long-term exposure to air pollution is linked to ageing of the skin and conditions linked to allergic processes (eg urticaria) and infection (eg acne).

Table continues...

Cancers	Chronic exposure to air pollution is associated with an increased risk of lung cancer, but also of cancers associated with other organ systems. Links have been found to liver carcinoma, gastric cancer, colorectal cancer, bladder cancer, breast cancer, prostate cancer, kidney cancer, leukaemia and others. Many air pollutants generate reactive oxygen free radicals that can damage DNA, which could be a cellular trigger for cancer. In addition, air pollution promotes tumours by triggering existing DNA mutations. In 2013, ambient air pollution and particulate matter were classified as group 1 carcinogens for lung cancer by the International Agency for Research on Cancer (IARC). It is therefore not surprising that associations continue to be reported for cancers, especially in the lung – the site of highest exposure. A recent study using longer-term Taiwan nationwide cancer registry data reported that the increase in annual ambient/background $PM_{2.5}$ concentrations since 1968 was associated with increase in annual age-adjusted lung cancer (adenocarcinoma) incidence, especially in women, non-smokers, people aged above 65 and those with EGFR mutation, a genetic mutation commonly found in non-smokers.[80] The mechanistic basis for this association has recently been proposed by Hill and colleagues,[81] who found a significant association between $PM_{2.5}$ concentrations and the incidence of lung cancer for 32,957 EGFR-driven lung cancer cases in four within-country cohorts. Modelling this association in the mouse suggests that it is the capacity of particulate matter to induce inflammation, rather than direct effects on DNA, that underlies this association.[81]
Susceptibility to infection	Although the RCP's 2016 report[2] did not highlight the effect of outdoor air pollution on susceptibility to infection, there is clear epidemiological and mechanistic evidence that air pollution increases infection risk. For example, a recent study from Andersen and colleagues followed COVID-19 outcomes in all Danish residents 30 years or older who resided in Denmark on 1 March 2020 until 26 April 2021, and found strong positive associations with COVID-19 incidence/deaths and long-term exposure to $PM_{2.5.}$[82] This association is supported by a mechanistic study which showed that exposure of airway cells to PM_{10} in the laboratory increases expression of the receptor used by SARS-CoV-2 to infect cells, and thereby increases susceptibility to infection.[83] For pneumonia, a study of 445,473 adults recruited to the UK Biobank by Wang and colleagues reported increased risk for each interquartile range increase in $PM_{2.5}$, PM_{10} and NO_2, especially in those who smoked.[84] For new-onset and repeated lower airway infections, Zhang and colleagues using data from 23,912 participants in the Danish Nurse Cohort reported that, over a 21-year follow-up period, there were strong associations between long-term exposure (3 years) to all three outdoor air pollutants.[85]

Box 1.1. Mechanisms underlying the systemic effects of air pollution

Various cellular mechanisms are involved in the changes to how organs function after exposure to air pollution, most notably the formation of reactive oxygen species (causing 'oxidative stress') and induction of inflammation. One of the more challenging mechanisms to determine is how air pollutants that are inhaled into the lung lead to a change in the biology of systemic organs. Several pathways have been proposed:[86]

Systemic inflammation: Immune cells in the lung mount an inflammatory response in an attempt to protect the lung against the pollutant. However, high or persistent exposure may result in an excessive inflammatory response that can damage tissues. Inflammatory mediators may spill over into the blood and be carried to other organs of the body, inducing an inflammatory response in those organs as well.

Neuroendocrine activation: Air pollutants can act on sensory receptors on the surface of the lungs, activating sensory nerves. The nervous system may then transmit these signals to the nerves that regulate the function of other organs. The central nervous system may also respond by regulating the release of hormones to the blood, which then influence the functions of distant organs.

Translocation: This refers to when an air pollutant (notably ultrafine particles or soluble chemicals released from particulate matter) itself passes from the lung into the blood. The pollutant may then be carried between organs and interfere directly with their function.

1.9 Impacts on the adult heart and cardiovascular system

1.9.1 Health burden

The cardiovascular effects of air pollution are especially concerning given the high prevalence of cardiovascular diseases worldwide, and that cardiovascular diseases are one of the major causes of mortality. Over 7.6 million people in the UK have heart and circulatory diseases, which are responsible for more than a quarter of all UK deaths: over 170,000 deaths per year – or one death every 3 minutes.[91]

In 2010, the American Heart Association published a statement[88] concluding that '$PM_{2.5}$ exposure is deemed a modifiable factor that contributes to cardiovascular morbidity and mortality', noting that 'because of the ubiquitous and involuntary nature of PM exposure, it may continuously enhance acute cardiovascular risk among millions of susceptible people worldwide in an often inconspicuous manner'.

Over the intervening years, the links between air pollution and cardiovascular disease have only strengthened. At a global level, cardiovascular causes account for more than half of all premature deaths linked to air pollution.

In 2018, the UK COMEAP found clear evidence that exposure to air pollutants, primarily $PM_{2.5}$, has adverse effects on a wide range of diseases of heart and blood vessels.[89] More recent publications include reports of an association between long-term exposure to $PM_{2.5}$ and a higher risk of stroke in a prospective study of 40,827 Chinese adults[90] and increased risk of myocardial infarction in 329,189 UK Biobank participants.[91]

WHO data from 2019[92] estimate that annual $PM_{2.5}$ is responsible for 1.9 million deaths from ischaemic heart disease and 900,000 from stroke[93] (while stroke can be considered a neurological condition due to its consequences on the brain, it is caused through either a rupture of, or a blood clot within, a blood vessel in or leading to the brain). Population-standardised cardiovascular mortality linked to air pollution is falling globally. However, these improvements are small, with only a 1.1% reduction between 2010 and 2019, and the overall numbers of cardiovascular deaths linked to $PM_{2.5}$ are increasing in line with the growing world population.[93] In the UK, ischaemic heart disease and stroke are estimated to account for ~11,200 and ~3,100 premature deaths from ambient air pollution, respectively.[92]

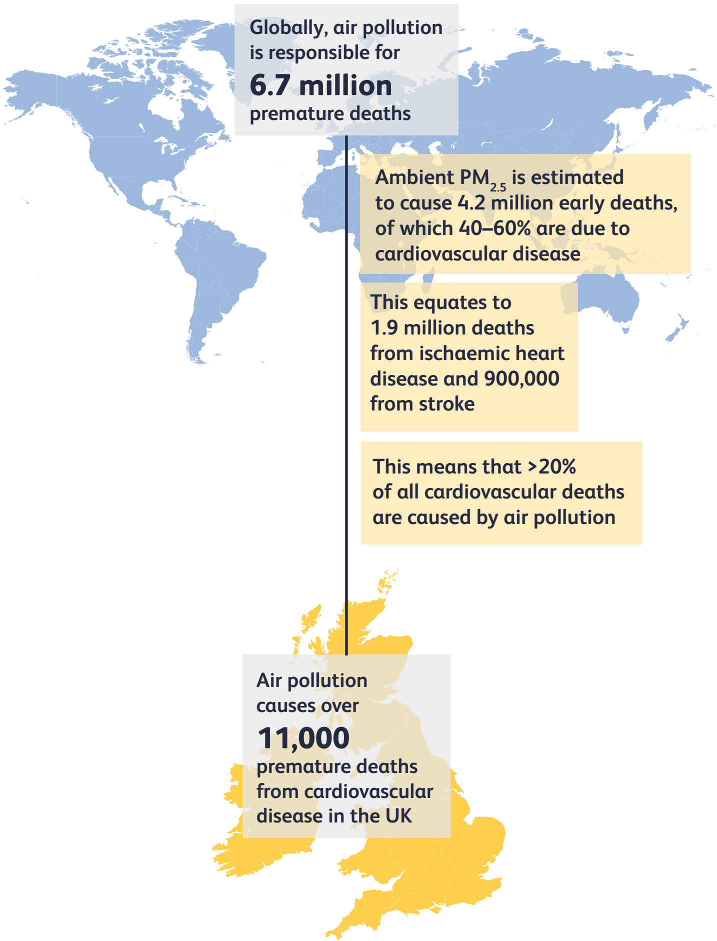


Fig 1.7. Summary of the cardiovascular effects of air pollution. Sources: British Heart Foundation,[87] World Heart Federation,[93] World Health Organization.[92]

The statistics in Fig 1.7 are undoubtedly huge underestimations for the true burden of cardiovascular disease linked to air pollution, as these estimates are largely based on the actions of a single air pollutant ($PM_{2.5}$) and just two causes of cardiovascular mortality. Meta-analyses have found robust associations between many air pollutants and all major cardiovascular conditions. Associations between air pollution and cardiovascular disease tend to be strongest for $PM_{2.5}$; however, gases such as NO_2, SO_2, O_3 and CO also have cardiovascular effects, especially with long-term exposure.[93,94]

1.9.2 How does air pollution affect our cardiovascular health?

The diversity of cardiovascular conditions caused by air pollution reflects the multiple ways that air pollution can impair cardiovascular function. This includes effects on the heart (eg changing heart rhythm and increasing the susceptibility of the heart to ischaemic damage), the blood vessels (eg altering the balance of vasoconstriction and vasodilation, increasing blood pressure, stiffening arteries) and the blood (eg increasing the propensity of the blood to clot, and limiting the breakdown of blood clots).[86] The weight of mechanistic evidence suggests that associations between air pollution and cardiovascular disease are causal.[89]

The acute effects of air pollution will also instigate and mediate chronic cardiovascular conditions; for example the vascular disease atherosclerosis, which underlies most cardiovascular conditions, develops over the course of many decades. Atherosclerosis is characterised by the build-up of fatty lesions on the inner surface of arteries, which grow into complex plaques, impeding the blood supply to downstream organs. The plaque may erode or rupture, causing a blood clot to form, which may occlude the artery, which can cause a heart attack if it occurs in a major coronary artery, or a stroke in the brain. Air pollutants have an array of mechanisms in their arsenal to exacerbate many stages of this disease; from oxidation of circulating fats that preferentially accumulate in the blood vessel to inflammation, accelerating all stages of plaque development, to increasing the thrombogenicity of the blood to promote occlusive clots. Ultrafine particles, like those found in diesel exhaust, have prominent cardiovascular effects, potentially due to translocation into the circulation and accumulation at sites of atherosclerosis.[95] Indeed, individuals admitted to hospitals for a myocardial infarction (heart attack) were more likely to have been in traffic (a prominent sources of ultrafine particles) in the 2 hours prior to admission.[96]

The cardiovascular effects of air pollution are especially concerning because they are insidious: they are largely silent, and can be for many years, with the individual only becoming aware of them when they become severe enough that symptoms become apparent or worse, or there is a cardiovascular event such as a heart attack or stroke. However, the cardiovascular effects of air pollution occur across the lifecourse. Exposure to air pollution in pregnancy has effects on the developing baby that manifest after birth, leading to signs of poor health later in life, including the development of risk factors for cardiovascular disease.[2] Prenatal exposure has been linked with congenital heart defects,[97] and early life exposure linked to rheumatoid heart disease later in life.[98]

The UK population is, on average, living longer. While this is encouraging, the ageing population is at a greater risk of developing a cardiovascular disease and having a cardiovascular event, but also of having comorbidity with another type of disease. A recent study with UK data found that air pollution increased the risks of cardiovascular–kidney–metabolic multimorbidity.[99] Given that the circulation feeds every organ of the body, the functioning of the cardiovascular system will influence the development of conditions in other organs of the body. The cardiovascular effects of air pollution, described above, could play key roles to increase the risk of neurological disease (eg through vascular dementia and stroke) and diabetes, where cardiovascular consequences are a hallmark of the condition.

Guideline levels for air pollution are becoming more stringent, in line with observations of adverse health effects at low levels of air pollution. Recent large-scale studies have demonstrated that air pollution increases the risk of cardiovascular deaths at levels below average $PM_{2.5}$ concentrations in the UK (Fig 1.8).[100] Moreover, populations already at higher risk for cardiovascular disease due to other factors such as advanced age, lower socio-economic status, and pre-existing conditions like COPD, obesity or diabetes are further harmed by exposure to poor air quality.

Studies have shown that interventions to reduce exposure to air pollution, such as face masks or air purifiers, can ameliorate some of the cardiovascular effects of air pollution.[101–3] More research is needed to establish the long-term effectiveness of these approaches on firm outcomes, such as hospitalisation or death from cardiovascular disease. While individual interventions can offer some protection, they don't address the root cause of pollution and can be impractical for everyone. Emission reductions, achieved through policies, regulations and technological advancements, offer a more sustainable and widespread solution. However, what these studies do offer is further reassurance that improvements in air quality will have cardiovascular benefits. Given the high prevalence and steep socio-economic gradient of cardiovascular disease with its severe impact on life and wellbeing, it follows that, if reductions in air quality can be realised, significant health gains and reduced inequality and health/social care costs from improved cardiovascular health would follow.

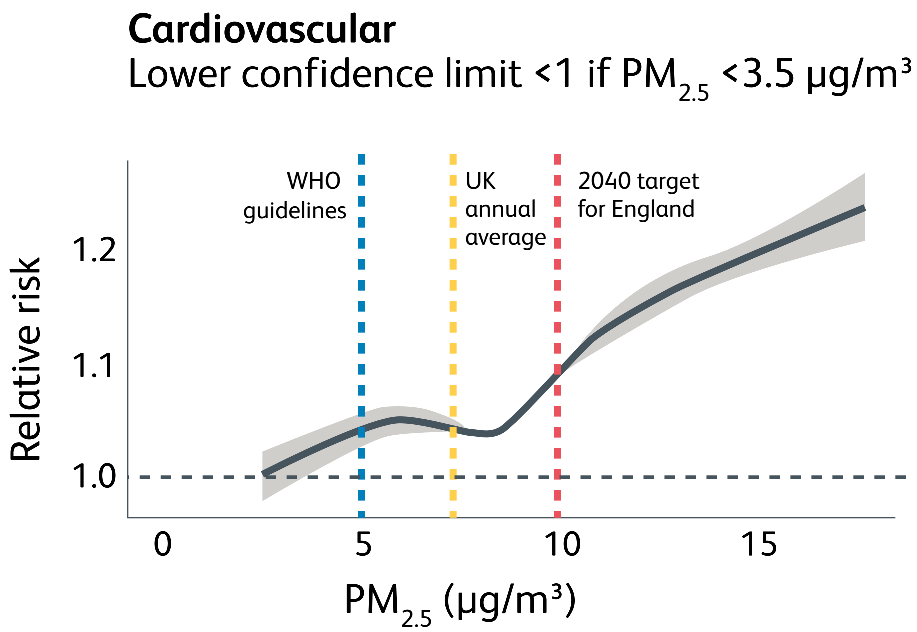


Fig 1.8. $PM_{2.5}$ is associated with an increase in cardiovascular risk at low levels of air pollution. Adapted with permission from Brauer *et al* (2022).[100] The yellow line shows average annual urban background levels for $PM_{2.5}$ in the UK in 2023 (Gov.UK statistics).

1.10 Impacts on the brain and mental health through our lives

1.10.1 Emerging evidence

The impact of indoor and outdoor air pollution on mental health is under-researched and poorly recognised. This section sets out the main evidence based on two rapid reviews undertaken as part of the BioAirNet network[103a] and more recent published data.[104,105]

There is an interplay between environmental, social, interpersonal and biological factors when considering how air quality impacts on brain and mental health. Yet, there are sufficient emerging data and many plausible mechanisms which suggest that we must take seriously the risks of poor air quality for brain and mental health.

1.10.2 Pregnancy, early years and adolescence

Studies of early exposure to air pollution and mental health are scarce and the findings are somewhat mixed. Prenatal air pollution exposure has been linked with cognitive impairments at age 5.[106] In a Spanish study of 1,889 children, exposure to NO_2 and benzene was inversely associated with mental development, but this did not remain a statistically significant finding after adjusting for confounders.[107] During pregnancy, exposures to PM_{10}, $PM_{2.5}$, NO_2 and NO_x were associated with 29–74% increased odds of unspecified mental disorders that complicated pregnancy.[108] Exposure pathways *in utero* and early childhood also differ from those in adulthood; for example, *in utero*, neonatal and infancy-related pathways may include ingestion (non-nutritional as well as nutritional), inhalation, transplacental, transdermal and breastfeeding.[109]

Psychotic experiences (among 2,063 adolescents) were significantly more common among those with the highest (top quartile) level of annual exposure to NO_2 and $PM_{2.5}$.[110] Together, NO_2 and NO_x explained 60% of the variance. There was no evidence of confounding by family socio-economic status, family psychiatric history, maternal psychosis, childhood psychotic symptoms, adolescent smoking or substance dependence.[111]

In the Environmental Risk Longitudinal Twin Study of 2,039 participants, after adjustment for family and individual factors, interquartile range increments in NO_x exposure were associated with a 1.4-point increase in general psychopathology.[112] There was no association between continuously measured $PM_{2.5}$ and general psychopathology. The psychopathology scores among those in the highest quartile of $PM_{2.5}$ exposure were greater than those in the bottom three quartiles. On the other hand, NO_x showed statistically significant findings. NO_x exposure was associated with all secondary outcomes, but associations were weakest for internalising and strongest for 'thought disorder', a symptom of psychosis. A series of comparative studies based in Mexico used similar designs, comparing Mexico City with less polluted areas. Among these, one post-mortem study compared prefrontal white matter between children and teenagers who had lived in Mexico City versus a less urbanised area and found ultrafine particulate matter in the brain cells of the former group, but not the latter.[113]

1.10.3 Adult mental illness and dementia

A recent systematic review shows convincing evidence of associations between depression and $PM_{2.5}$.[114] This includes five cohort studies, but mostly cross-sectional and time series studies from high- and low-income countries. The authors report significant heterogeneity and potential selection biases. After excluding single studies, the association between $PM_{2.5}$ and depression was strengthened by the absence of heterogeneity and publication bias in long- and short-term exposure studies. They concluded that further investigations should involve larger samples, better define diagnoses for depression, control potential confounders and understand underlying mechanisms.

There is much less research on psychoses, and specific conditions such as schizophrenia or personality disorders. Observational evidence implicates outdoor air pollutants as risk factors for a variety of mental health problems, including depression, anxiety, personality disorder and schizophrenia.[115–7]

There are critical periods in which mental illnesses arise. These are in childhood, or if there is already a physical health problem. Air pollution exposures in these periods are likely to have impacts in the short term and over the lifecourse. Studies demonstrate that air pollution can lead to ischaemic stroke and neurodegeneration, with some evidence of direct transmission through olfactory bulbs to the brain, as well as through systemic circulation and inflammation.[118] Particularly worrying are a series of studies showing that children exposed to fine and ultrafine particulate matter already show evidence of the hallmarks of Alzheimer's and Parkinson's diseases, namely hyperphosphorylated tau, amyloid plaques and misfolded α-synuclein.[119] This has significant implications for prevention policy to protect children's health over their lifecourse, as well as to prevent dementia. Traffic-related air pollution has been shown to have detrimental effects on the working memory of children in schools in Barcelona, the strongest effects related to outdoor NO_2 and indoor ultrafine particles, over a 3.5-year period.[120] A trial of using air purifiers in schools led to a reduction in air particles, but did not show effects on attention.[121]

The number of people with dementia globally is estimated to increase from 57.4 million to 152.8 million between 2019 and 2050, especially affecting sub-Saharan Africa and East Asia, as well as western Europe.[122] Air pollution is implicated in cognitive impairment and in dementia from epidemiological and systematic review evidence.[123–5]

A review of 70 studies undertaken by the UK COMEAP concluded that air pollution can contribute to a decline in mental ability and dementia in older people.[126] In particular, small particles were implicated through effects on the heart and the circulatory system, including circulation to the brain, raising the risk of vascular dementia. Since the committee had already concluded that there is strong evidence that exposure to air pollutants damages the cardiovascular system, it found that these associations are highly likely to be one of the underlying causes. Experimental studies imply that air particles stimulate the immune cells in the brain, which can then damage nerve cells, although it was not clear whether the levels of pollution in the UK are sufficient to have such effects.[126] Yet, taken together, the evidence suggests that very small air pollution particles can enter the brain and may cause direct damage, but this may not be the most important mechanism.[122] Recent analysis using UK biobank data has found **t**hat exposure to multiple air pollutants ($PM_{2.5}$, PM_{10}, NO_2 and NO_x) at the same time substantially increases the risk of dementia, especially among those individuals with high genetic susceptibility, for example those with the APOE ε4 (apolipoprotein E4) genotype.[123]

Exposure to xenobiotic heavy metals (such as lead and cadmium), particulate matter, nitrogen and sulphur oxides, organic solvents and other constituents of environmental pollution could be component causes of neurodevelopmental disorders such as schizophrenia.[127] A recent systematic review suggests that depression, suicide and neurodevelopmental disorders (such as autism for pregnancy-related exposures) may be more common among those exposed to air pollution.[128]

A study of air pollution (air quality index) considered 87 potential air pollutants in the USA and 14 in Denmark. PM_{10} and $PM_{2.5}$, diesel emissions and NO_2, and organic substances (such as polycyclic aromatic hydrocarbons) were significantly associated with an increased risk of psychiatric disorders.[129] The country-specific data showed associations with bipolar disorders in both countries, and with depression, schizophrenia and personality disorder in Denmark. A recent systematic review and meta-analysis showed associations of $PM_{2.5}$ and PM_{10} with depression, anxiety, bipolar disorder, psychosis and suicide in adults. The most apparent association was between long-term (>6 months) exposure to $PM_{2.5}$ and depression.[130] Depression and suicide were the most-studied outcomes; however, there were no studies of long-term particulate matter exposure and suicide, nor of particulate matter exposure and bipolar disorder. A number of studies show associations between air pollution and service use for mental disorders, including greater admissions and emergency care attendance.[131–3] These suggest exacerbation of existing conditions, requiring greater levels of healthcare.

1.10.4 Brain health and indoor air pollution

There is emerging evidence that exposure to air pollutants (both indoors and outdoors) may lead to neurocognitive disorders and affect mental health (directly and indirectly) through a range of potential causal pathways.[131,134] A recent trial of air purifiers shows that reduced $PM_{2.5}$ levels in an office environment were associated with better cognitive function on nine of 16 measures, including memory, suggesting that there are significant short-term effects.[135] Indeed, given that people living in urban industrialised environments spend up to 90% of their time indoors, there are calls for legislated indoor air quality standards for public spaces, alongside better design of buildings and public spaces.[136]

The Royal College of Paediatrics and Child Health, together with the RCP, considered indoor air quality and found that emissions from construction materials, building design (eg ventilation and heating systems) and activities inside buildings (eg cooking, fireplaces, cleaning products, moisture production) all impact on indoor air quality and affect health.[137] The underpinning studies found links between poor indoor air quality and neurological and psychological symptoms with cognitive and behavioural effects. For example higher CO_2 levels, and indoor air pollutants associated with CO_2, can impact negatively on cognitive function and concentration. Yet, there is ongoing debate on the effects of CO_2 concentrations on cognitive performance in settings such as schools and offices.[138]

1.10.5 Mind–body studies

Poor air quality is a risk factor for a range of non-communicable diseases, including mental health conditions.[104] While much of the evidence is based on ecological data,[111,139] there are also noteworthy and intriguing service use and incidence studies, which suggest important connections between air pollution and adverse mental health outcomes.[114,130] Depression, both as a clinical diagnosis and as less severe symptoms, includes pessimism, poor self-care and a lack of motivation, and can compound the adverse effects of poverty by reducing social support and risking unemployment. Poverty and food scarcity are known to impact directly on cognitive decisions,[140] and these make brain health vulnerable to additional risks such as poor air quality. Poor housing conditions and fungal exposure can directly and indirectly impact mental health through respiratory issues.[137,141]

There are plausible pathways to poor health outcomes for those with severe mental illness, impaired lung function and/or respiratory disease, if they encounter high levels of air pollution.[142–144] People with psychosis are already more likely to have poor lung function and may be disproportionately affected.[145] People with asthma who are taking antipsychotics are at greater risk of mortality than those not taking those medications.[146] Adversity and poverty can produce inflammation in mothers, the fetus *in utero*, young children and young adults, as well throughout the lifecourse.[147] Among deprived inner-city areas, health risk behaviours are more common and can add additional harms; for example, through smoking and excessive use of alcohol, a lack of physical activity, greater risk of adverse childhood experiences, poor early-life care, neglect, parental mental illness, poor educational achievement and school exclusion, and incarceration.[148] These all promote ‘inflammogenic’ environments that are vulnerabilities for additional risk exposures. Indeed, these are the mechanisms by which, for example, COVID-19 was proposed to more specifically affect people facing multiple social inequalities and marginalisation.[149] Therefore, among people with established physical or mental illnesses, particulate matter can exacerbate and precipitate additional episodes of ill health, requiring more specialist and intensive interventions.

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02

Health inequalities and economic impacts of outdoor and indoor air pollution

Air pollution is harmful to everyone but disproportionately affects the most vulnerable groups in society.

Tackling air pollution equitably would decrease health inequalities.

In 2023, people living in the 20% most deprived areas **experienced 8% higher average $PM_{2.5}$ concentrations** than those in the 20% least deprived.

Air pollution has negative impacts on the population's health and the environment, and is bad for the economy.

Indoor air quality must be considered **– people spend 80–90% of their time indoors** yet there are few standards for pollutant concentrations in indoor air.

In 2019, air pollution was estimated to have an economic cost of **£27 billion** per year in core healthcare costs and productivity losses, and may be as much as £50 billion when wider impacts, such as dementia, are accounted for.

Net zero policies are an opportunity to deliver co-benefits that improve air quality and address climate change.

Key points

- The distribution of health impacts attributable to outdoor air pollution is inequitable with a higher attributable disease burden generally experienced by people from socially disadvantaged groups, ethnic minority communities and those with higher levels of chronic disease and poor health. The arising geographical and sociodemographic differences in disease burden leads to worsening social and health inequalities experienced throughout the lifecourse.
- Health and economic impact assessment methods that integrate local health and demographic data can help understand the distribution of air pollution-related health and economic impacts and support policy decisions that achieve the maximum health gains for a given population.
- The economic impact of air pollution is linked to healthcare costs, productivity losses and lost utility (the advantages that come from being well and not experiencing ill health). The economic losses of air pollution are estimated at £27 billion in 2019; increasing to £50 billion in sensitivity analysis, when wider effects, such as dementia, are accounted for.
- People spend the majority of their lives indoors and there is a clear link between our health, housing, and the wider built environment. An estimated 904,000 homes in England have damp problems and are more likely to be occupied by older people, lone parents, children, families on low incomes and people from minority ethnic groups, thereby contributing to health inequalities.
- Exposure to viruses and bacteria that cause infectious diseases in indoor environments is a substantial cause of ill health that affects a very large proportion of the UK population. The COVID-19 pandemic has resulted in over 230,000 deaths in the UK alone, and around an estimated 2 million people are living with long COVID.
- A large proportion of UK buildings require ventilation improvements, including settings where occupants may be particularly vulnerable, such as schools, hospitals, care facilities and homes.
- There are important co-benefits and possible dis-benefits of climate action on air pollution with implications for health and wellbeing. A broad range of net zero policy actions – spanning housing, transport and active travel – are required to achieve a more equitable distribution of future air quality and health co-benefits.
- Net zero policy actions also influence indoor air quality; increasing insulation and air tightness in homes may increase indoor air pollution exposure if ventilation is not also adequately improved. Decarbonising heating and cooking by removal of gas stoves, and oil and gas heating appliances could deliver substantial reductions in indoor and outdoor air pollution exposure.
- Air quality modelling plays a central role in the development and evaluation of air quality policy and can be used to develop and appraise 'what if' scenarios and policy relevant questions. Measurements of air quality can be used to support model validation and understand if a policy has achieved its predicted impact in 'real-world' settings.
- The application of artificial intelligence (AI) has the potential to significantly change how we develop our tools for determining the quality of the air we breathe by enhancing analytical capabilities, enabling future predictions and personalising pollution exposure insights.

2.1 Introduction

Air pollution is harmful to everyone, but some individuals and groups are more vulnerable to the adverse health impacts from air pollution than others. The factors influencing these vulnerabilities are complex, including interacting biological, social/behavioural and environmental factors that shape both air pollution exposure and susceptibility to air pollution impacts. Vulnerabilities are typically most evident among those living in the most deprived communities in the UK who are already at risk of health inequality, and who are also more likely to experience cumulative adverse impacts from psychosocial stressors and multiple environmental stressors, including inadequate housing, poor indoor air quality and exposure to noise pollution.

This 'triple jeopardy' of health, environmental and social inequality experienced by vulnerable communities is also increasingly recognised in relation to the benefits of air pollution reduction strategies, which may be unevenly distributed across individuals and society. Policy actions may, therefore, risk widening existing environmental inequalities. Health and economic impact assessments are essential tools informing environmental policies, enabling prioritisation of actions that will deliver the greatest and most equitable health gains, while mitigating potential unintended consequences. However, existing assessment methods do not typically evaluate differential impacts across a range of socio-economic groups, or among vulnerable populations.

Part 2 considers inequalities in exposure to, and arising health impacts of, outdoor and indoor air pollution and explores advances in our understanding of the benefits and trade-offs of policy interventions. We also consider the implications of climate change and related policy actions, including strategies to achieve net zero, for improving air quality and reducing health inequalities.

2.2 Environmental health inequalities

Air pollution and climate change are strongly linked; burning fossil fuels pollutes the air we breathe and warms the planet. Both are matters of social justice and health inequality. The industrial revolution, led by the global north, has driven the shift from the Holocene to the Anthropocene era where human activity has a dominant influence on the planet. In economically developed nations, health impacts of air pollution are largely concentrated in cities and urban areas, where combustion moves traffic and heats homes. With the proportion of the global population living in cities set to rise from 56% to 70% by 2050,[1] there is an urgent need to understand air quality-related health impacts, how they are distributed across vulnerable populations, and to act to prevent harms. Considering the differences in health that arise due to the harms of poor air quality requires reference to several key concepts, as depicted in Box 2.1

Box 2.1. Concepts of vulnerability to the effects of air pollution and arising health disparities.

- **Health equity** may be defined as the 'absence of unfair and avoidable or remedial differences in health among population groups defined socially, economically, demographically or geographically'.[2] Health equity can be influenced (for good or bad) through several processes.[3]
- **Distributive justice** refers to the equitable or otherwise distribution of air pollution exposure across groups; procedural justice pertains to access to decision making and legal processes, while policy justice concerns the positive or negative impacts of air quality policies.[3]
- **Disadvantaged populations** are often exposed to adverse living environments, but, in addition, may have higher vulnerabilities to these exposures – for example, due to differences in underlying health status – putting them at greater risk of adverse health impacts for a given level of exposure.[4]
- Within a population, susceptibility and **vulnerabilities may differ,**[5] for example children and adolescents are vulnerable because respiratory ventilation is greater than in adult life, leading to a greater inhaled load, and because organs, notably brains and lungs, are developing rapidly. Older people living with multiple health conditions are also likely to have greater vulnerabilities to air pollution exposure.

The distribution of health impacts attributable to outdoor air pollution is inequitable with a higher disease burden generally experienced by more deprived and ethnic minority communities.

In a systematic review of 31 national and regional studies relating air pollution exposure to social position in Europe, Fairburn[6] found higher deprivation indices and lower economic position were consistently associated with higher air pollution concentrations (PM_{10}, $PM_{2.5}$, NO_2, NOx). However, in some studies, a 'J shaped' relationship was seen with more advantaged groups exposed to higher levels of pollution, reflecting more affluent people living in city centres.[4]

There are also important sociodemographic and geographical influences on the distribution of air pollution-related inequalities. In an epidemiological study, Fecht[7] compared the Netherlands and the UK using small area statistics, showing that environmental inequality can manifest differently between subpopulations, local areas and countries. Overall, people of lower socio-economic status (SES), such as those receiving income support/benefits, and people from ethnic minority backgrounds were exposed to higher levels of air pollution, due for example, to residing near air pollutant sources, such as high-volume traffic roadways or industrial facilities. In some cases, neighbourhoods with a high percentage of children and those with a high percentage of older residents experienced lower levels of air pollution. Urban areas had greater air pollution-related inequalities, suggesting that measures to reduce these inequalities should be focused on city transport and traffic-related solutions.

A study undertaken by Woodward and colleagues[8] using Lower Super Output Area (LSOA) level Index of Multiple Deprivation (IMD) data in England indicated that in 2018, population-weighted annual average $PM_{2.5}$ pollution concentrations across all IMD deciles were within the range 9.5 to 10.5 μg/m^3 (fig 2.1). The highest mean exposure coincided with deciles 2 and 3, reflecting high $PM_{2.5}$ concentrations and proportion of people living in these deciles in London. This overall pattern also reflects geographical differences, with a higher proportion of people living in the most deprived decile (decile 1) in the north of England, compared with the south of England, and high $PM_{2.5}$ concentrations in south-east England due to emissions from mainland Europe and international shipping.

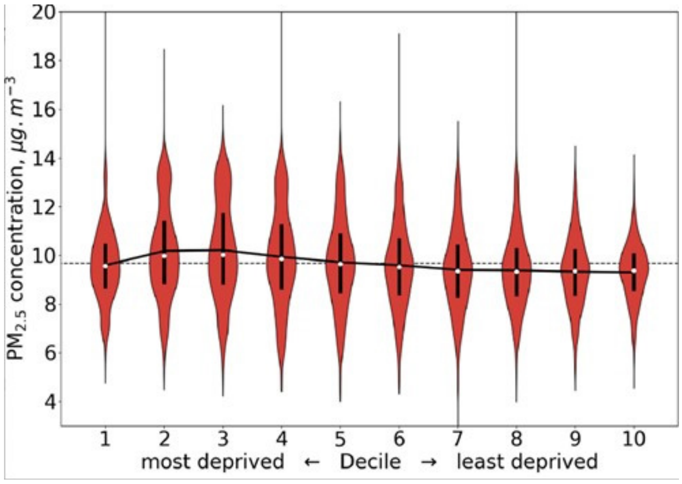

Fig 2.1. Distribution of England LSOA level average $PM_{2.5}$ exposures for each decile, given in red. The black line across deciles shows the mean exposure for each decile, the white circle shows the median, the vertical black lines show the interquartile range. The dashed line indicates the mean exposure across all deciles from most deprived (decile 1) to least deprived (decile 10).

Reproduced from Woodward *et al* (2024)[8] under the CC BY-NC-ND 4.0 licence.

In the UK, research has shown that people from ethnic minority backgrounds typically experience a greater burden of air pollution compared with White populations. NO_2 and $PM_{2.5}$ concentrations are, on average, 83% and 27% higher, respectively.[9] Studies of individual level exposure have also found that higher air pollution exposures are experienced by vulnerable subgroups, including pregnant women and mothers.

A study in Bradford found that children from minority ethnic backgrounds were disproportionately exposed to the highest levels of pollution around their homes. Findings showed that 53% of children of Pakistani origin, and 48% of children from other ethnic minority groups were living in areas with the highest quintile of pollution exposure, compared with only 18% of White British children.[10] Although more exposed to air pollution, people living in disadvantaged areas typically contribute the least to emission generation. For example, Barnes[11] examined data on UK car ownership and use in the UK, identifying that people living in more deprived areas are less likely to own a car, and travel fewer miles per year than those living in less deprived areas.

Higher air pollution exposures in vulnerable populations lead to worse health and health inequalities.

Greater air pollution exposure for people in lower socio-economic groups is associated with worse health outcomes and greater health inequality. Assessing associations between air pollution, deprivation and health outcomes in Wales, Brunt[12] identified increased rates of all-cause mortality and respiratory disease for communities living in the most deprived areas. Using UK Biobank data from people aged 40–69 years living in England, Wales and Scotland, Doiron and colleagues[13] showed that higher exposures to pollutants $PM_{2.5}$, PM_{10} and NO_2 were associated with lower lung function, and chronic obstructive pulmonary disease (COPD) prevalence was associated with higher exposures to the same pollutants. Lung function associations were stronger for people from low-income households, with large and clinically important harms; impacts on forced expiratory volume in 1 second (FEV1) and forced vital capacity (FVC) levels were twice those of high-income individuals.

Higher air pollution exposure worsens health equity across the lifecourse.

Low birth weight (LBW) is a well-recognised marker of poorer childhood outcomes and future health. Pooling data from 14 population-based mother-child cohort studies in 12 European countries, Pedersen and colleagues[14] found that a 5 $\mu g/m^3$ increase in $PM_{2.5}$ concentration during pregnancy was associated with an increased risk of low birth weight at term (adjusted odds ratio [OR] 1.18, 95% CI 1.06–1.33). These findings were supported by a study in London, which indicated that a 2–6% increase in the likelihood of low birth weight was associated with higher exposure to both $PM_{2.5}$ and NO_2 during pregnancy, after accounting for other potential risk factors including road traffic noise.[15] Research has further demonstrated that exposure to particulate pollution is recognised to accelerate epigenetic ageing in children aged 7 years, with implications for accelerated biological ageing in later life.[16]

In a cohort of over 68 million older Americans, Dominici and colleagues[17] evaluated risk of death associated with air pollution exposure at low concentrations, using annual exposure models for $PM_{2.5}$, NO_2, and O_3 at a high spatial resolution. In subgroup analyses, the authors found larger mortality effects for long-term $PM_{2.5}$ exposure among men and among people of Hispanic, Asian and African American heritage, compared with White people. Individuals eligible for Medicaid (of low SES) had a slightly higher risk per unit of $PM_{2.5}$ exposure. Black and Hispanic individuals had a higher risk of death associated with exposure to $PM_{2.5}$ than other ethnic subgroups. In a health impact assessment in Bradford, UK, mortality linked to key environmental exposures was highest among multi-ethnic communities and those living in the most deprived parts of the city.[18] These findings suggest that tightening the annual air quality standards for $PM_{2.5}$ will produce public health benefits overall, but especially among minoritised ethnic groups and people of low SES, thereby contributing to reducing inequalities.

Understanding the complex relationship between air pollution and health inequalities is important for policy development.

Explaining the effects of air pollution on inequality based on differences in population exposure only provides a partial impression of health inequalities linked to air pollution. It is recognised that the prevalence and incidence of health impacts associated with air pollution are substantially greater among deprived populations in the UK than for those who are less deprived. With respect to mortality, in England in 2017, the stillbirth rate in the most socio-economically deprived areas was 5.5 per 1,000 total births, compared with 3.0 per 1,000 total births in the least deprived areas[19] with a difference in life expectancy of 9.4 years for males and 7.6 years for females.[20] There is a similar pattern for healthy life expectancy with a difference of 19.0 years for males and 19.3 years for females.[20] Similar patterns are seen for stroke,[21] dementia,[22] emergency respiratory hospitalisations,[23] diabetes[24] and asthma.[25]

Quantifying air pollution-related health impacts typically involves combining air pollution data with concentration-response functions, using routine data for mortality and disease incidence. This process may not capture differences in air pollution susceptibility related to socio-economic deprivation or other biological or social characteristics. The overall estimate of health burden in the population may be broadly correct; however, it can fail to recognise the burden in more deprived communities, where the impact per person per unit of exposure is greater than in less deprived communities. This has important consequences for air quality policy development. First, targeting air pollution controls in areas with the highest exposures may not generate the highest health benefit per unit of economic expenditure, leading to policy inefficiencies. Second, it underplays the importance of air pollution as a driver for poor health among deprived communities. Health and economic impact assessment methods, which integrate local or regional demographic and disease incidence data with high resolution air quality modelling, may help address this challenge by enabling policymakers to appraise the distributional benefits of air quality control measures across a given population.[26]

Interventions to improve air quality and health can be effective and reduce health inequalities.

Better air quality improves health and reduces health inequalities. Analysing data from 73 million Americans aged 65 years or older, Josey and colleagues[27] showed that lower $PM_{2.5}$ exposure was associated with lower mortality in the full population, but marginalised subpopulations – Black and White people on low incomes – benefited proportionately more as $PM_{2.5}$ levels decreased.

Interventions such as low emission zones (LEZ) or clean air zones (CAZ) (Fig 2.2) in cities have the potential to improve health and reduce inequalities.[28] London implemented its first LEZ in 2008 and while the most deprived communities still tend to live in the most polluted areas, air pollution concentrations have declined faster in areas of deprivation and more markedly since 2016.

Fig 2.2. Clean air (low or zero emission) zones in the UK (at January 2025)[29]

The most deprived areas in London (based on the Index of Multiple Deprivation) experienced decreases in annual mean NO_2 and $PM_{2.5}$ concentrations of 24% and 32%, respectively, compared with 19% and 33% reductions in the least deprived areas, between 2013 and 2019.[30] The difference in average NO_2 concentration between the most and least deprived IMD deciles reduced from 7.7 to 4.4 μg/m^3, showing that the socio-economic inequalities in NO_2 exposure have reduced over this time period. The forecasts show that the exposure differential between the most and least deprived deciles will continue to reduce but at a slower rate in future years, with the difference estimated at 2.8 μg/m^3 in 2025, and 2.2 μg/m^3 in 2030. More recent assessment of the Bradford Clean Air Plan suggested that the plan may be linked with improved pollution levels, and cardiovascular and respiratory health within the first 2 years of implementation.[29] Longer follow-up will explore if these effects are sustained over time.

Greater Manchester Combined Authority has rejected plans for a charging LEZ, stating concerns about public perception and potential negative impacts on residents, particularly those in more deprived areas. Due to the presence of significant socio-economic hardship, the proposed scheme was deemed unpopular and potentially unfair. Instead, Greater Manchester chose to focus on an investment-led 'Clean Air Plan' with no charges, relying on investments in cleaner buses, taxis and targeted traffic management measures. This approach was approved by the government, bypassing the need for a traditional LEZ with charges.[31] While emissions of most pollutants have decreased, NO_2 levels are still above targets in some areas, which is causing some child health concerns.[32]

Two studies that used modelling to assess predictive health impacts of Paris' LEZ also illustrate this concept. Firstly, Host and colleagues[33] assessed the health and equity effects of four hypothetical Paris LEZ scenarios. The most stringent scenario was predicted to have the greatest health benefits and reduce inequalities if the intervention included subsidies to low-income populations to help replace the oldest and most polluting vehicles. Otherwise, the intervention could reinforce existing inequalities. More recently, Moreno and colleagues[34] assessed health impacts, evaluating the most equitable approach to implementing the second phase of the Paris LEZ. The authors identified that the most equitable LEZs are the most stringent with expansive parameters and high restrictions on polluting vehicles. If sufficiently ambitious, LEZs have the potential to equitably impact the distribution of health inequalities, especially childhood asthma. The most stringent scenario has the potential to prevent over 800 premature deaths and over 3,000 childhood asthma cases per year. As a policy intervention, LEZs have the potential to significantly reduce health inequalities, given the transportation sector is the largest contributor to NO_2 emissions in many urban areas.

2.3 Economic impacts of air pollution

The economic impact of air pollution is linked to healthcare costs, productivity losses and lost utility (the advantages that come from being well and not experiencing ill health). Valuation data are available from various sources. Mortality costs are assessed by multiplying the loss of life expectancy (life years lost across the population) by the value of a life year derived from earlier research for UK government on public willingness to pay for a reduction in mortality risks. Healthcare costs and productivity losses are taken from cost-of-illness studies, drawing for example on NHS data on treatment costs and information on lost productivity due to illness, including time spent by carers (both paid and unpaid). Utility losses (through pain and suffering, lost opportunities for undertaking desired activities) are quantified by multiplying the change in incidence of each impact by its associated quality-adjusted life year (QALY) score and the value of a QALY (£70,000) adopted by the UK government.[35] Results are shown in Table 2.1.

Based on the mortality and morbidity impacts shown in Part 1, we estimate the economic cost of air pollution in 2019 to be £27 billion. This figure declines to £19 billion in 2040 when we take into consideration current policies targeted at reducing air pollution for core effects (those considered quantifiable with the greatest confidence). Results are dominated by utility, particularly from the loss of life expectancy, with utility contributing 87% to the total (Table 2.1). Healthcare costs contribute around 10% and productivity losses 3% for the core effects. The share in results across healthcare, productivity and utility is similar in 2019 and 2040. When sensitivity effects are added in, totals rise to £50 billion in 2019 and £30 billion in 2040. The largest sensitivity effect by some margin is dementia, which causes utility losses to fall as a percentage of the total damage to around 74%, healthcare costs to rise to 22% and productivity losses to rise to 4%.

Table 2.1. Aggregate annual costs of air pollution health impacts in 2019 and 2040 (£billion/year).

	2019	2040
Core effects		
Healthcare	2.6	1.6
Productivity	0.8	0.4
Utility	23.6	17.1
Core total	**27.0**	**19.1**
Sensitivity effects		
Healthcare	10.0	4.9
Productivity	1.5	0.7
Utility	11.4	5.4
Sensitivity total	**22.9**	**11.0**
Core + sensitivity total	**49.9**	**30.1**

A series of health impacts (mortality, asthma, acute myocardial infarction, cardiovascular and respiratory hospital admissions, COPD, lung cancer, stroke, acute lower respiratory infections, dementia, diabetes and school absences) have been quantified and valued in terms of healthcare costs, productivity and utility.[36]

Modelling also suggests that LEZs can deliver health economic benefits; for example, Moreno *et al*[34] found substantial economic benefits associated with LEZ implementation, with estimates ranging from €0.76 billion to €2.36 billion for prevented deaths. The benefits associated with asthma reduction ranged from €2.3 million to €8.3 million (annual monetary valuation of preventable cases). Empirical studies are needed to confirm these projections.

2.4 Indoor air pollution

2.4.1 Introduction

We spend 80–90% of our time in indoor settings, including homes, schools, workplaces, healthcare, social settings and transport. Exposures in indoor settings comprise complex mixtures of chemicals and particles that are specific to the environment and depend on both the infrastructure and human behaviours.

The importance of biological aerosols – small airborne particles (eg microbes) or from organic sources (eg aeroallergens from pets) – in indoor settings has become a significant focus of research over the past 4 years. Awaab Ishak, a 2-year-old child, died in 2020 as a result of prolonged exposure to spore-forming moulds in his home. This tragic case has focused attention on the number and type of homes in the UK that fail the Decent Homes Standard owing to the extent of damp and mould, leading to injurious exposures to indoor bioaerosols. The COVID-19 pandemic also substantially raised awareness of the role that indoor environments play in the transmission of communicable diseases, particularly the importance of ventilation in mitigating airborne exposures to respiratory infections. These events have accelerated research into the links between indoor environments, air quality and health.

2.4.2 Importance of indoor air pollution

Health starts in the home. There is a clear link between our health, housing, and the wider built environment. The RCP has raised this as an issue in its expert commentary in the Town and Country Planning Association's guidance[37] on securing Healthy Homes at the local level. Housing quality has a significant impact on the health and wellbeing of its inhabitants, and there is clear evidence linking poor quality housing to social inequality, health and wellbeing.[38] The most recent English Housing Survey[39] reported that an estimated 904,000 homes in England suffered damp problems. These issues were more prevalent in homes with specific occupants, including 'households with an older person living in them, households with a lone parent, households with children, low-income households and households with people from minority ethnic backgrounds'. Through the Renters (Reform) Bill and Social Housing Regulation Act,[40] legislative changes to improve housing standards are planned to be introduced, including (i) 'Awaab's Law' to address damp and mould, and other hazards to health, in social homes, (ii) provide new powers to the Housing Ombudsman to act on complaints, (iii) to review the Decent Homes Standard, (iv) to introduce new professional standards and (v) apply legislation to private rented accommodation.

Major reports in 2022 from the Defra Air Quality Expert Group (AQEG)[41] and the UK chief medical officer (CMO),[42] as well as the 2024 CMO report *Health in cities,*[43] outlined the importance of indoor air quality, and the need to understand and mitigate exposures within buildings. Both the likelihood of exposures and the availability and successful application of solutions are related to a wide range of social, economic, political and environmental factors. This includes the impacts of climate change where there may be direct effects on the amount and type of exposures to air pollutant and bioaerosol sources, as well as indirect impacts from net zero measures in the built environment. As stated by the CMO: 'Effective ventilation, while minimising energy use and heat loss, is a priority for reducing air pollution, respiratory infections and achieving net zero'.

2.4.3 Bioaerosols

Indoor environments contain diverse aerosols that are biological in origin (bioaerosols) that can come from three sources: (i) those that are imported from outdoors and include tree and grass pollens, fungal spores and airborne bacteria, (ii) contagious bioaerosols that are produced by those with active infections (usually respiratory), which include viruses and bacteria and (iii) the complex community of indoor organisms that includes pets and their dander, mites, and microorganisms that include fungal moulds growing in and on the structure of the home.

2.4.4 Health impacts of indoor air pollution

Quantifying exposures and measuring the health impacts of indoor air pollution remains a substantial challenge. While the effects of some indoor pollutants such as radon, carbon monoxide, asbestos fibres and cigarette smoke are well recognised, the impacts of many other pollutants are difficult to characterise. This is partly due to the lack of data on pollutant presence and exposure in many indoor settings, as well as the effects of multiple exposures happening within the same environment. AQEG[41] notes that while the National Atmospheric Emissions Inventory (NAEI) is not designed specifically for indoor air, data suggest that over 14% of emissions of volatile organic compounds (VOCs) occur indoors, while less than 0.1% of NO_2 and less than 1% of $PM_{2.5}$ emissions are thought to be from indoor sources. AQEG also highlighted that there is considerable uncertainty over concentrations of pollutants in UK homes and how these levels have changed over time.

A global systematic review[44] identified that the most studied pollutants in the home environment are $PM_{2.5}$ and PM_{10}, NO_2, VOCs and polycyclic aromatic hydrocarbons (PAHs). Exposures are highly dependent on occupant activities including $PM_{2.5}$ through cigarette smoke, NO_2 from gas appliances and VOCs and PAHs from household products. Smaller houses, lower air exchange rates, location near high-traffic-density roads and redecoration are all associated with higher indoor air pollution. While CO_2 at the levels normally seen in buildings is not a pollutant with direct health concerns, it is associated with short-term effects such as drowsiness and impacts on performance. CO_2 is widely recognised as a proxy for ventilation and hence a potential indicator for risks from indoor sources including infectious diseases.[45]

A recent UK Health Security Agency (UKHSA) led study[46] used a modelling approach with 2019 data to evaluate the burden of disease in UK homes. It was estimated that exposure to formaldehyde was associated with approximately 4,000 new cases of childhood asthma (~800 disability adjusted life years (DALYs) lost), and exposure to damp and/or mould was associated with approximately 5,000 new cases of asthma (~2,200 DALYs) and approximately 8,500 lower respiratory infections (~600 DALYs). The study also indicated that the population burden was unequally distributed by income and ethnicity. Inequalities in childhood $PM_{2.5}$ exposures are also highlighted through a recent modelling study[47] that considers housing, activities, and indoor and outdoor sources across London, with higher exposures predicted for those living in the lowest income quintile households.

Although most indoor air quality studies focus on home environments, recent studies highlight poor air quality in other indoor settings including schools and public transport environments. However, there is a substantial lack of data on most environments; beyond specific occupational exposures, there is a lack of studies investigating workplaces, hospitals and social settings. Indeed, data on the range of indoor pollutants that we are all exposed to, and the levels of these exposures in most built environments, remain limited. This gap in knowledge within the UK is being addressed by the UK Research and Innovation / Met Office Clean Air Programme.[48]

2.4.5 Health impacts of bioaerosol exposures

The relationship between exposure to bioaerosols and health is very complex and includes both positive and negative aspects. On one hand, it appears that encountering a wide diversity of microbial exposures as a child is an important aspect of maturing a balanced immune system.[49] On the other hand, it is clear that there are adverse health effects that are associated with bioaerosol exposures, and especially when there are high concentrations of spore-forming moulds in indoor environments[50] or pathogens that cause infectious diseases.

Of paramount importance is the potential for mould exposures to cause, and then to subsequently trigger, allergic reactions in sensitised individuals, and especially children that have a predisposition to sensitisation (atopy[51]). There are over 150 allergens found in up to 100 genera of indoor fungi, and epidemiological evidence clearly links mould exposures to diverse superficial (skin) and systemic allergic reactions. Reactions to upper respiratory tract exposures can include symptoms such as sinusitis, cough, wheeze and asthma that are disabling and sometimes – but rarely – fatal. Some species of mould found indoors can directly cause serious invasive infections; however, these normally only occur in those individuals with pre-existing conditions. Common indoor fungi, such as species of *Aspergillus* and *Stachybotris*, produce diverse metabolites that include non-volatile mycotoxins and microbial volatile organic compounds (mVOCs) that cause the characteristic ‘mushroom’ smell in homes with a mould problem. While the health impacts of mVOC exposures are unclear, direct exposures to mycotoxins are known to be unhealthy. However, the concentrations that are normally found indoors are thought to be below the amounts that are known to be problematic.

Exposure to viruses and bacteria that cause infectious diseases in indoor environments is a substantial cause of ill health that affects a very large proportion of the population. There is significant evidence for health effects from airborne respiratory diseases including TB, influenza and COVID-19. It is likely that direct inhalation of aerosols and indirect exposure on surfaces provide major routes of transmission for all respiratory infections.[52] While most respiratory infections result in short-term and mild illness, to date the COVID-19 pandemic has resulted in over 230,000 deaths in the UK alone, and around 2 million people are affected by long COVID. Transmission risks are recognised to be highest in settings where people are particularly vulnerable (eg hospitals, care homes), and public spaces that are poorly ventilated and crowded, including schools. Higher levels of deprivation are associated with lower vaccination rates as well as higher rates of long COVID. Beyond respiratory diseases, aerosols have been implicated in communicable diseases such as norovirus, hospital-acquired infections that include pathogenic bacteria, fungi and their antimicrobial-resistant variants, and pathogens with environmental sources including *Legionella* associated with building water and ventilation systems.

2.4.6 Indoor air pollution: causes, mitigation and solutions

Indoor air quality is influenced by multiple factors, with good evidence indicating that actions taken to address other factors, such as energy use or comfort, can have a knock-on effect on air quality. The *Health effects of climate change in the UK* report published in 2023[53] highlighted the impacts of climate and net zero measures on indoor air quality, as these can bring both positive and negative health impacts. Decarbonising heating and cooking results in substantial reductions in exposure to pollutants from fossil fuel sources. This includes indoor by-products from gas stoves during cooking, as well as emissions from solid fuel, oil and gas heating that can impact both indoor and outdoor air. However, evidence indicates that a large proportion of UK buildings have inadequate ventilation, including settings where occupants may be particularly vulnerable such as schools, hospitals, care facilities and homes. In domestic settings this includes modern and retrofitted homes where energy efficiency measures lead to lower infiltration rates and inadequate ventilation.[54] While these measures can sometimes have a benefit for improved thermal comfort in the winter, poor building design and implementation bring risks of summer overheating and increased exposure to indoor air pollutants.[55]

The CMO 2022[42] report details a range of mitigation measures for tackling indoor air pollution. Measures to remove or reduce sources are most effective, followed by addressing pathways of exposure and finally, protecting people (Fig 2.3). The most appropriate measure depends on the particular environment, the sources and the people – there is no 'one size fits all' solution. Some measures, such as avoiding certain pollution-generating activities or managing damp and humidity, can be straightforward; however, removing human sources from an environment is considerably more challenging. In some circumstances an action to mitigate one source, for example opening a window for ventilation to reduce an indoor source, can increase other exposures, such as bringing in outdoor pollutants. Mitigation measures may also have significant barriers in some settings, including cost, technical feasibility, acceptability and unintended consequences such as impacts on safety, security and comfort.

The issue of damp and mould in housing, particularly in social and private rented sectors, has led to the creation of guidance and directives aimed at preventing future deaths, as highlighted by the case of Awaab Ishak. While these guidelines exist, concerns remain about their implementation and the need for greater enforcement, including increased funding for local authorities. A lack of action leads to continued health risks for tenants and impacts the overall quality of housing.

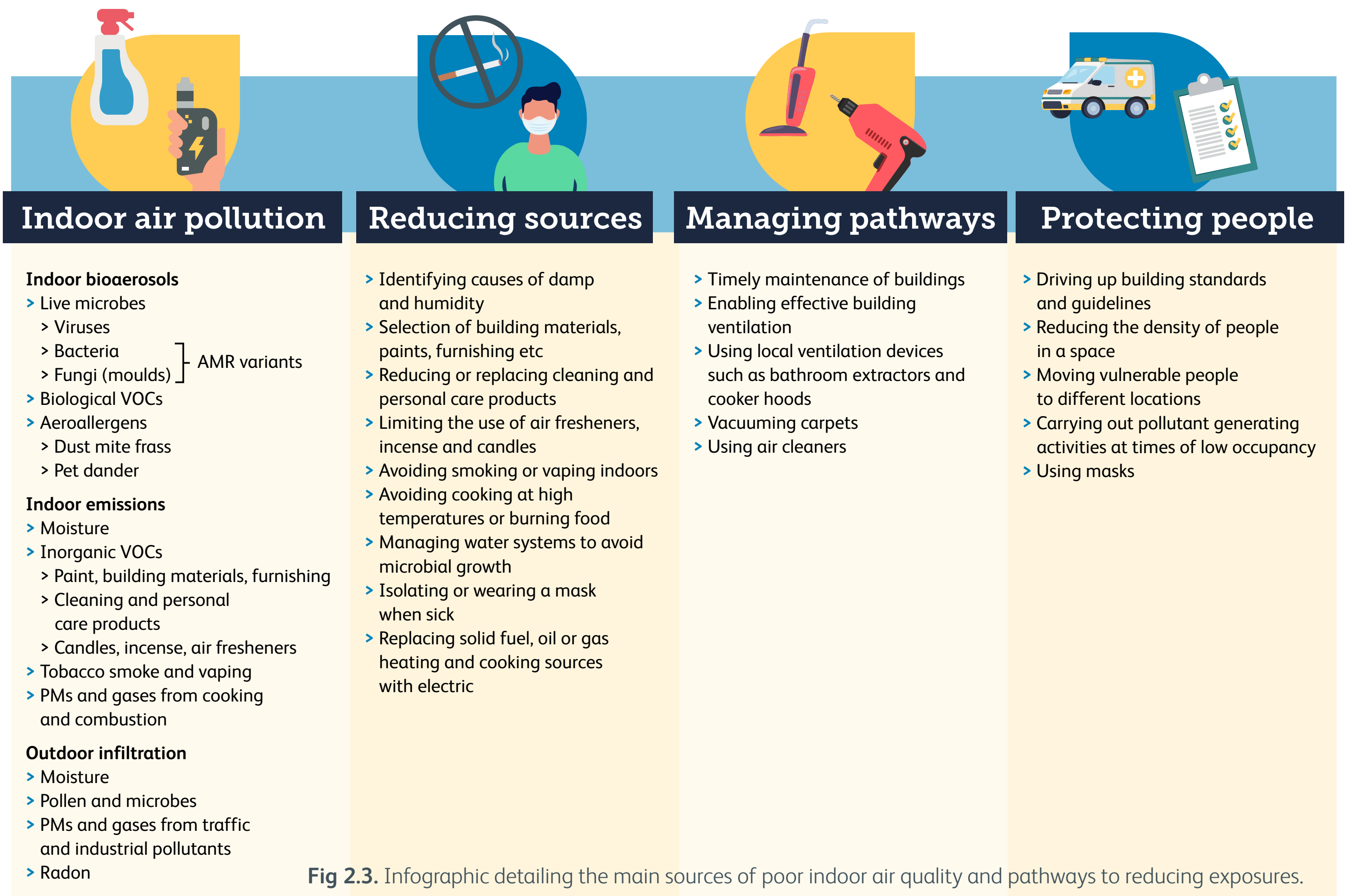

Fig 2.3. Infographic detailing the main sources of poor indoor air quality and pathways to reducing exposures.

2.4.7 Performance standards for indoor air quality

Unlike outdoor air, there are currently very limited regulatory standards for pollutant concentrations in indoor air. The UK Building Regulations and guidelines from organisations such as the Chartered Institution of Building Services Engineers (CIBSE) set out minimum requirements for ventilation rates, define overheating and recommend temperature and humidity ranges. These cover domestic and a wide range of public and commercial buildings, but largely apply to new buildings. It is worth noting that the UK has far more older housing than most of Europe: 78% of homes were built before 1980, compared with an EU average of 61%, and 38% of the UK's housing stock was built before 1946, compared with an average of 18% for the EU.[56]

Concentrations of pollutants have started to be reflected in requirements. The Scottish Building Regulations recently introduced a requirement to monitor CO_2 in bedrooms as a proxy for ventilation, and the Building Regulations part F in England for non-domestic buildings, for the first time in 2021, included requirements to monitor the indoor environment (predominantly CO_2) in certain spaces.[57] In 2010, the World Health Organization (WHO) set out guidelines for a small number of selected indoor chemical pollutants, including recommended threshold values.[58] Meanwhile exposure limits exist for higher hazard pollutants in some workplace settings.

Despite these emerging standards, actions to effectively regulate indoor air in general public, domestic and commercial settings are relatively modest due to the lack of agreed metrics for many indoor air pollutants, and the challenges in enabling reliable data collection to measure performance. Even for well-established metrics relating to ventilation and temperature, ensuring compliance with standards and guidelines has been a substantial challenge.[59] However, the advent of low-cost sensors and smart buildings raises the prospect of new approaches to developing and applying performance-based standards that consider the concentration of key pollutants or relevant proxies such as humidity. The COVID-19 pandemic prompted greater consideration for indoor air performance standards to support building owners, occupants and regulators in managing indoor air.[45]

2.4.8 Summary

Ensuring good indoor air quality, and identifying and implementing effective indoor air quality and ventilation solutions, needs a multidisciplinary approach. Tools and frameworks are needed to assess indoor air quality and identify problems and their causes, which need to be underpinned by appropriate research evidence. While this is increasing, there is still limited data on many pollutants and a lack of longitudinal monitoring data and in-situ evaluation of solutions that include robust analysis of health impacts. Work led by the Royal Academy of Engineering[59] highlighted the importance of effective regulatory and legislative frameworks, along with clear standards and guidelines, to support the appropriate design, application and enforcement of buildings, products, materials and technologies. This study also highlighted the need for better education and training for the public and professionals, and identifying 'win-win' solutions where air quality measures align with net zero and climate adaptation strategies.

2.5 Air pollution and climate change

Climate forcing pollutants (also known as short-lived climate pollutants [SLCPs]), such as black carbon (soot), methane, tropospheric ozone and hydrofluorocarbons (HFCs), and health-related air pollutants often share the same emission sources and so there are important co-benefits and possible dis-benefits of climate action on air pollution.[60] To tackle climate change, the UK has adopted legally binding net zero targets[61] that are consistent with the Paris Agreement,[62] and are supported through independent advice from the Climate Change Committee (CCC), which publishes 5-year carbon budgets. Options within the range of available net zero policies present an opportunity to achieve 'win-wins' for climate and clean air; however, it is also important to understand how benefits will be distributed throughout the population and which actions will effectively reduce existing health inequalities.

Recently, Beevers *et al*[63] used the CCC's Sixth Carbon Budget data[64] to test the benefits of the net zero transition for road transport, active travel and building emissions on air pollution. They used the balanced net zero pathway (BNZP), a 'middle ambition' route to compliance with UK net zero by 2050, which is predicted to reduce greenhouse gas emissions to 78% below 1990 levels by 2035, and the widespread innovation (WI) pathway, which assumes greater success in reducing costs of low-carbon technologies, allowing more widespread electrification and active transport. Comparisons in 2030 and 2040 were made between a business as usual (BAU) case,[65] that represents currently agreed air quality policy, with BAU plus BNZP and WI. Indoor exposure changes due to improved insulation and gas cooking removal were tested using methods outlined by Vu.[66] Outputs from the project included outdoor concentrations of NO_2, $PM_{2.5}$, PM_{10} and O_3, population weighted exposure to air pollution and indoor NO_2 and $PM_{2.5}$,[67] mortality and morbidity impacts, including for active travel,[36] the effect of exposure on different societal groups,[68] and cost benefit analysis.[63]

2.5.1 Results

Advances in our understanding of net zero, air quality and health

Under existing UK policy, BAU reductions in NO_2 and PM are predicted by 2030, driven by new vehicle technologies, but these reductions are expected to plateau by 2040. The BNZP and WI scenarios show further reductions, particularly by 2040, fuelled by accelerated electric vehicle uptake, reduced vehicle kilometres travelled and low-carbon heating in buildings, with the building contribution to particulate matter reduction being two- to three-times greater than road transport.

There are potential trade-offs for air quality in the transition to a cleaner transport fleet through vehicle electrification. The increased weight of electric cars and vans, compared with their internal combustion (ICEV) equivalents, risks an increase in non-exhaust particulate matter (due to brake, tyre and road wear, and resuspension) emissions in future.[69] However, study findings based on roadside measurements,[70] albeit uncertain, suggest that the removal of exhaust emissions, combined with large reductions in particulate matter emissions from brake wear, counteracts other non-exhaust sources, resulting in an overall particulate matter emissions benefit of electric vehicles.[63] Another benefit of EVs is that they run efficiently at low speeds, thus removing the argument that 20mph speed limits would increase air pollution as petrol/diesel engines run less efficiently at this speed.[71]

As previously outlined, inequalities in NO_2 exposure across the socio-economic spectrum have been large and study results show that these still exist in 2040. However, the differences were reduced by net zero policy. For $PM_{2.5}$, the pattern across the socio-economic spectrum was less clear with similar concentrations across all deprivation index quintiles, as measured by the Carstairs index.* These findings are consistent with previous research that explored the impact of net zero policies on air quality in the West Midlands metropolitan area, identifying a small reduction in air pollution inequality by 2030 – as assessed by the relationship between annual mean concentrations and the Index of Multiple Deprivation (IMD).[72] However, in a transport-focused net zero scenario (vehicle electrification only), air pollution inequality for NO_2 decreased, while inequality for $PM_{2.5}$ increased.

Net zero policies can reduce mortality and morbidity associated with $PM_{2.5}$ and promote health benefits through active travel. Notably, the health benefits from improved air quality outweigh those generated by increased active travel, despite 2040 WI forecasts of a six-fold increase in the use of e-bikes. This reflects the fact that CCC net zero scenarios modelled a wide range of air pollution reduction policies, such as the greater use of electric public transport, rather than just a modal shift from cars to active travel. However, the scenarios were relatively unambitious in terms of a shift to active travel, especially walking as a mode of transport.

Importantly, net zero policy actions also influence indoor air quality with implications for health and wellbeing. Increasing insulation and air tightness in homes may increase indoor air pollution exposure, while excessive ventilation increases the ingress of air pollution from outdoors. However, the removal of air pollution sources due to indoor fossil fuel burning, such as gas cooking as part of net zero policies, is beneficial and may result in greater exposure reductions than outdoor air pollution, especially for NO_2.[63]

Future modelled ozone concentration changes were small, complex and difficult to interpret, reflecting the influence of meteorology, changes in hemispheric contribution, changes to anthropogenic emissions at European to UK scales, changes to biogenic emissions and local reductions in NO_X. NO_X emission reductions in urban areas generally resulted in O_3 increases; however, the UK population weighted average 8-hour maximum O_3 concentrations between 2019 and 2040 were forecast to change very little.[67]

These findings emphasise the importance of a broad range of net zero policy actions – spanning housing, transport and active travel – to achieve a more equitable distribution of air quality co-benefits at a population level. Shipping, aircraft and industrial processes remain important air pollution sources to tackle in a net zero future.

2.5.2 Future uncertainties

There are areas of uncertainty associated with predictions of future net zero impacts, including the complexity of modelling future meteorological impacts, emissions and air pollution; that more work is required to understand and model indoor air and its health effects; and that the extent to which $PM_{2.5}$ health impacts account for NO_2 effects and vice versa is unknown.

*The Carstairs index was developed in the 1980s using census data. It comprises four indicators judged to represent material disadvantage in the population: lack of car ownership, low occupational social class, overcrowded households and male unemployment.

2.6 Approaches to measuring and modelling outdoor air pollution

2.6.1 Measuring outdoor air pollution

Throughout our daily lives, we are exposed to a range of atmospheric pollutants that comprise the ambient air that we breathe. Whether indoors (at home, in offices or schools) or outdoors (walking in the countryside or travelling by public transport) we are exposed to a variety of atmospheric pollutants. These pollutants are emitted from many sources and, once in the atmosphere, are subjected to the influence of the weather. To understand their impact on both human health and the environment, we must first determine what their ambient concentrations are and how they vary spatially and temporally. Air quality is influenced by pollutant emissions into the atmosphere and the chemistry of these pollutants. The chemistry determines how a pollutant changes and interacts with the meteorology while in the atmosphere, as well as its impact at the receptor site. Additionally, the weather affects atmospheric processes, which determine the eventual fate of emitted pollutants. Weather systems, especially with global warming, are unpredictable and not subject to direct control. Nor can we control the pollutants' inherent chemistry. Air quality management has traditionally focused on controlling our pollution emissions (as we cannot control the weather), therefore aiming to reduce them at source by providing economic incentives for both reducing emissions and developing cleaner processes. Alternatively, the pollution sources may be relocated away from main population centres.

The atmosphere is a hugely complex and reactive fluid system in which a range of physical and chemical processes are at play. The nature of these complex processes means that employing monitors that record ambient measurements can only, at best, provide us with a snapshot of ambient concentrations for a particular time and location. Although useful, these measurements by themselves are not as useful as they might be to inform policy decisions or to determine the impact on our health. A national network of air quality monitors exists in the UK – the Automatic Urban and Rural Network (AURN).[73] These monitors provide measurements of specific pollutants at various locations and are used to assess compliance with legal limit values. However, some complications do exist. Installing and maintaining the network is very expensive, which limits the number of monitors used as well as their distribution. Those monitors located at kerbside sites are significantly influenced by their proximity to the strong traffic emissions that may maximise during rush hour and can record pollution levels that are not representative of the wider area. Although these measurements might indicate concentrations exceeding those to which most of the population are exposed, it should be noted that, for some of our most deprived populations living alongside busy road networks, or in schools or workplaces, and for those working in certain professions, exposure to these concentrations is the norm. Those monitors situated at locations where measured levels are not influenced significantly by any single source (or street), but rather measure the integrated contribution from all upwind sources (so called background sites), do a better job of identifying levels that are typically representative of several square kilometres. Over longer periods of time, some monitoring stations are set up or shut down, while instrument faults and maintenance may lead to gaps in measurement records. In addition, not all measurement stations record the same pollutants. Some will measure the five pollutants that are used to determine the UK Daily Air Quality Index (DAQI),[74] an index that indicates pollution levels and provides recommended actions and health advice, while others will not. Spatial coverage may also present a problem as there are large areas throughout the UK that are not adequately represented by measurements – this is particularly true in remote rural areas. With the growth in availability and accessibility of 'low-cost' air quality sensors, it may soon be possible to achieve better spatial coverage thus allowing a better assessment of ambient concentrations, and how they change across different locations and over time. This approach could be particularly useful in areas of the UK that have limited coverage by regulatory monitoring. Research is still ongoing to ascertain their suitability for such tasks. However, the European Directive on Ambient Air Quality and Cleaner Air for Europe (2008) expressed a desire to reduce reliance solely on monitoring for policy development, instead emphasising the use of models to complement monitored data.[75]

2.6.2 Modelling outdoor air pollution

Atmospheric dispersion models have become a valuable tool used to provide information about ambient outdoor air pollution concentrations. Also referred to as atmospheric chemistry transport models, these computer models use mathematical relationships to describe and simulate the physics and chemistry responsible for the processes that transport, transform, disperse (or dilute) and deposit pollutants emitted by a range of sources to the atmosphere. These models vary in the level of science that they employ. Some use very basic science and are used as 'screening' tools to indicate the potential for harm and are very quick to run. Others will incorporate complex chemistry, routines to cope with complex flow situations (around buildings and/or complex terrain) or different types of pollutants (eg gases, particulates or dense gas releases). These more sophisticated models may take longer to complete their analyses. Some of the differences we notice between different model predictions often relate to the difference in the levels of science that they employ or how well they can simulate real world atmospheric behaviour. Models therefore integrate our understanding of atmospheric processes.

Dispersion models need to represent different types of emissions – whether emerging from point sources such as chimney stacks, or line sources such as road networks emitting traffic fumes. Once the pollutants are emitted, the models will contain a meteorological input that helps simulate the various processes that collectively may transport and dilute pollution plumes. Those with complex chemistry routines allow for chemical transformations to occur while in transit in the atmosphere, forming secondary pollutant products that will differ from those pollutants originally emitted.

Some models describe how conducive the atmosphere's capacity is to facilitate mixing, which helps dilute pollutants. The way that pollutants are lost from the atmosphere is also important, whether dry deposited under gravity or literally washed out in the rain, this needs to be well characterised. Fig 2.4 illustrates the various processes that some models attempt to simulate. In addition, changes to the general wind flow patterns brought about by air masses as they pass over obstacles such as buildings, forests and large hills or mountains are important. Each alteration to the general unobstructed flow will cause a variation in the expected downwind pollution concentration.

Other data-driven techniques (such as statistical methods and, more recently, those based on AI or machine learning (ML) orientated) avoid trying to represent the physical and chemical attributes of the atmosphere. Instead, they rely on historical observed or modelled data to identify patterns, enabling the modelling and prediction of air quality.

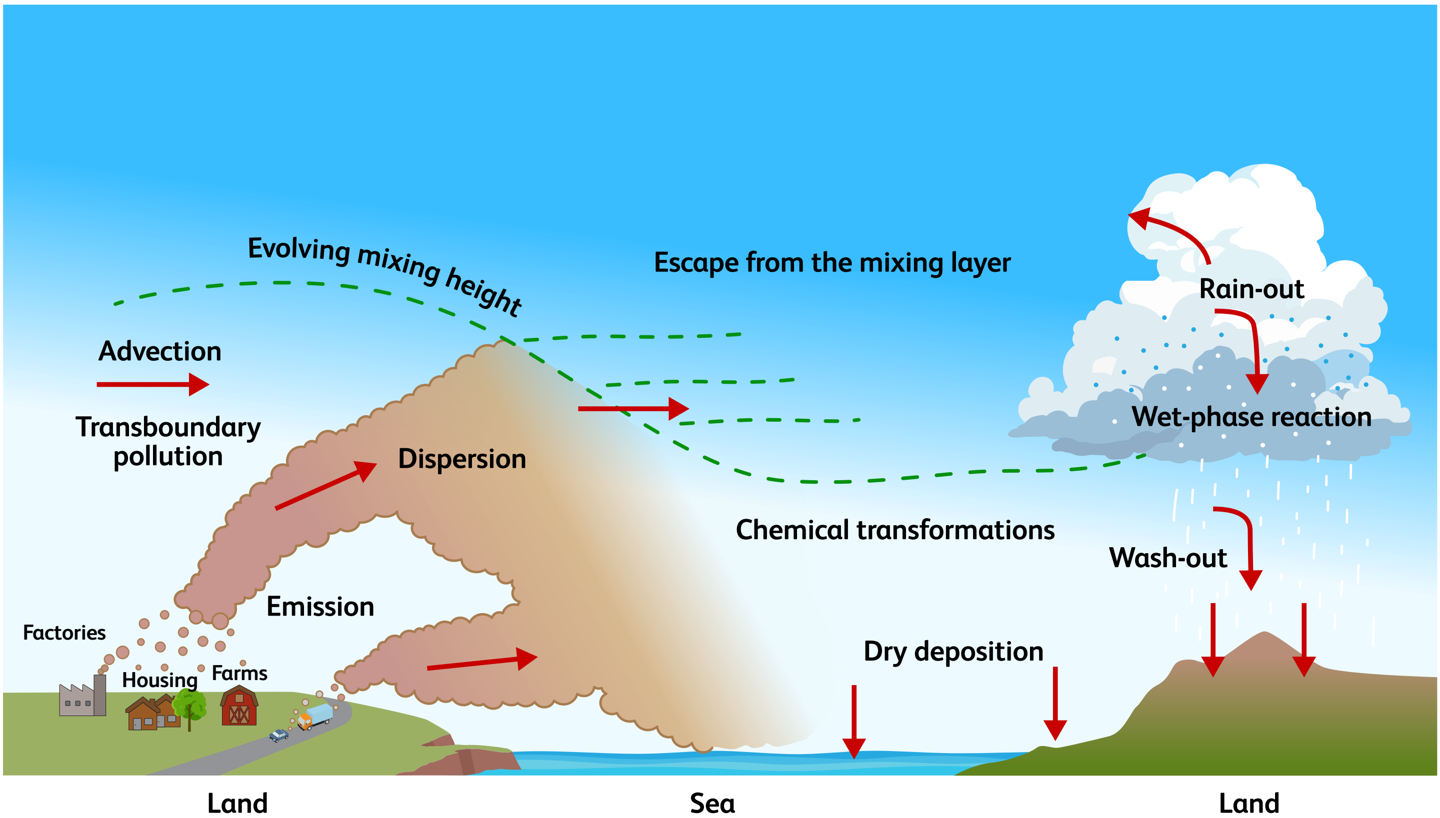

Fig 2.4. Schematic showing some of the main features that atmospheric dispersion models will attempt to simulate. ©Met Office 02817

Dispersion models are powerful tools but, like any model, they have their own shortcomings as they rely on various assumptions and approximations. They are also reliant on the accuracy of the data they are given (eg pollutant emissions and amounts) to perform their analyses. It is therefore important for users to understand the limitations of their models and input data to ensure that they are not applied in ways that are beyond their capabilities, especially when considering policy-relevant applications.

Dispersion models require two main inputs to perform their analyses: pollutant information and weather data. Pollutant information includes the chemical composition, source of the emissions (eg traffic or local industry), emissions profiles (eg whether the emission strength changes over time), release height into the atmosphere and buoyancy. If these models are provided with forecast weather data, it becomes possible to predict probable air quality levels ahead of time, making it possible for people – particularly vulnerable groups – to take actions to manage their exposure (Fig 2.5).

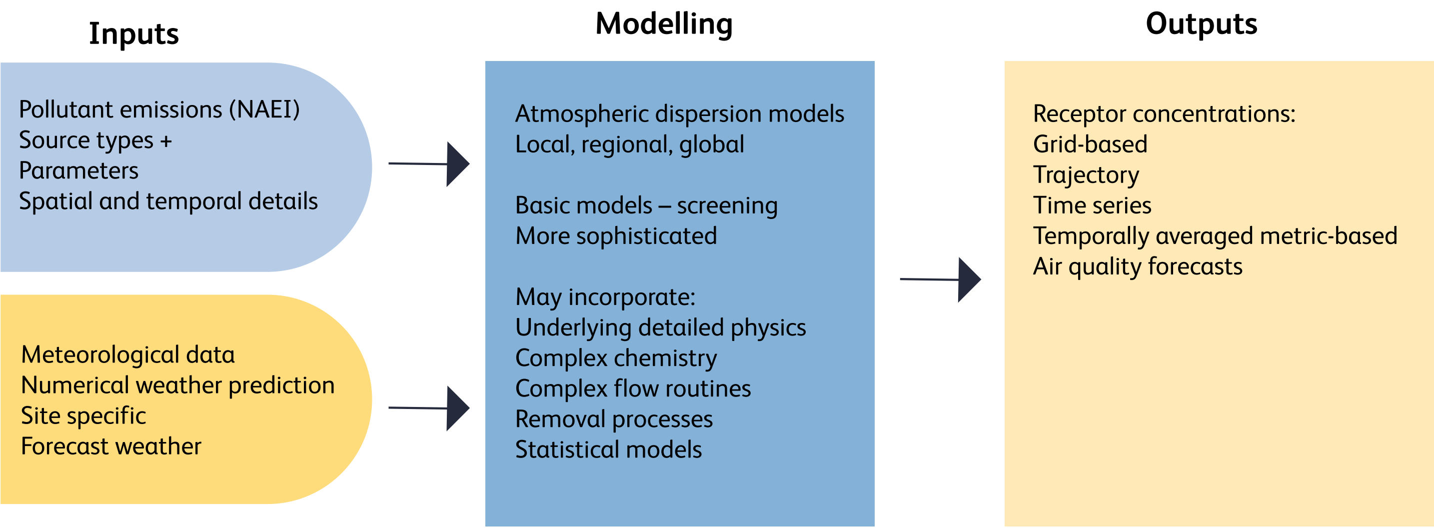

Fig 2.5. Dispersion models require good quality input data, including pollutant emissions data provided by the National Atmospheric Emissions Inventory (NAEI), and a good description of the weather, which may be obtained from numerical weather prediction (NWP) models or obtained from on-site weather stations. They can also be provided with forecast meteorology to estimate pollution levels. The dispersion models can vary in their level of sophistication and analysis response times, some are used for screening purposes while others investigate more complex problems. They output pollution concentration estimates that may take various forms depending on the questions being asked.

2.6.3 Air quality modelling to support and inform policy

Modelling of air quality plays a central role in the development and evaluation of air quality policy in the Department for Environment Food and Rural Affairs (Defra).[76] One of the main advantages that atmospheric dispersion models have over measurements is that they can be used to answer speculative questions – an attribute that makes them particularly appropriate for policy support. Observations recorded at measurement sites can, in some cases, provide a retrospective indication of how effective a particular policy decision has been. The use of models, however, can help answer a much wider range of 'what if' scenarios and policy-relevant questions:

- What proportion of a particular poor air quality event was due to transboundary movement of pollution originating on the near continent? What proportion was due to home-grown emissions?
- What is the most cost-effective way of reducing concentrations to meet a particular air quality standard?
- What will the air quality be tomorrow? If poor, how long will it last?
- If the electrification of the national fleet were to increase by X% over the next Y years, what impact will that have on pollution levels?
- As the climate changes, what impact will warmer winters, wetter summers and other changes have on our seasonal pollution events?

Given the broad range of potential questions that could be asked by the policy developer, and the variety of models with differing strengths and weaknesses, it is essential to match the right modelling approach to the questions being posed. In the UK we have adopted a 'horses for courses' rather than a 'one size fits all' approach for our modelling requirements. When used for policy development, matching the model to the type of question being asked, which plays to the strengths of that model, is paramount. In addition, model results for critical policy questions are usually confirmed using another similar model.

2.6.4 The future of air quality modelling

As computing techniques and power improve, there will be a drive towards providing the public with more local estimates of pollution concentrations. Informing the public about street-level concentrations and how they might change throughout the day, may prove useful to those who are particularly sensitive and may provide them with the information they need to manage their exposure.

The descriptions given thus far relate to the way we examine outdoor air quality, the tools used to determine areas of poor air quality or hotspots, and to forecast pollutant episodes. Although useful, this by itself does not tell us a great deal about our actual exposure to these pollutants (required for improving our understanding of health impacts and outcomes), especially as we tend to spend more of our time within indoor environments such as our homes, schools, places of work, and on public transport etc. The importance and priority of indoor air quality has risen in recent years, and it is possible that we can adopt a similar approach to understanding the impact on our health within indoor spaces. As with outdoor pollution, generating an understanding of the relevant pollutants, their sources, sinks and emission factors will be crucial. Linking these emissions to mathematical models that characterise the indoor environment would be the next step.

With improved characterisation of both indoor pollution levels as well as street-level concentrations, it is possible that we may gain a clearer understanding about our total exposure to a range of pollutants. This information would be invaluable to health communities, aiding in predicting likely health outcomes based on specific levels of exposure. Modelling the indoor environment could also inform the design of our indoor spaces – balancing the need to develop energy efficient living spaces with reduced heat losses while at the same time permitting better ventilation and therefore less build-up of harmful pollutants or spores. This would require multisector involvement from building design, developers and regulators, as well as those responsible for the modelling. Modelling could also help identify high-risk areas, especially those with high deprivation and poor air quality, for prioritised and targeted action. Such models are able to map out areas where multiple factors like pollution sources, air dispersion and social deprivation intersect, highlighting communities that are particularly vulnerable to the negative impacts of poor air quality.

There are many limitations to the current use of modelling and monitoring of air quality. As with many areas of environmental science, the application of AI has the potential to significantly change how we develop our tools for determining the quality of the air we breathe. Broadly speaking, AI comprises a series of technologies that enables computers and machines to approximate human learning, comprehension, problem solving, decision making, creativity and autonomy.[77] AI can be considered as a group of nested or derivative concepts built up over the past 70 years or so (Fig 2.6). AI is an umbrella term that could include other concepts such as ML, deep learning (DL) and generative AI (gen AI). In the context of air quality control and the wider environmental sciences, the most relevant forms of AI are ML and DL. Although some are already investigating their usefulness in this area, the future is likely to see these techniques become more commonplace.

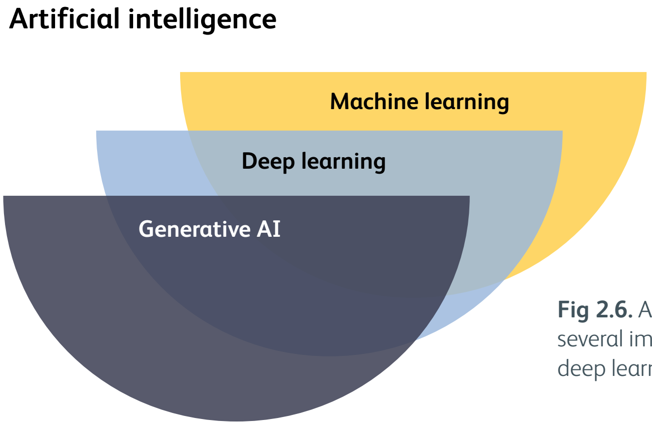

Fig 2.6. Artificial intelligence is an umbrella term that includes several imbedded or nested concepts such as machine learning, deep learning and generative artificial intelligence.

The proliferation of low-cost remote sensors and the availability of large quantities of environmental and clinical data has led to a surge in pollution datasets available for health outcomes analysis.[78] Data sources can include those from sensors, satellites and historical records as well as other forms of data such as meteorological and geospatial data (land use, traffic patterns etc). These large complex datasets can be challenging for traditional epidemiological and environmental health models to utilise. Standard statistical linear regression models struggle to capture the non-linear relationships effectively.[79] AI methods involving both ML and DL techniques are showing themselves up to the task of improving traditional epidemiological and environmental health models.[80] AI methodologies can also prove useful for developing real-time tracking of pollution hotspots, identifying pollution trends and modelling the impact of meteorological factors. Furthermore, the algorithms incorporated within ML, such as artificial neural networks or random forest, excel at handling multidimensional air quality datasets, resulting in improved understanding of the complex relationships between air pollution and its health impacts.[81]

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03

Creating policies fit for the future

Limit values encourage action, but continuous improvement needs to be embedded into air quality policy.

Effective urban planning and space design can reduce air pollution.

The government needs to set a pathway towards **WHO's 2021 air quality guidelines** and regularly review progress.

Air quality must be seen as a public health issue, not just an environmental one.

Tackling all air pollution sources should be prioritised over individual interventions.

Policies need to be **developed with public engagement.**

The government should deliver a coordinated, UK-wide public health clean air campaign.

Policy development must respond to new evidence on its health harms and impacts, including on brain health and dementia.

Health professionals must take greater ownership of this public health challenge, speak about it with their patients and advocate for cleaner air.

Key points

- Recent studies have provided compelling new evidence on the detrimental impact of toxic air on brain health across the lifecourse from development to older age. This includes effects on early-life cognitive development, later-life neurodegenerative disorders, and mental health. Policies should address these impacts across the lifecourse, especially for vulnerable populations.
- Local initiatives such as clean air zones, low traffic neighbourhoods and London's Ultra Low Emission Zone have achieved some success in lowering vehicle emissions. However, they have also faced concerns and opposition. Further work is required to ensure public support for policies aimed at benefiting public health and protecting the most vulnerable.
- Transparency and evidence should be used to address the politicisation of clean air initiatives and untruthful narratives, while raising the profile of public health in central and local policies.
- Regional variations in emissions and the vulnerabilities of different communities should be considered when setting local strategies to reduce population exposure. Limit values of air pollutants are important as legally binding targets. However, regulating around a maximum limit for acceptable air quality tends to focus disproportionately on those locations with the highest concentrations.
- Given that sources of emissions are continually changing, new approaches should be explored in setting air quality standards in the UK, including co-development with people affected and application of complexity methods to take account of political, environmental, social, technological, economic and ethical considerations.
- Urban planning can effectively reduce people's exposure to air pollution. The urgent push for building new homes and retrofitting to meet net zero targets in the UK creates opportunities for lowering air pollution by moving away from cars and increasing green space, cycling lanes and physical activity. Health should be a priority in any urban planning and health professionals need to become more engaged in this activity.
- Given that air pollution is a significant factor in many diseases and developmental processes, it is important for health professionals to take greater ownership of the problem. Educational programmes should be put in place to support them to protect the health of the public, as directed by the GMC's *Good medical practice*. Examples are given to illustrate the types of activities that this may involve.
- Given the need to see behavioural change across the population, there should be support for the healthcare workforce to help them to change their behaviour as well.

3.1 Introduction

Our understanding of the adverse effects of poor air quality has grown considerably since the publication of the *Every breath we take* report in 2016. Part 3 uses the evidence outlined in Parts 1 and 2 to examine policy measures aimed at improving air quality. It includes a focus on brain health, outlines current central and local air quality policies across the UK, and explores possible future policy development. It considers how urban planning influences air quality and the co-benefits of improvements to the wider environment and people's lived experiences. Finally, with improved health becoming a key focus for greater action, it calls for improved health practitioner education on issues relating to air quality, including communication with patients.

3.2 Air quality policy and brain health

3.2.1 The impact of air pollution on brain health

As discussed in Part 1, a major addition to the air quality literature – and a fast-growing topic of study – is the impact that air pollution has on brain health across the lifecourse. Of particular concern is the effect of exposure to air pollution at critical stages in our lives, such as on early-life cognitive development, as well as the effect of cumulative exposure across time, such as on the development of dementia, cognitive frailty and Parkinson's disease.[1–4] More broadly, air pollution is also associated with general mental health issues such as depression and anxiety and is also an identified risk factor for schizophrenia and personality disorders.[5,6] Its impact on people who have existing brain and mental health vulnerability is an additional concern.

While most studies focus on the increased mental health risks resulting from air pollution exposure, research has begun to explore the post-diagnostic impact of air quality. For example, there is now strong evidence that air pollution exposure contributes to dementia progression and Alzheimer's disease deterioration.[7–9] Research also suggests that for people with dementia, air pollution exposure can have an impact even at concentrations below the current US EPA annual standard for $PM_{2.5}$ of 9 $\mu g/m^3$, and well below the limits of the UK (20 $\mu g/m^3$) and the European Union (25 $\mu g/m^3$).[10]

3.2.2 Interactions between air pollution, inequalities and mental health

As outlined in Part 2, pre-existing or ongoing vulnerability is not just biological or psychological, it is also social. The impact of air pollution on brain and mental health appears to be interwoven with the wider determinants of health, including systemic inequalities, pre-existing public health vulnerabilities, the built environment, transport, discrimination and entrenched socio-economic deprivation. Examples include how the causal loop between poverty, living near an industrial air pollution source, and social inequalities across the lifecourse impact upon cognitive decline and neurodegenerative disorders in older, urban populations. Or, how air pollution exposure in early life impacts adolescent global cognition, on account of poor health behaviours, limited access to green space, living in congested housing with poor indoor air quality, and walking to school on busy more polluted roads.[11] People living in poverty due to mental health disorders are more likely to have additional breathing issues, making them more susceptible to the impact of air pollution. The places where people are born, live, work and grow old matter very much in terms of the quality of air they breathe and its effects on their brain and mental health.

3.2.3 The need for brain health to be built into air quality policy

Current public policies have been developed to mitigate the impact of air pollution on a variety of health outcomes – from asthma and heart disease to chronic obstructive pulmonary disease (COPD) and lung cancer. However, their implications for brain and mental health are only just beginning to be explored.[12,13] There is a need for new policies that specifically address mental health, given that the effects of air pollution on the risk factors for vascular dementia and Alzheimer's disease for example (such as dose response, pollutant mixture, pathways to disease), differ from those for exacerbating lung disorders such as asthma and COPD.

In 2022, Castellani *et al* published the first policy agenda for mitigating the impact of air pollution on brain and mental health, including dementia. They identified three policy domains – research and funding; education and awareness; and policy evaluation – and 14 priority areas, each of which contain a set of immediate to long-term actionable items (Fig 3.1).[11] Some of these priority areas are explored further below.

Policy agenda for mitigating the impact of air pollution on brain and mental health

1. Policy needs to focus on how the cities and towns in which we live impact the air we breathe
2. Strategies need to focus on the air quality of highly vulnerable groups such as older people
3. Scientists need to build historical models of air quality going back to the 1970s
4. More research is needed on indoor air pollution – we spend 80 % of our time indoors
5. We need greater understanding of how air pollution impacts brain health
6. Air quality policies need to focus on prenatal care, childhood and ageing – the critical periods in life where they can have the biggest impact
7. Governments and foundations need to provide more funding in this area
8. We need to bring public attention to this issue
9. Schools, universities and healthcare providers need to educate children and adults about the effects of air pollution
10. Existing campaigns on brain health, dementia and climate change need to link to air quality
11. People need access to apps and monitors to assess the quality of the air they breathe
12. Scientists and governments need to better evaluate air pollution policies to improve brain and mental health
13. Everyone – from citizens to businesses – needs to be involved in developing and implementing policy
14. Research needs to show how air quality impacts on climate change and other environmental health issues
15. Policy needs to address how air pollution may worsen the health of people with dementia and other mental health issues

Fig 3.1. Policy agenda recommendations to mitigate the impact of air pollution on brain and mental health. Wording adapted from Castellani et al (2022)[11] under the CC BY 4.0 licence.

1. **Rethinking funding.** At present there are few if any research funding calls to explore the impact of air pollution on brain or mental health. To address the priority areas outlined in this domain, air pollution and public health funding needs to finance high-risk/high-reward research. Otherwise developing the evidence necessary to develop cost-effective, scalable, high-impact public policy, particularly in terms of the long-term historical impacts that air pollution has on cognitive decline, dementia and later-life neurodegenerative diseases, will remain intractable.[11]
2. **Ensuring that the effects of air quality on brain health are recognised in existing environmental health strategies.** Policies directed at environmental health, such as clean air strategies, green urban planning, improving public transport, transitioning to net zero policies, healing ecosystems and promoting better diet and exercise also include benefits for brain and mental health. For example, third sector and governmental organisations focused on dementia or neurodegenerative diseases should emphasise the importance of clean air for brain and mental health. Similarly, school systems focused on cognitive development should consider that the impact of idling cars at drop-off and pick-up, for example, is damaging to a young person's brain.[14,15] The sheer volume of cars on the roads not only increases air pollution but also stops parents from allowing their children to travel to school independently.[16] Alternatively, clean air strategies could include improved mental health and wellbeing among their benefits, and link these to climate change and urban development strategies.
3. **Engaging in co-production and participatory research.** Air quality is one of the more politically charged global social problems that affects communities worldwide. The politics of air quality are due, in part, to news and social media misinformation, the lobbying by industry and corporations, voting practices and vote share across different groups, the agenda of different political parties, the challenges of public transport, regressive car taxes on people on lower incomes, the complex ways in which clean air strategies are intertwined with economics and workforce issues, and the inability for citizens to directly see air pollution's influence, particularly in the case of long-term impact. Given these 'political' complexities and associated power imbalances, inequities and inequalities, it is vital that stakeholders at local, regional or national levels are involved in developing this policy area. This will ensure that the conflicting needs of governments, businesses, organisations and citizens are kept at the forefront of policymaking and evaluation, which is crucial to removing barriers and improving levers to change.
4. **Targeting policy at key points in the lifecourse**, with the two most important being early life, when brain development and mental health are critical, and later life, when people are more vulnerable due to ageing processes and the cumulative impact of lifetime exposures are evident. Improving indoor air quality in schools, homes and care homes is a good example, or requiring social and private landlords to install heat pumps to reduce both fuel poverty and carbon emissions.
5. **Understanding the post-diagnosis impact of air quality on dementia and other mental health and brain-based disorders.** While the research on this topic is still in its early stages, if air pollution is found to accelerate certain brain or mental health disorders for specific groups of people, it would offer the potential for major advances in secondary and tertiary prevention, which would not only help to improve the lives of people, but also significantly reduce healthcare expenditure.

3.2.4 Summary

The link between air pollution and brain health, including early-life cognitive development and later-life neurodegenerative disorders such as dementia, Parkinson's disease and cognitive frailty should be taken seriously and needs further research. The mental health burden of air pollution is not just an increase in diagnosed psychiatric disorders, but also a worsening of mental health in general. It disproportionally impacts vulnerable populations experiencing poverty, inequality and deprivation. Future air quality policy needs to recognise and aim to mitigate the impact of air pollution on brain and mental health.

3.3 Recent developments in UK air quality policies

3.3.1 Air quality policies across the nations

Air quality policy, as a devolved responsibility, has evolved differently across the UK nations within the agreed air quality provisional common framework.[17] Since the publication of the RCP/RCPCH report *Every breath we take* in 2016 and the 2018 progress update, new legislation and a shifting policy focus have emerged in response to changing pollutant trends and sources. The 2019 Clean Air Strategy[18] set out plans and actions in England to reduce emissions, not only from transport, but also from homes, farming and industry, to protect public health and the environment. These plans and actions have begun to be implemented in subsequent national and local policy documents. The following section explores the policies related to the UK and England with separate boxes highlighting policies specific to Scotland, Wales and Northern Ireland.

3.3.2 Clean air zones – do they work?

Clean air zones (CAZs) have continued to be introduced by local authorities across England (and low emission zones [LEZs] in Scotland) to reduce NOx and especially NO_2 from road traffic to help national governments to achieve long overdue health-based air quality standards.[19] As of April 2024, there are CAZs in seven towns and cities[20] as well as London's Ultra LEZ (which was expanded in August 2023 to include Outer London). The four classes of CAZ cover a range of vehicle types from Bristol and Birmingham's Class D CAZs, which include private vehicles, to Bath and Sheffield's Class C CAZs, which only extend to commercial vehicles. While some local authorities have also adopted other types of CAZ (eg York's bus-only CAZ), others have rejected CAZs due to falling trends in NO_2 and/or implementation of other pollution reducing measures (eg Leeds, Southampton and Manchester). Early indications are that CAZs have been effective in reducing NO_2[21–23] and may be linked to improvements in respiratory and cardiovascular health,[24,25] as well as sick leave and mental wellbeing,[26] although trend data over the post-implementation periods were also affected by traffic reductions due to the 2020/21 COVID-19 lockdowns. Currently, there is insufficient evidence to show whether CAZs will meet the 2021 World Health Organization (WHO) air quality standards, although recent studies back up their effectiveness in terms of benefiting health.[26a,26b]

There have also been challenges with implementation in some areas, such as Greater Manchester, with vocal local opposition.[27] It is unclear whether the Department for Environment, Food & Rural Affairs/Department for Transport (Defra/DfT) Joint Air Quality Unit will require local authorities to cease to impose emissions-based restrictions on vehicles once the legislative thresholds have been achieved, or whether they will continue to pursue lower concentration levels in recognition of the WHO air quality guideline 2021 update for annual NO_2 (10 $\mu g/m^3$) and the 2030 EU limit values (20 $\mu g/m^3$). It is worth noting that any new CAZs based on the existing emission standard restrictions are likely to deliver less benefit than those already in place. This is due to progressive changes to the vehicle fleet through current mandated and future technological improvements in vehicle pollutant emissions, including replacement by electric vehicles. As a result, the original emission restrictions will most likely no longer continue to drive improvement. However, there may be scope for local authorities to go further and adopt more ambitious zero emission zones (ZEZs), as in Oxford.[28] While ZEZs are beneficial for reducing NO_x and CO_2 emissions, they may be less effective in reducing PM concentrations due to increased particles from heavier vehicle non-combustion sources such as tyres, brakes and road wear when replacing petrol and diesel engines with electric ones.[29]

Local government progress on reducing NO_2 from road traffic (also a statutory responsibility under the Local Air Quality Management [LAQM] framework) has been undermined by mixed messaging from national government. Historically, reduced vehicle excise duty[30] in the 2000s encouraged drivers to shift to more fuel-efficient, and therefore lower carbon-emitting, diesel vehicles, and more recently in 2023, the then prime minister Rishi Sunak announced that the planned 2030 ban on sale of new fossil-fuelled vehicles would be pushed back to 2035.[31] This response was in light of objections from some to the extension of the London ULEZ and implementation of low traffic neighbourhoods (LTNs), as well as retained measures introduced during the COVID-19 lockdowns to repurpose road space for walking and cycling as public transport was more limited then.[32] The Labour government confirmed its decision to reinstate the 2030 ban in September 2024. This means that no new petrol or diesel cars will be allowed to be sold in the UK after 2030.[33] The politicisation of road transport policies has undermined the public health rationale for their implementation. It also highlights a lack of awareness about the significance of air pollution, as well as the challenges faced by authorities when sectors of society do not feel adequately consulted about measures that are perceived to have the potential to inhibit their freedoms.[34]

It also emphasises the importance of stronger health and economic framing of air pollution problems, especially recognising the importance of demonstrating the economic/financial consequences of continued air pollution and the high return on investment of interventions to reduce it.

3.3.3 Integration of air quality with other policy initiatives

To provide consistency in air quality policy that gives the public, local authorities and businesses confidence to invest in cleaner technologies and behaviours, it is important for national government to ensure integration with other policy areas, such as decarbonisation strategies (eg net zero, renewable energy), to avoid these trade-offs at the expense of public health. It is also apparent that further work is required to ensure that people are brought onboard with policies that are ultimately for broad public health benefit and to protect those most vulnerable, through more actively listening to their concerns and shifting the narrative away from a false 'them and us' dichotomy.

3.3.4 Measures to reduce exposure to different pollutants

Although NO_2 is itself a health-damaging pollutant, CAZs have not significantly reduced particulate matter[35] which, as a complex pollutant, has a greater impact on public health, especially in the long term. In England, the 2021 Environment Act introduced new $PM_{2.5}$ concentration targets (annual mean concentration target 10 µg/m^3 to be achieved by 2040 and a population exposure reduction target of 35 % by 2040),[36] with interim targets set in the Environmental Improvement Plan.[37] It also introduced civil penalty notices to make it easier for local authorities to challenge non-compliance with smoke control areas under the Clean Air Act 1993.

Further regulations relating to reducing emissions from domestic solid fuel burning were brought in under the Air Quality (Domestic Solid Fuels Standards) (England) Regulations 2020,[38] which banned the sale of traditional house coal completely in England from May 2023 (although 'smokeless' fuels are still permitted). It also introduced regulation of the sale of wood fuel to control its moisture content in order to reduce $PM_{2.5}$ emissions when burned. Domestic burning is now responsible for 20 % of UK emissions of $PM_{2.5}$.[39] The growth in homes with wood burners is especially concerning – these alone produced 11 % of UK $PM_{2.5}$ in 2023.[39] Responsibility for implementing these regulations falls to local authorities, which can issue £300 fixed penalty notices or more substantial fines via the courts for repeat offenders.[40]

However, it is not an insignificant burden for local government, with limited available resources, to manage both the sale and use of solid fuels. Indeed, only one prosecution and three fines were issued in nearly 2 years for illegal wood burning in smoke control areas since January 2022, despite councils receiving over 10,600 complaints.[41]

Furthermore, public awareness is low and there has been very limited (if any) active public messaging at a national level around the health impacts of solid fuel burning, which then makes it challenging for local authorities to broach the issue in their areas. A Defra-commissioned evaluation of the Air Quality (Domestic Solid Fuels Standards) (England) Regulations 2020 is pending at the time of writing.[42] It is therefore of great concern that wood-burning stoves may be allowed as secondary heating for new-build homes in England despite overwhelming evidence showing their significant contribution to air pollution and carbon emissions.[43]

3.3.5 The evolution of local air quality policies

As required by the 2021 Environment Act, Defra's Air Quality Strategy for England[44] was published in May 2023. This represents an update to the previous 2007 Air Quality Strategy for England, Scotland, Wales and Northern Ireland[45](which still applies in Scotland and Northern Ireland), with a commitment to update every 5 years thereafter. This recent England-only strategy sets out expectations for local government, building on their existing local air quality management (LAQM) duties from the 1995 Environment Act (Part IV) and incorporating these additional responsibilities.[44]

Some of these changes were also introduced in the August 2022 update to the LAQM Policy Guidance.[46] This guidance includes new responsibilities for local authorities to take account of air quality disparities and health, recognising that higher concentrations of pollutants, such as NO_2, are often found in more socially disadvantaged areas and that this can further compound and entrench health inequalities. Therefore, local authorities should consider disparities resulting from differential exposures to air pollution, as well as the implications of policy implementation for those with least ability to limit their exposure or change their behaviours (eg through limited choices over where they live, work, travel or heat their homes). SHAPE Place,[47] an interactive mapping tool that is free to the public sector, includes a pilot air pollution vulnerability indicator (APVI) developed by the UK Health Security Agency (UKHSA) to enable local authorities to identify focus areas.

The APVI is based on the population characteristics (percentage of young people [<16 years] and older adults [65 years and older]), levels of deprivation (Index of Multiple Deprivation score), location of vulnerable populations (hospitals, schools, care homes and childcare facilities) and the concentration of air pollution (NO_2 and $PM_{2.5}$) modelled for 2018. The Office for Health Improvement and Disparities' Fingertips tool also includes an indicator for the fraction of mortality attributed to particulate matter, which local authorities can use to benchmark against national and other local data and observe trends (Fig 3.2).

Air pollution: estimated fraction of mortality attributable to particulate air pollution 2023 — Proportion - %

Area	Recent Trend	Count	Value	95% Lower CI	95% Upper CI
England	–	-	5.2	-	-
South West region (statistical)	–	-	4.3	-	-
Swindon	–	-	5.0	-	-
Bristol	–	-	4.7	-	-
South Gloucestershire	–	-	4.7	-	-
Gloucester	–	-	4.6	-	-
Bournemouth, Christchurch and Poole	–	-	4.5	-	-
Cheltenham	–	-	4.5	-	-
Wiltshire	–	-	4.5	-	-
Bath and North East Somerset	–	-	4.4	-	-
Cotswold	–	-	4.4	-	-
Tewkesbury	–	-	4.4	-	-
Plymouth	–	-	4.3	-	-
Stroud	–	-	4.2	-	-
Exeter	–	-	4.2	-	-
Dorset	–	-	4.2	-	-
Somerset UA	–	-	4.2	-	-
North Somerset	–	-	4.1	-	-
Torbay	–	-	4.1	-	-
Mid Devon	–	-	4.1	-	-
Teignbridge	–	-	4.0	-	-
Cornwall	–	-	4.0	-	-
East Devon	–	-	4.0	-	-
Forest of Dean	–	-	3.9	-	-
South Hams	–	-	3.9	-	-
West Devon	–	-	3.8	-	-
North Devon	–	-	3.7	-	-
Torridge	–	-	3.7	-	-
Isles of Scilly	–	-	3.3	-	-

Fig 3.2. Public Health Outcomes Framework (OHID Fingertips tool) for $PM_{2.5}$ by district/UA for the SW region as an example. Office for Health Improvement and Disparities. Public health profiles. [Accessed 3 June 2025]. https://fingertips.phe.org.uk © Crown copyright, 2025.

3.3.6 Raising the profile of public health in setting policies

The role of public health professionals, including directors of public health, has increased with an explicit requirement for them to be engaged in LAQM, and for them to consider air quality in their Joint Strategic Needs Assessments. In 2017 Defra and (then) Public Health England produced a briefing for directors of public health on air quality, engaging local decision-makers and communicating with the public.[48] Since July 2022, integrated care boards and partner local authorities have been required to establish an integrated care partnership, bringing together health, social care, public health and wider representatives to develop an integrated care strategy, with air quality being a key area for public health focus in some areas. As part of the NHS's national bundle of care for children and young people with asthma, air pollution (including indoor air) should be accounted for as an environmental trigger.[49] The 2024 British Thoracic Society/NICE/SIGN asthma guidelines also now include outdoor and indoor air pollution as a causal factor and helpful advice relating to this.[50] However, while there is evidence that air quality is now being included in public health strategies, the effects on managing air pollution or reducing public exposure deserves more attention.

3.3.7 Air quality policies in the devolved administrations

Scotland

When compared with the rest of the UK, Scotland has a lower air quality target for $PM_{2.5}$ of 10 µg/m^3 annual mean to be achieved by 2020. In 2021, the Scottish government published its second 5-year air quality strategy, Cleaner Air for Scotland 2 (CAFS2) – Towards a Better Place for Everyone.[51] To support work on CAFS2, the Scottish government commissioned a global review of evidence on the health impacts of low-level air pollution in 2023,[52] which, as discussed elsewhere in this report, indicated that both physiological and mental health conditions are associated with concentrations below legislative standards. While traffic-related pollution continues to be addressed through the expansion of Scotland's LEZs, which are now fully up and running in Glasgow, Edinburgh, Dundee and Aberdeen, an ambitious new policy designed to reduce emissions from domestic heating systems was heavily scaled back following its initial publication. The New Build Heat Standard was introduced in April 2024 and, in addition to requiring new buildings to install climate-friendly heating systems rather than oil and gas boilers, limited the use of other direct emissions heating systems (eg wood-burning stoves) to (only) emergency heating.[53] Following review, the restrictions were scaled back, with both wood-burning stoves and peat heating systems now able to be installed in new buildings for any purpose.[53] This change was in response to public (particularly rural and island communities) and industry opposition, highlighting the importance of gaining public and wider stakeholder support for policy implementation.

Wales

In Wales, the Environment (Air Quality and Soundscapes) (Wales) Act 2024 has introduced new duties and responsibilities for ministers and local authorities, as outlined in the 10-year 2020 Clean Air Plan for Wales: Healthy Air, Healthy Wales,[54] with a delivery plan to promote awareness of air pollution due by March 2025. The Wales Environment Act 2024 committed the Welsh government to develop targets in line with the most recent WHO guidelines: '3 (2) … the Welsh Ministers must have regard to any guidelines for that pollutant published by the World Health Organisation in its most recent global air quality guidelines'. The $PM_{2.5}$ target will need to be set by February 2027, while at least two other pollutants will need to be set by February 2030. Reference plans for guidance and regulations on local air quality, domestic burning and vehicle idling are due in 2025.

The Clean Air Plan is thematically aligned to the Well-being of Future Generations (Wales) Act 2015, including health, equality, prosperity and resilience. Progress on the Clean Air Zone Framework in Wales has been subsumed within plans to develop a fair road user charging package of measures to improve travel choices.[55] However, the Welsh government has amended its ambitious 20 mph limit on restricted roads to improve road safety and encourage active travel, which was introduced in 2023, to allow highways authorities to decide whether to revert to 30 mph limits in some areas.[56] Although not explicitly an air quality policy, lower speeds will likely improve traffic flow thereby reducing frequent stop-start emissions,[57]. Reprioritising road user needs in favour of walking and cycling also encourages modal shift from private vehicles with road space reallocation being effective in increasing walking and cycling.[58] Policies to address $PM_{2.5}$ from domestic solid fuel burning are under consideration, however, ammonia from dairy and chicken farms in Wales are also potentially significant sources of secondary $PM_{2.5}$, requiring detailed source apportionment to target policy effectively.

Northern Ireland

Northern Ireland's air quality issues in many ways mirror those in Wales, but with a delay in policy implementation. In 2020, the Department of Agriculture, Environment and Rural Affairs (DAERA) launched a public discussion on the draft Clean Air Strategy for Northern Ireland.[59] Consultation responses were published in June 2022, but in the absence of an operational government in Northern Ireland at that time, progress has been limited. The Clean Air Strategy is due to be published in 2025.

$PM_{2.5}$ has been cited as a key issue with an associated mortality burden of 900 premature deaths[60] and significant impacts on morbidity,[61] although, contrary to wider literature, little evidence on the impacts on birth outcomes.[62] According to a recent study, achievement of the WHO air quality guideline for $PM_{2.5}$ could reduce excess mortality by 400 per year.[63]

There is an over-reliance on solid fuel burning (especially coal), which is the responsibility of the Department of Economy, and cross-border issues with smuggling and transboundary emissions into the Republic of Ireland (ROI restricted the sale of household coal, wet wood and turf in October 2022).[64] There are also significant secondary inputs from agricultural ammonia (Northern Ireland is responsible for 12% of UK ammonia emissions, primarily from cattle).[65] Further understanding of the relative contributions to $PM_{2.5}$ is therefore required.
A draft ammonia strategy has been published, but this is largely to protect vulnerable ecosystems.[65] There is also net zero energy policy that aims to phase out use of coal and other solid fuels for domestic heating.[66] To avoid trade-offs and to strengthen the public health outcomes, it is important to ensure synergies across these different policies with the Clean Air Strategy.

3.4 Limit values for controlling air pollution

Many jurisdictions worldwide set legal maximum concentrations for outdoor air pollutants that should not be exceeded. The apex standards used in the governance of public air quality are those associated with maximum daily or annual mean ambient concentrations known as 'limit values'.

Following the Environment Act 2021, in 2023 the government set an annual mean concentration target of reducing concentrations of $PM_{2.5}$ in England to 10 µg/m^3 by 2040, in line with the recommendations in the prevailing WHO 2005 global air quality guidelines.[67] Although the WHO subsequently issued new guidelines in 2021[68] recommending a lower maximum annual average for $PM_{2.5}$, these are not currently reflected in targets that apply to England.

Limit values function in law on the basis of a simple pass or fail test, but from a health perspective, this is scientifically misleading because air pollution harms do not stop at just below the limit value cut-off. The WHO 2021 air quality guidelines define 'the lowest exposure level of an air pollutant above which the guideline development group is confident that there is an increase in adverse health effects'.[68] These are often low ambient concentrations of pollution, for example an annual mean 5 µg/m^3 for $PM_{2.5}$ or 10 µg/m^3 for NO_2. The WHO provides a synthesis of health evidence to motivate actions, but the 2021 guidelines do not consider issues associated with achievability in each location and are not intended to serve as a regulatory blueprint.

Setting legal limit values for a country is complex and frequently contentious. The limit values must consider the latest health evidence regarding potential harms (such as the WHO 2021 guidelines) and should be ambitious in terms of the challenges they present. However, standards must also reflect practicability, social acceptability, enforceability and economics and not lead to unintended negative impacts in other domains. Stakeholders can weight these various factors differently in their assessments. Achievability is important – if failure to meet air quality standards is perceived as inevitable no matter what actions are taken, this may lead to effective policy deprioritisation, because investment and change brings no likely compliance benefit.

An air quality limit value alone does not directly improve air quality. It simply sets a desired destination, with the force of law behind it, but says nothing about how it can be achieved. Improving air quality to meet a limit value requires actions that aim overwhelmingly to reduce emissions, sector by sector, process by process. The nature and type of those air quality-improving interventions mirror some of the concepts used in a public health intervention ladder.[69] At the bottom of the ladder sit public information, behavioural nudges and opt-in community initiatives, further up the ladder are voluntary industry codes of practice, local or national government advice, guidance and best practice, and at the top of the ladder sit the most restrictive and punitive interventions, for example regulations that set legal limits on emissions, which limit personal or business activities, or sanction and fine polluters.

Of course, it is possible to improve air quality without a statutory obligation to do so, but case histories from around the world show that without legal limits on pollution in ambient air, action to improve air quality is slow.[70] A consequence of regulating based on a maximum limit of pollutants for acceptable air quality is that it can disproportionately focus policies, action and investment on locations with the highest concentrations. This limitation was noted by the European Commission Working Group on Particulate Matter as part of the Clean Air for Europe programme 20 years ago and led to the introduction of additional $PM_{2.5}$ objectives for continuous reduction in the exposure of the population to fine particles.

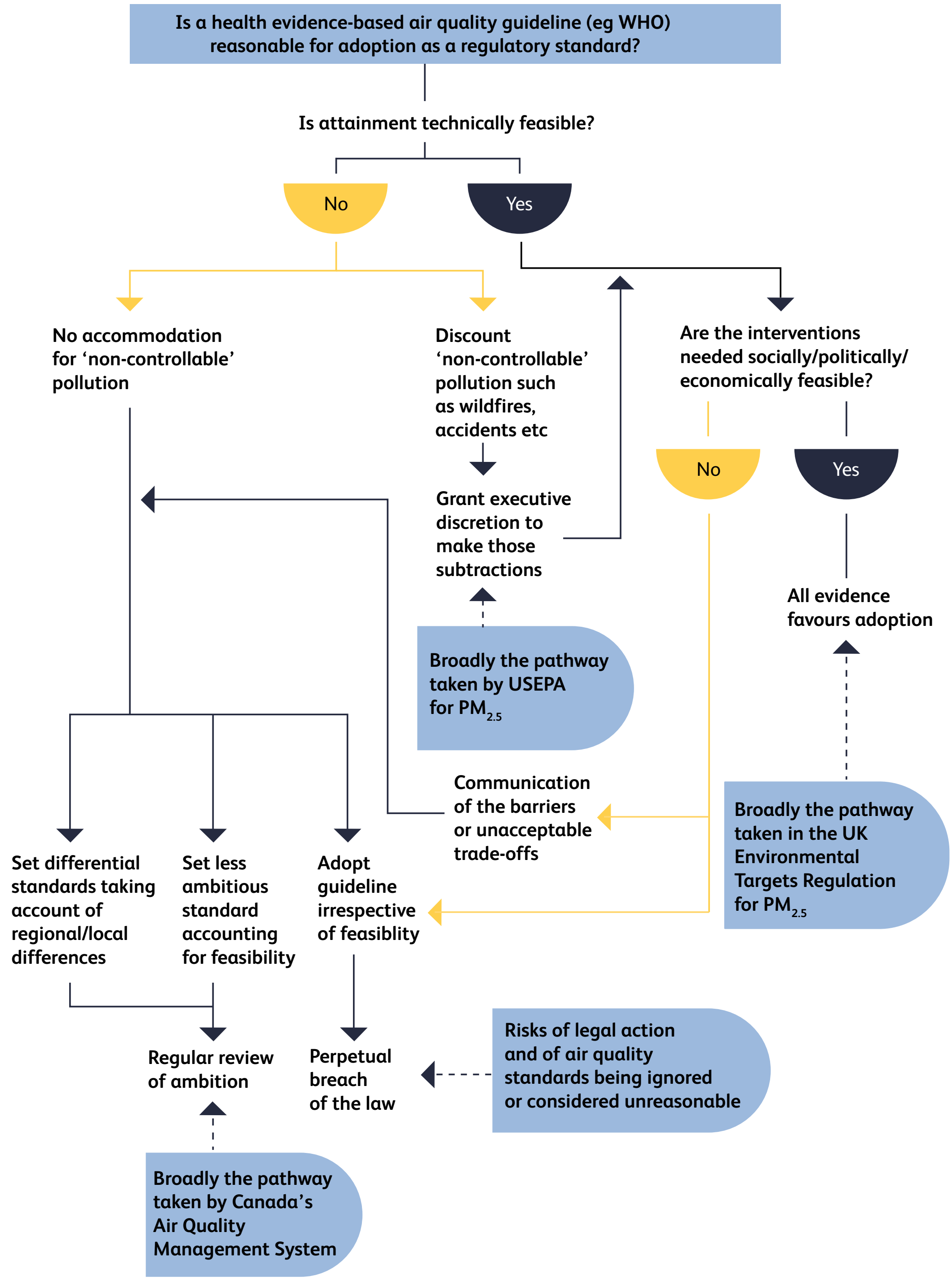

Fig 3.3. Decision tree depicting some options and considerations when assessing whether a health evidence-based air quality guideline is reasonable for adoption as a regulatory standard.

The decision tree in Fig 3.3 shows some considerations for adopting a health evidence-based air quality guideline (eg WHO 2021) as a regulatory standard. It includes suggestions of alternative options where feasibility is an issue, and highlights where these are similar to the approaches taken by other countries. Table 3.1 identifies the advantages and disadvantages of some of these options as well as the two types of standard that are currently in place in the UK. The option of a national standard with accommodations for 'non-controllable' pollution sources is not included in the table as this is a variant of a universally applicable national standard. Discounting for non-controllable pollution may be less appropriate in a UK context as sources such as wildfires, industrial accidents, and wind-blown dust from desertification are not major causes of non-compliance with existing limit values. Introducing this kind of accommodation creates a complexity that does not at present appear warranted.

The issue of continuous improvement and ability to track progress towards longer-term goals is important and one that was included in the Environment Act 2021 with the setting of interim targets and dates for their attainment. It is possible for some areas/sectors to take no action or even to deteriorate and the target still to be met.

For those towns and cities that meet the national air pollutant limit values there is a risk of disengagement with the topic more generally. The nature of a pass or fail ambient air quality legal test creates a perception that air quality is at a safe level if the data show a 'pass'. In these circumstances it is, anecdotally, difficult to get buy-in from councillors or the public for measures to further improve air quality, and perhaps understandably so, with many local authorities facing financial difficulties and other competing priorities.

A population exposure reduction target can also address the issue of delivering continuous improvement. For instance, the 2023 Environmental Targets (Fine Particulate Matter) (England) Regulations set a target of

Table 3.1. Advantages and disadvantages of different conceptual approaches to air pollution standards.

Standard type	Advantages	Disadvantages
Nationally applicable standard for maximum concentrations (eg national limit values)	Prioritises action in areas with the worst air quality. Easily communicated and understood. Is based on a well-tested understood practical and legal concept. Simple for local government to apply to its areas of responsibility and assess progress.	No requirement for continuous improvement for areas already below the limit value. Requirement that this must be achievable everywhere and so ambition is driven by those areas with the greatest air pollution problems. It is perceived as a ceiling that can be polluted up to.
National population exposure reduction target	Requires continuous improvement nationally. Does not require attainment of the same level of air quality in all areas. Is a better indicator of the expected public health burden of air pollution.	Difficult to communicate what this is and how it is calculated. Difficult for local authorities to interpret, apply to their areas of responsibility, and assess progress against. Only averaged national improvement is required so some areas could regress. Lack of interpretability may lead to limited proactive intervention; it is used as a check on progress after action has taken effect.
Regional standards or targets for maximum concentrations	Allows different levels of ambition based on area-specific situations and sources. Delivers action in areas of poorest air quality as well as requiring progress in other areas. Can be used to support continuous improvement and non-regression. Easy to communicate. The underlying concept is well-understood by public groups and local authorities.	Perception of geographical inequality. Need to determine multiple values that are suitable for different geographic situations rather than a single national value. Regional geographic air quality standards may not align to units of local or regional government.
Local standards or targets for concentrations	Allows different levels of ambition based on highly localised situations and sources. Delivers progress both inside and outside of pollution hotspots. Can be used to drive continuous improvement. Easy to communicate. The underlying concept is well-understood by public groups and local authorities.	Determination of suitable values at high spatial resolution would be difficult, resource intensive and dependent on the quality of information available for different localities. Outcomes would be highly sensitive to very local emissions changes and might therefore be a barrier to industry, transport infrastructure or housing development.

35 % reduction in population exposure to $PM_{2.5}$ by 2040, which is assessed nationally.[36] Exposure reduction targets are applicable to pollutants that do not have a clear zero effects threshold. In these cases, greater public health benefit arises from reducing exposure for everyone rather than targeting interventions only at those 'hot spot' areas that exceed a limit value. This is illustrated in Fig 3.4

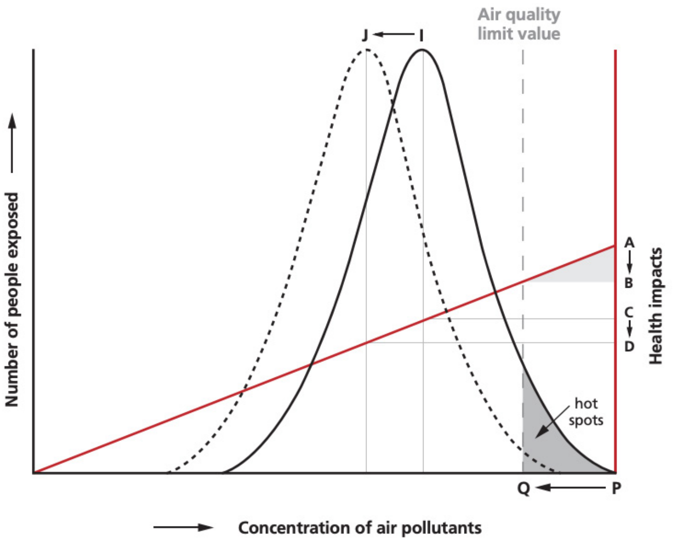

Fig 3.4. The effects of different air pollution control measures.[71] Royal Commission on Environmental Pollution (2007) © Crown copyright. Legislation that requires actions to reduce air pollution in hot spots to below an air quality limit value (from P to Q), but with no requirement for air quality improvements in other areas, will improve the health of those exposed above the air quality limit value (in the shaded hot spots area). This will provide health gains of A to B for this relatively small population but will not improve the health of others who experience lower, but still harmful, concentrations.

A framework that also requires action to reduce exposure in the general population will shift the whole curve to the left (from curve I to curve J) and produce the health gains C to D, with these gains affecting the whole of the population.

3.5 A new approach to setting air quality standards in the UK

3.5.1 Air quality standard management levels for $PM_{2.5}$

One potential solution to address various concerns raised with limit values – particularly the issue of ambition being constrained by feasibility in the most polluted areas of the country – is to establish regional concentration standards or targets. Canada's Air Quality Management System is an example of the way in which this could be applied.[72] Rather than setting differential limits that could be seen to introduce geographical inequalities, there is a single standard set for each pollutant in the Canadian Environmental Protection Act 1999. These standards are then supported by four colour-coded management levels, with action required at all levels. Examples are given in Table 3.2 and the guidance document provides more information.[73] Only the highest level (red) represents non-compliance with the legal Canadian Ambient Air Quality Standard. Management levels are assessed for each air zone, defined as zones that have unique air quality characteristics such as pollutant sources, topography, meteorological patterns and population density. The Canadian government asserts that this approach is intended to ensure that the standards 'are not treated as pollute-up-to levels and actions will be taken to keep clean areas clean'. The standards and management levels are reassessed every 5 years to maintain a suitable level of ambition.

Table 3.2. Canadian ambient air quality standard management levels for $PM_{2.5}$ and examples of the associated actions that are required.

Air quality management level	Example of levels for annual $PM_{2.5}$ (μg/m³)	Example actions required
Red	>8.8 This represents areas that are above the air quality standard	> Development and implementation of a comprehensive air zone management plan, including short-, medium- and long-term milestones and targets > Compile emission inventory for air zone > Engage local stakeholders
Orange	6.5 to 8.8	> Development and implementation of a comprehensive air zone management plan > Compile emission inventory for air zone > Engage local stakeholders
Yellow	4.1 to 6.4	> Development and implementation of an air zone management plan > Compile emission inventory for air zone
Green	4.0	> Basic monitoring for trends

3.5.2 Connecting limit values to emission regulation

While limit values are the most publicly visible component of policy and regulation, a complex ecosystem of other regulations and rules underpins the delivery of good air quality, and ultimately, the attainment of limit values. Individual emissions regulation covers a vast range of sources from the very large, such as power stations, to the very small, such as individual lawnmowers. Local policies to improve ambient air quality frequently aim to limit activity related to certain sources in sensitive or non-compliant locations, eg car journeys or wood burning. However, over the long term and at the national scale, it is stricter national (and international) emissions regulations that best deliver air quality improvement. Setting those individual emissions standards is a technical endeavour that balances engineering innovation in abatement or emissions reduction with feasibility and cost. Managing transboundary pollution relies on a combination of activity and emissions control at source via agreed national annual emission ceilings.

3.5.3 Innovation to improve air quality

While ambient air quality legislation is a key motivator for policy and action to improve air quality, delivery requires engagement from many different stakeholders. Broad policy directions for air quality standards set the stage for industry to then invest in innovation for emissions reduction. This is potentially undertaken voluntarily as part of environment, social and governance (ESG) objectives, or as a minimum to ensure that a business will be able to meet any future legislative requirements. Wider market forces are also important in driving industrial change; the green agenda is having considerable impact on how businesses want to be perceived. Many companies now consider being environmentally responsible as an integral part of their corporate strategy.

Research by the New York University Stern Business School[74] has shown sustainable products growing twice as fast as their conventional counterparts, with people prepared to pay a premium for those products. Companies with higher ESG ratings perform better financially, have a higher market value and are more resilient to shocks such as the COVID-19 pandemic.[75] Many companies are now using sustainability claims on the front pages of their websites or in advertising campaigns; for example, Ikea has set a goal of becoming a fully circular and climate positive business by 2030.

Consumer-driven trends demonstrate the potential power that informed public groups have in order to influence change, particularly in terms of what is demanded from companies and their products. In turn, public and business investment and prioritisation of environmental issues may then create greater political engagement. These influences potentially create reinforcing cycles where increased public interest and expectations drive increased reporting in the media, which drives wider awareness, which sustains media interest, and these two effects combined generate increased interest from policymakers and potential for action.

There is a substantial role for industry innovation and technology to improve air quality. However, adoption in new products often follows the relatively slow timelines by which sectoral emissions regulations are updated. For example, passenger car tailpipe emissions of NO_x and particulate matter have improved significantly over the past 30 years, making technological jumps approximately every 5–7 years as new regulations were introduced via the 'Euro' emissions standards scheme. In other areas regulation changes are less frequent, and instead lower air pollution emissions often emerge as a consequence of other drivers, such as improved energy efficiency or reducing consumption of chemicals.

The need for businesses to adapt to reduced greenhouse gas emissions is both a risk and an opportunity for air quality. The demanding requirements to deliver low or net zero environmental performance may prompt many industries to switch away from fossil fuel use, resulting in benefits for both climate and air quality. The extent to which low carbon innovation and transformation may deliver lower air pollution may depend on how much importance is placed on air quality as a commercial priority.

3.5.4 Learning from recent case studies

In the aviation industry, the transformation needed for net zero climate impact will probably require a combination of bio/synthetic sustainable aviation fuel (SAF) and hydrogen, both combusted in gas turbine engines. The importance of addressing the climate challenge in aviation is generally considered more critical than the air quality impacts of flying. The business model for aircraft manufacturers is not substantially impacted by local air quality performance, so innovative technologies are first and foremost designed with climate change in mind. Should SAF be fully adopted, the climate impacts of aviation could be much reduced but some fraction of the air pollution emissions, notably ultrafine particles (UFP, $PM_{0.1}$) and NO_x would be retained even under net zero.

However, in the construction and off-road sector the air quality performance of equipment is more prominent in business decision-making.

The permitting of development in cities often comes with requirements to use the most up-to-date low NO_x and particulate matter-emitting construction equipment. Similarly, permits for new backup generators demand the latest low emissions technology as a prerequisite, irrespective of their greenhouse gas credentials. This more evenly balanced set of requirements for new technologies to benefit both climate and air quality has resulted in the development of hydrogen internal combustion engines (H2ICE) by multiple manufacturers. The significantly improved air quality performance of H2ICE compared to existing diesel stage V engines was seen as a prerequisite, since it ultimately meets the requirements of customers (construction companies). Low carbon emissions in isolation are not a strong enough business case for investment.

The construction industry example shows how interlocking governance structures and regulation can drive positive change for both climate and air quality simultaneously by focusing on low-carbon materials, emissions reduction strategies and sustainable project practices. Top-down national air quality standards create the imperative for action, powers devolved to local authorities and mayors provide a mechanism that enables new, cleaner innovations to be prioritised, and regularly revised and tightened sectoral emissions regulations support a business case where new lower emissions products outcompete their older counterparts.

In the case of domestic space heating boilers, the ability of the Mayor of London to attach air quality performance requirements to new building developments, going beyond those specified in national emissions regulation, has led to manufacturers working to a more stringent *de facto* standard. It would simply not be economic to develop one product for London, and one for the rest of the UK, hence most new gas boilers sold today emit less NO_x than the standard requires. The ability of a major internal market to move the dial on air quality, irrespective of national regulation and obligations has been a significant factor in improving air quality in the USA, where standards set at a state level in California are ultimately adopted into products sold nationally.

3.5.5 Thinking in complex systems

Throughout this report, we have stressed that air pollution is a complex issue or a 'wicked problem' – it is the result of multiple, highly interconnected and dynamic systems such as transport, energy and urban environments. Emissions are processed through the atmosphere, which is itself a complex system. The social-ecological systems that influence air pollution emissions, concentrations and exposure also involve many actors with often differing perspectives on both the issue itself and the evidence surrounding it. Actions to improve air quality need to take account of political, environmental, social, technological, economic and ethical considerations.

The complexity sciences and the literature on complexity in evaluation provide tools and approaches to take account of complexity, enabling decision-makers to make more informed choices.[76,77] The field is extensive including many and varied 'systems' approaches from 'soft' people-focused techniques to qualitative, data-driven modelling, as in the case of systems mapping.[78] The value of systems approaches for policymaking has been articulated in academic literature and in toolkits and guides produced for and by the UK government (for example, the Centre for the Evaluation of Complexity across the Nexus),[79] but their application to air pollution issues has been relatively limited.

3.5.6 Complex systems in driving policy change

Interest in the use of complex systems approaches in UK government has been growing, and in 2019 Defra launched a Systems Research Programme to explore the use of systems thinking to deliver innovative, evidence-based solutions for the UK's most challenging environmental issues.[80] One of the five focus areas of this programme was air pollution. The resulting publication, *A primer for integrating a systems approach into Defra*, provides guidance on the use of systems thinking in policy development and articulates the perceived value of using systems thinking in policymaking: 'Systems thinking is more than a practical way of working, it changes mind-sets, how issues and opportunities are approached and the philosophical basis upon which decisions are made'.[80] Systems approaches enable visualisation and understanding of the interconnections between different parts of a social-ecological system, making it easier to see how change would impact key outcomes. This tries to be holistic within set boundaries, recognising the complexity and enabling exploration of possible system responses, rather than simplifying the system to well understood and quantifiable relationships to provide definitive 'answers' as reductionist evaluation (as in the case of clinical trials) often does. As with systems mapping, many systems techniques also enable decision-makers to see the differing perspectives of system actors who may view key outcomes and pathways differently to the policymakers themselves.[81] These insights enable policy development to take account of broader impacts of change, considering the potential for unintended consequences, both positive and negative, and including how the response of systems actors could alter the outcomes.

3.5.7 Co-production as a way forward

The value of engaging in co-production and participatory research is highlighted by more recent systems approaches and specifically featured as one of 14 priority focus areas in a study advocating for a whole systems approach to addressing the emerging issue of air pollution and brain health.[11] To effectively tackle air pollution and improve public health, enhancing public health capacity within local government and strengthening the role of directors of public health (DsPH) is crucial. This includes increasing public health specialist resources in local authorities and giving DsPH more influence, potentially by raising their position in the hierarchy, as well as clarifying the public health role with the Department of Health and Social Care.

The importance of stakeholder engagement and consideration in the development of evidence for policy becomes clear when their key concerns are considered. It was found that for people living with dementia, air pollution's role in disease progression was key; for parents and school systems priorities were cognitive development, school performance and early-life screening; local planning boards focus was on the benefits of green urban planning and public transportation; whereas civil servants were concerned with sustainable development goals and the health burden and economic costs of brain conditions over the next two decades. Consideration of this range of interests can broaden discussions of priority areas for action thereby opening greater opportunities for progress as well as enabling areas of conflict or neglect to be identified.

As examples, there are good illustrative case studies demonstrating the use and effectiveness of complex systems thinking in policymaking from the Government Office for Science (GO-Science).[82] This includes two from the Defra Systems Programme and one specifically focused upon on air quality and climate change. Here, soft systems methodology[83] was used to integrate thinking on climate change and air quality. This was undertaken in response to an announcement by the UK government on its commitment to achieving net zero greenhouse gas emissions by 2050. Stakeholders from across government departments, the government Climate Change Committee (CCC) and Air Quality Expert Group (AQEG) were brought together to discuss potential net zero policy measures, their implementation, and how they would impact air pollution. This resulted in a report from AQEG summarising the risks, which has been used by Defra to engage other government departments in early discussions of decarbonisation policy.[84] The CCC also submitted a progress report to parliament stating that air quality and human health impact must be considered alongside climate change policies.

3.5.8 Applications of complexity methods to setting air quality policy

Different complexity methods for evaluation can be used in different ways depending on the issue, timescales, resources and stage of policy development.[78] They can be particularly effective where policies will impact multiple outcomes, there is potential for significant co-benefits or trade-offs and where more than one government department or other key actor has responsibility for the outcomes of interest. This was demonstrated in the air quality and net zero case study above as well as in a study using participatory systems mapping to explore unintended consequences of accelerated transitions to electric vehicles (EV) as part of transport decarbonisation.[85] Policies that sought to incentivise increased EV uptake had the potential to result in more miles travelled in private vehicles due to perceptions of lower environmental impacts and reduced per-mile driving costs.[86] This led to increasing congestion and community severance, reducing neighbourhood liveability and uptake of active travel, with impacts on particulate matter emissions and levels of physical activity, and consequently human health. Increased congestion leads to a reduction in the desirability of public transport due to uncertain journey times and reduced reliability, and this in turn leads to reduced service revenue and financial viability. Ever-reducing use of public transport and increased reliance on private vehicles generates a reinforcing negative feedback loop.

There were also potential knock-on impacts on health, such as access to green spaces, leisure opportunities and fragmentation of social networks. These negative impacts have a disproportionate impact on more deprived communities. These outcomes contrast with the government's decarbonising transport plan, which asserts that moving to EVs with no tailpipe emissions and less noise will 'support levelling-up and help reinvent the high streets as enjoyable places to live, work, visit and spend leisure time'.[87] Taking a systems view of the issue that takes account of both greenhouse gas reductions and other government targets, such as air quality and public health, would enable greater benefit to be delivered from the specific implementation of decarbonisation policy and would help to mitigate unintended consequences.

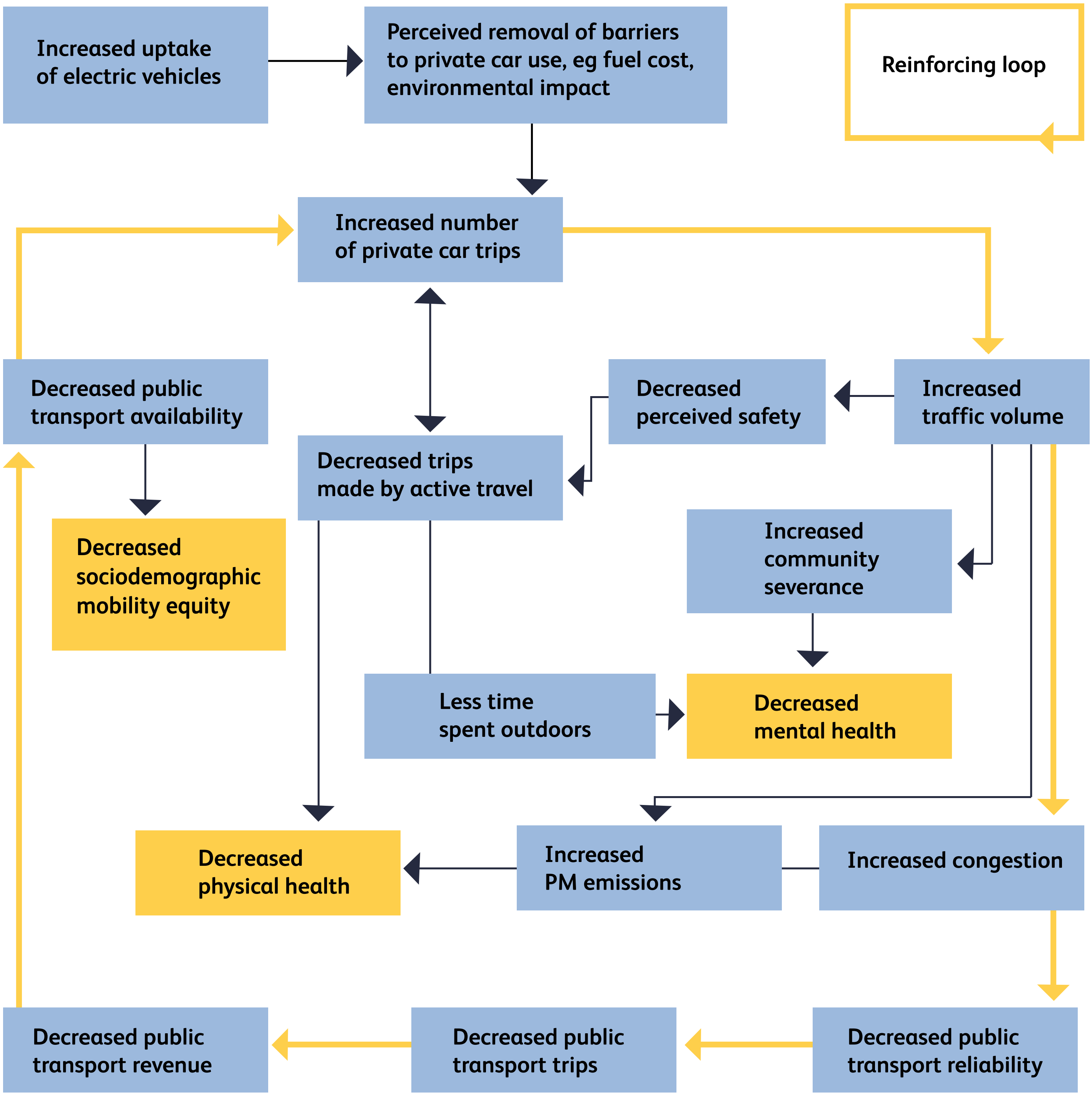

Fig 3.5. Example of the impacts of the increased number of private car trips resulting from increased electric vehicle uptake taken from participatory systems mapping.[85] Visualisation of data collected for Penn *et al* (2022) under Creative Commons CC BY 4.0 licence.

Factors have been edited to be directional (ie decrease or increase) to aid visual interpretability. Some steps have been removed to simplify the figure and only selected impacts of changing factors are included.

3.5.9 Moving policy setting to embrace the complexities of air pollution

Complex systems thinking should be seen as complementing rather than replacing more conventional and necessarily reductionist modelling assessments used to quantify policy impact. An example of this was the use of systems thinking in the setting of the particulate matter targets in the UK Environment Act 2021.[88] A map of the factors affecting emissions of particulate matter was developed and used to explore the breadth of areas that could influence achievability of targets. It included socio-economic factors such as the economy, urban planning and population distribution that affect $PM_{2.5}$ concentrations but that would not be included in modelling scenarios. It demonstrated the complexity of interdependencies, for example a robust economy is more likely to result in greater investment in developing and installing lower emission technology by government, industry and individuals, enabling lower emissions. However, it also tends to increase travel and consumption of goods and services, which would increase these activities and potentially create more sources of emissions. The map helped to inform the sector studies and sensitivity analysis carried out as part of the modelling, aiding identification of the areas with the greatest influence and uncertainty.

A systematic review of complex systems thinking application in public policy conducted in 2023 suggested that public policy has yet to realise the full benefits of this approach and its various methods, and that there are significant challenges to fuller uptake despite an increase in interest.[89] The review cites that unfamiliarity with complex systems concepts and methods, lack of capacity to apply systems approaches, lack of confidence in its rigour, lack of acceptance and buy-in among civil servants and policymakers, time and resource constraints, political, structural and operational barriers within the government and public sector, and lack of evidence on its usefulness and contribution are contributing factors. Some of these significant organisational and operational challenges are also reflected on in the GO-Science case studies.[82] However, progress is taking place: some government departments now have systems teams or systems champions, and there is a cross-departmental Systems Thinking Interest Group where members share best practice, events, training and resources, as well as providing opportunities to discuss and try out systems approaches on current issues, supporting each other in designing appropriate processes for applying complex systems approaches in their work.

3.6 Urban planning and air quality

3.6.1 City life

The majority of people now live in cities. Cities are still hotspots of air pollution, partly as a result of higher residential and traffic density, which are some of the main sources of air pollution.[90,91] However, because of the higher population density cities have also many possible advantages such as reducing the amount of travel and shortening commute time; decreasing car dependency; lowering *per capita* rates of energy use; limiting the consumption of building and infrastructure materials; offering a diversity of choice among workplaces, service facilities and social contacts; and limiting the loss of green and natural areas.[92]

3.6.2 The concept of compact cities

The compact city is recognised as a leading model for sustainable urban living. However, if not well designed it will have drawbacks such as high air pollution levels, lack of green space and heat island effects leading to a high mortality and disease burden.[92–95] A recent study of nearly 1,000 European cities identified four basic urban configurations on the continent, which were labelled compact-high density cities, open low rise-medium density cities, open low rise-low density cities and green-low density cities.[96] The results showed that high-density compact cities had not only poorer air quality (NO_2), but also a stronger urban heat island effect and 10–15% higher mortality. They had lower greenhouse gas (CO_2) emissions per capita. In contrast, greener and less densely populated cities had not only lower air pollution levels (NO_2) but also a lower urban heat island effect and lower mortality. They had higher carbon footprints per capita though.

This does not mean that compact cities should be abandoned, only that we need to introduce appropriate policy measures to reduce the current detrimental exposures such as air pollution. An example is Barcelona, a compact city with a mortality comparable to the average mortality of compact cities in the study.[97] Lowering air pollution levels, shifting away from cars and increasing green space, cycling lanes and physical activity would substantially reduce the mortality. Green spaces are crucial for public health, providing benefits like stress reduction, increased physical activity and improved air quality. However, access to these spaces is often unequal, with residents in deprived areas experiencing less access to high-quality green spaces, exacerbating existing health inequalities. This disparity is further compounded by biodiversity loss in these areas. Furthermore, there is still ongoing urban sprawl, with Europe leading the way, which increases car dependency.[98] Sprawl increases travel distances and reduces the opportunity for cost-effective public transport systems and active transportation.

3.6.3 Development of air quality policy fit for purpose

The measures and policies to reduce air pollution depend on the air pollutant. For the two most important air pollutants, $PM_{2.5}$ and NO_2, the contribution of different sources to air pollution-related mortality is quite different and context specific. In European cities, the residential sector (23%), agriculture (18%) and industry (14%) account for half the $PM_{2.5}$-related mortality, while the transport sector accounts for just under half of NO_2-related mortality (49%).[90] $PM_{2.5}$ is largely generated outside the city (86%), while a large proportion of NO_2 (34%) is generated inside towns and cities (63% in European capitals). Different policies and interventions are therefore needed to reduce levels of the two pollutants (Fig 3.6).

A few of these policies and interventions are discussed below in more detail, particularly related to urban and transport planning. Some of these measures have the advantage that they not only address air quality but also contribute towards mitigating the climate crisis and improving health beyond the reduction in air pollution. As widely discussed, there is an urgent need to reduce, or even better, eliminate the use of fossil fuels and replace them with renewable energy sources in all sectors.[99]

The residential sector contributes a considerable proportion of $PM_{2.5}$ air pollution through, for example, heating and cooking. There is a trend towards large houses, which often require more heating. There is therefore a need for denser and more carbon neutral housing (eg carbon neutral 3–4 storey apartment blocks, solar power, heat pumps[100]) and using clean fuel sources. Improved insulation is a major factor in reducing domestic fuel use. A shift to zero carbon and healthier urban and transport planning is essential, for example shifting from private car use to (electric) public transport and active transport together with 'greening' cities. Electric vehicles are often proposed as the panacea, but these only go some way to reducing emissions and do not address important issues such as a healthy use of public space, urban heat islands, and lack of physical activity in the population that is essential for good physical and mental health.[101] If households were to revert to the 1985 level of eight cars per 10 households rather than the 2022 level of 12 per 10 households, more public areas could be used to benefit communities, such as recreational spaces.[102]

Densification is essential to reduce travel distances, thereby reducing the distance driven by motorised transport and promoting active transportation.[84] However, it is essential to reduce or eliminate air pollution emissions sources to ensure that the increased number of sources does not lead to increased air pollution levels (hot spots) as still often seen in densely populated areas.

More stringent legislation for air pollution guidelines
Local air quality plans, coordinated with actions at national and international levels

Local actions (NO_2)	Intersectoral and interregional actions ($PM_{2.5}$)
> Low emission zones	> Fuel regulations
> Changes in urban design	> Stove replacement schemes
> Urban greening	> Fuel burn bans
> Accessibility and proximity	> Building insulation
> Public and active transport	> Clean and renewable energy sources
> Speed limits	> Manure management and fertiliser use
> Reductions in motorised traffic	> Emission controls (transport, industry, shipping)
	> Industrial materials, fuels and processes optimisation
	> Complete phasing out of coal and fossil fuel burning

Fig 3.6. Pollutant-specific policy measures to reduce air pollution.
List from Khomenko *et al* (2023)[90] reproduced under the Creative Commons CC-BY-NC-ND licence.

3.6.4 Innovative urban models for community benefit

Innovative urban models such as the Paris 15-minute city,[103,104] Barcelona Superblocks,[105,106] London low traffic neighbourhoods[107–109] and Vauban car-free neighbourhood in Freiburg, Germany that prioritise people over cars have been shown to reduce private car use, lower air pollution levels, and increase physical activity, which together contribute to better health.[101,110]

The Barcelona Superblock model (Fig 3.7) can be relatively easily implemented in existing urban areas to reduce NO_2 from motorised traffic by up to 25%.[111]

'Superblocks' are created by reducing motorised traffic and allowing active travel in selected streets along with greening those streets (Fig 3.8). The model is particularly suitable for any urban area with a grid-like system and sufficient population and facility densities, as in Barcelona. Typically, a superblock consists of closing four road junctions in a grid of nine apartment blocks. This has allowed for a proposal of 503 superblocks in Barcelona as pioneered by Salvador Rueda, an urban planner.

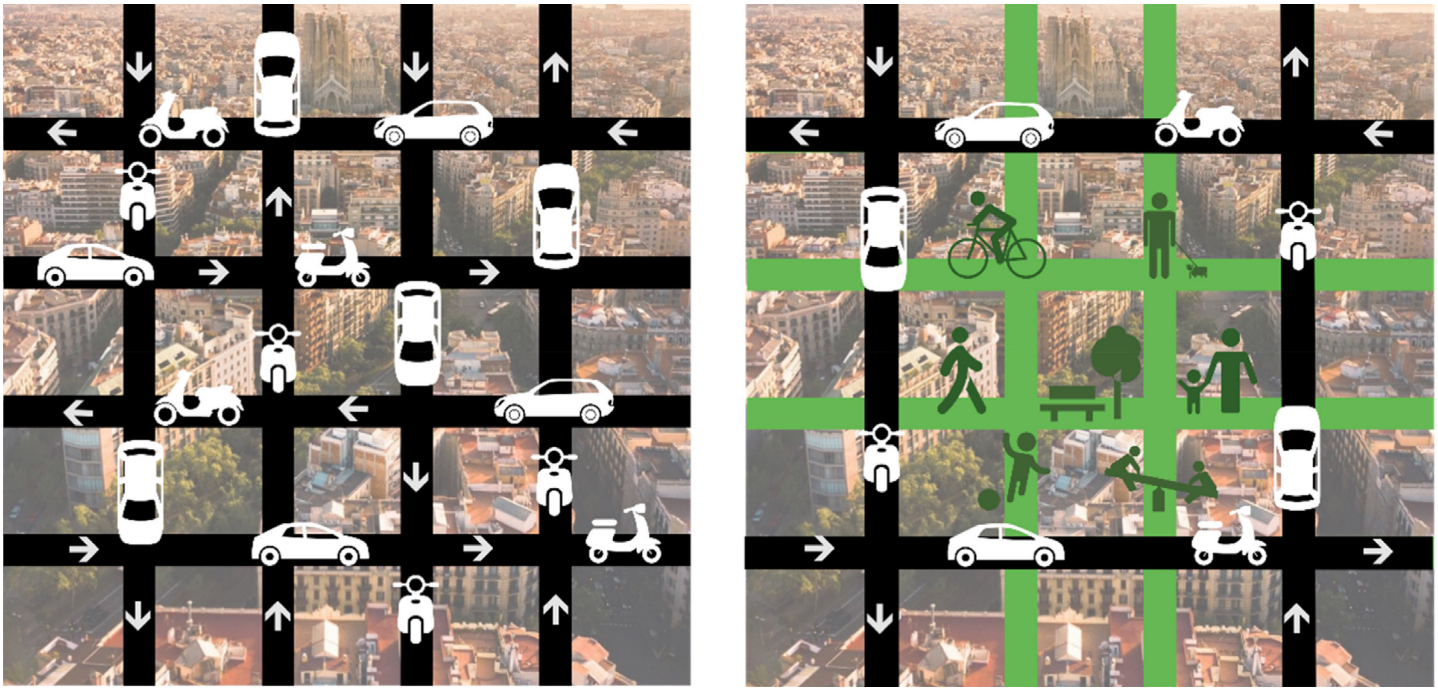

Fig 3.7. The Barcelona Superblock model.
Image from: Nieuwenhuijsen *et al* (2024)[111] reproduced under the Creative Commons CC-BY-NC-ND licence.

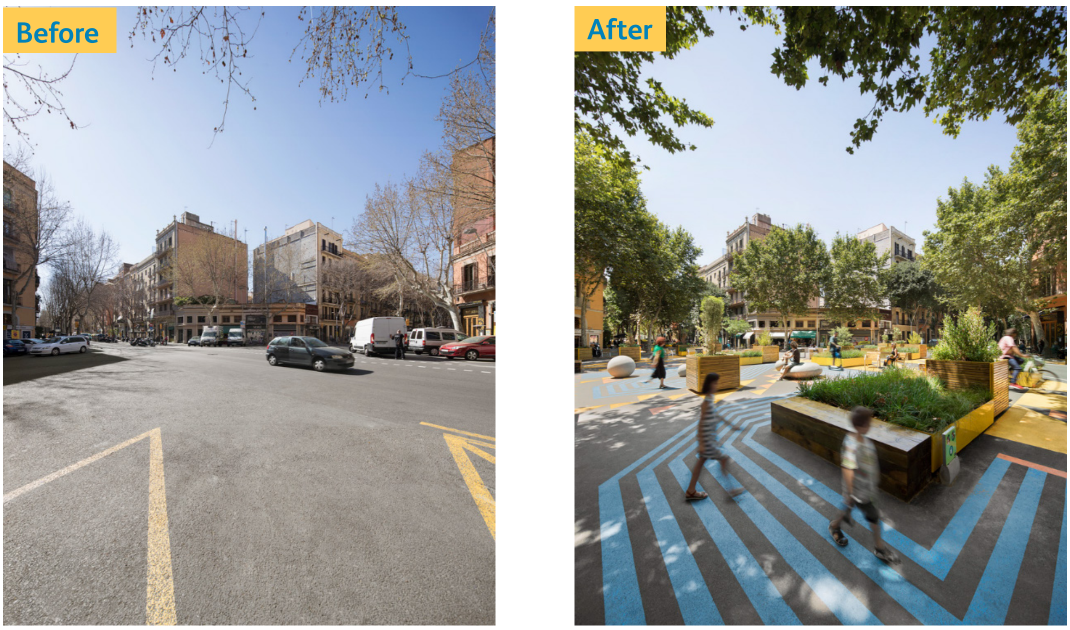

Fig 3.8. The Barcelona Superblock in Sant Antoni, Barcelona. © DEL RIO BANI

Increasing the infrastructure for active transport, eg more safe cycling lanes, increases the uptake of cycling, increases physical activity and reduces air pollution, all of which contribute to reduced morbidity and mortality[112,113] (Fig 3.9). Fiscal policy measures such as road pricing[114,115] through (ultra) low emission zones[116] are also effective ways to reduce private car use and air pollution emissions, but as discussed earlier, such interventions can be controversial and require political support and careful negotiation with residents (see Section 3.3). Policy interventions which combine infrastructure changes (including road-space reallocation) in combination with social and behaviour change programmes, and e-bike and cycle sharing initiatives are recognised to have the most impact on active travel uptake.[58]

An example of an effective UK scheme intended to reduce traffic congestion is the Workplace Parking Levy (WPL) introduced by Nottingham City Council in 2012 – a charge on employers that provide workplace parking spaces in the city.[117] Over the first 10 years this scheme generated over £90m of revenue, which was reinvested into sustainable transport across the city. However, Nottingham remains the only UK city to adopt this policy approach. In this context, effective national legislation is essential to enable regional and local government to introduce measures that effectively protect public health and guide businesses in the right direction.[118]

Fig 3.9. Urban transformation in Amsterdam to reduce car use.

The 1971 image is protected by copyright, but the copyright holder is unknown to the City Archives of Amsterdam.
2014 image © iStock

Nature-based solutions are an effective way to increase green infrastructure and can reduce air pollution, although the reduction is generally small, unless there is some conversion of the public space allocated to cars (ie roads) to green space.[119] New concepts such as the 3-30-300 green space rule provide both air pollution and health benefits.[120]

An important factor in the implementation of new policies and measures is to consider their impacts on health (Fig 3.10). Health in all policies (HiAP) is an approach to public policy across sectors that systematically takes into account the health implications of decisions, seeks synergies, and avoids harmful health impacts in order to improve population health and health equity. HiAP is key for local decision-making processes in the context of air pollution policies to promote public health interventions, as these actions involve many sectors.[121] Central to HiAP is the concept of addressing the social determinants of health as key drivers of health and health inequalities.

As described earlier in this report, these policies have faced opposition from a vocal minority that can threaten their implementation. Strong political leadership and local citizen participation and support are essential for these measures to succeed.[122]

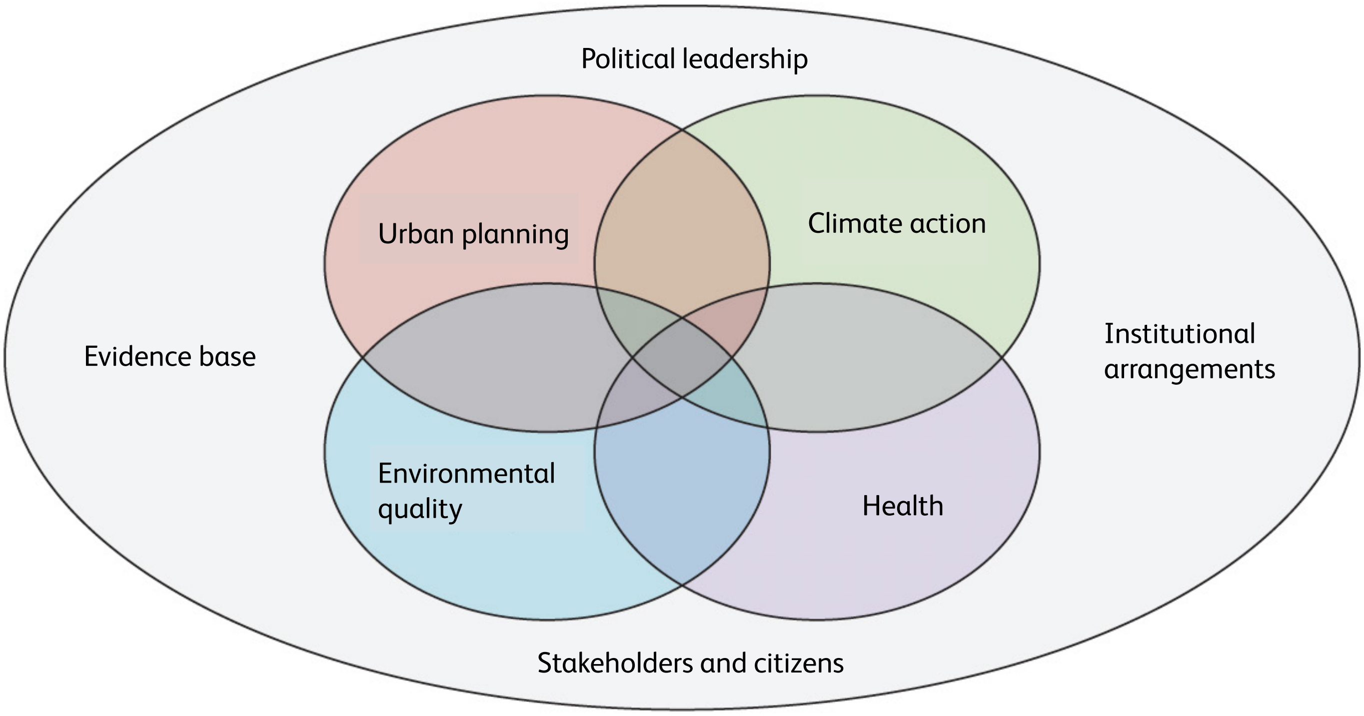

Fig 3.10. Close collaboration between urban planning, environment, climate action and health is essential for a transitional and healthy change. Reproduced with permission from Nieuwenhuijsen (2024).[97]

3.7 The role of clinicians in communicating the benefits of clean air

3.7.1 Why clinicians need to know about air pollution

Published evidence of harm from polluted air has increased dramatically since our report in 2016 but health professions have struggled to stay abreast of developments. This lack of awareness means that many clinicians are not sufficiently equipped to understand and discuss the health impacts of poor air quality with their patients and fulfill their responsibilities to protect the health of the public.[123]

In February 2013, 9-year-old Ella Adoo-Kissi-Debrah died during an acute asthma exacerbation in South London. The possibility that air pollution could have exacerbated her asthma was not raised with her mother, Rosamund, on any of her 27 admissions to six hospitals and was not considered at the initial inquest.

Following a second inquest in 2020, the South London coroner concluded that 'Ella died of asthma contributed to by exposure to excessive air pollution'. The coroner issued a prevention of future deaths (PFD) report outlining three 'matters of concern', including that 'the adverse effects of air pollution on health are not being sufficiently communicated to patients and their carers by medical and nursing professionals'.[124] The coroner's report stated that this needed to be addressed at three levels: the undergraduate curriculum, the postgraduate curriculum (the responsibility of royal colleges) and professional guidance. Several bodies were required to respond to this concern, including the Royal College of Physicians (RCP), Royal College of Paediatrics and Child Health (RCPCH) and National Institute for Health and Care Excellence (NICE).

In its response to the coroner's report, the RCP said that air pollution was not specifically mentioned in the medical curriculum but that it referenced the GMC's generic professional capabilities framework, which includes health promotion and illness prevention.[125] The RCPCH was also required by the coroner to respond to the matter of concern about the education of clinicians. Likewise, the RCPCH said in its response that 'in line with the GMC standards, all medical curricula have moved away from being prescriptive in relation to disease and conditions, to focus on capabilities and learning outcomes. The RCPCH curriculum includes a domain on health promotion 'requiring all paediatricians to demonstrate capabilities around understanding the environment, economic and cultural contexts of health and healthcare illness on illness prevention'.[126]

The RCP said that doctors, and all healthcare professionals, need to understand that they have a responsibility to talk to patients about air pollution and how to avoid it. The RCP recommended integrating alerts into electronic medical records (EMRs) to notify doctors when a patient was living in an area of high pollution, helping them know when to discuss air pollution with patients. The RCP also said it would consider how to support clinicians to become advocates for clean air in their communities, undertake a review the delivery of the curriculum at a local level, add questions on air pollution to examinations that it administered and increase physicians' knowledge about the impacts of air pollution on health.[125]

The RCPCH recommended that paediatricians act as role models for others and make personal changes to reduce air pollution such as active travel and encourage change within the NHS.[126] As a result, paediatricians are now beginning to use their collective voice and expertise to influence the national and international agenda, focusing on the health impacts faced by children and young people, and recommending action.[127,128]

In 2023 the RCPCH appointed three clean air fellows to develop policy and resources. The RCP has had a special adviser on air quality since 2016 who is a member of both the RCP Inequalities in Health and Sustainability in Healthcare and Climate Change Advisory Groups. These encouraging initiatives to operationalise change are most welcome.

NICE stated that healthcare professionals should be knowledgeable about air pollution, what it means for patients, and what actions are recommended. The March 2021 update of NICE asthma guidelines clarified that 'approaches to minimising indoor air pollution and reducing exposure to outdoor air pollution should be included in a personalised action plan because pollution can trigger and exacerbate asthma'.[129]

The story of Ella's preventable death and her mother's campaign for clean air[130] demonstrate why action on air quality is so vital. Many health professionals and members of the public noticed the improvements in air quality during lockdowns during the COVID-19 pandemic, where road traffic was suddenly greatly reduced. In many cities, it also manifested the health benefits of cycling and active travel, including in some cases the expansion of safe infrastructure. Yet in the years following, many of the beneficial changes to air quality seen during the pandemic have been lost.

While there is broad agreement within the clinical community that clean air is important for health, but this is not sufficient considering the magnitude of this 'wicked problem'. Healthcare professionals (doctors, nurses, AHPs and pharmacists) must be equipped with the knowledge and confidence to discuss this issue with their patients and also recognise their key role as advocates for air quality being tackled as a public health issue. Indeed, the chief medical officer for England, Professor Chris Whitty, chose air pollution's impact on non-communicable diseases (NCDs) as the most important issue to address in his first post-COVID report in 2022, recommending that all healthcare staff should be trained on air pollution and how to communicate its risks to patients.[131] This now needs to be translated into reality with meaningful action.

3.7.2 Assessing healthcare professionals' knowledge of air pollution

Internationally, as of 2020, only 11% of medical schools included air pollution in their syllabus.[132] Encouragingly, of 32 medical schools surveyed in the UK for the Planetary Health Report Card 2023, all but one included the health impacts of air pollution in their core syllabus, although in 50% it was only briefly mentioned in passing.[133] It was clear from the narrative report that several universities were treating the subject seriously. Medical education is often slow to respond to clinical knowledge. The questions asked in a routine medical history are often based on tradition rather than the diagnostic utility of the information gathered. It would be interesting to further explore the relative value of standard questions about exposure to air pollution compared with exposure to pets, for example, given the current evidence on relative harm from the two risks.

At postgraduate level in the UK, the General Medical Council sets the standards for and approves medical curricula and assessments for specialties and subspecialties, which are designed by royal colleges and faculties. Since 2019, all medical curricula have moved away from a prescriptive and exhaustive list of competencies to overarching capability-based high level learning outcomes.

The Joint Royal College of Physicians Training Board (JRCPTB) sets the internal medicine training (IMT) stage one curriculum, which forms the first stage of training for physicians, as well as overseeing the curricula for higher specialty training for physicianly specialties. Heads of school, who are responsible for implementing the IMT curriculum, confirmed in the RCP's 2022 clean air progress report that teaching of the curriculum did include the impact of air pollution.[134] Since then, the JRCPTB has asked the specialist advisory committees for IMT, general internal medicine, acute internal medicine and respiratory medicine to consider air pollution in some form in the next curricula review, though the nature of capability-based curricula means that even if a change is made, the term 'air quality' may still not appear specifically in curricula. This will help to ensure that the question of whether air quality is getting enough attention and focus under the relevant high level learning outcomes is kept under review.

Education beyond the curriculum is key, too. Global Action Plan offers several frameworks on air quality, including a Clean Air Framework for integrated care system leaders[135] and another for hospitals.[136] In 2024, the WHO launched a free online course with modules on the health effects of air pollution and the role of healthcare workers.[137] To date (2024), it has been completed by over 1,800 health professionals, 3,000 students and 500 government officials.

3.7.3 The importance of the health practitioners' voice to create change

Some clinicians feel inadequately trained on this topic, with few feeling comfortable discussing it with their patients.[138] Where clinicians may gain knowledge of air pollution from traditional or social media, there is a risk that not all of this information will be of a high standard, and that in some cases the health impacts of air pollution may be portrayed as highly contentious and/or political.[139] This may discourage clinicians from discussing air pollution with patients.

Clinicians have reported vexatious complaints for speaking up publicly. It is vital that they have access to evidence-based information about the health impacts of air pollution and advice and guidance on how to broach this topic in clinic. This will enable them, supported by their professional organisations, to highlight myths and misrepresentations of air quality and its effects, and reiterate its status as a public health problem.

Ten top tips for clean air communication

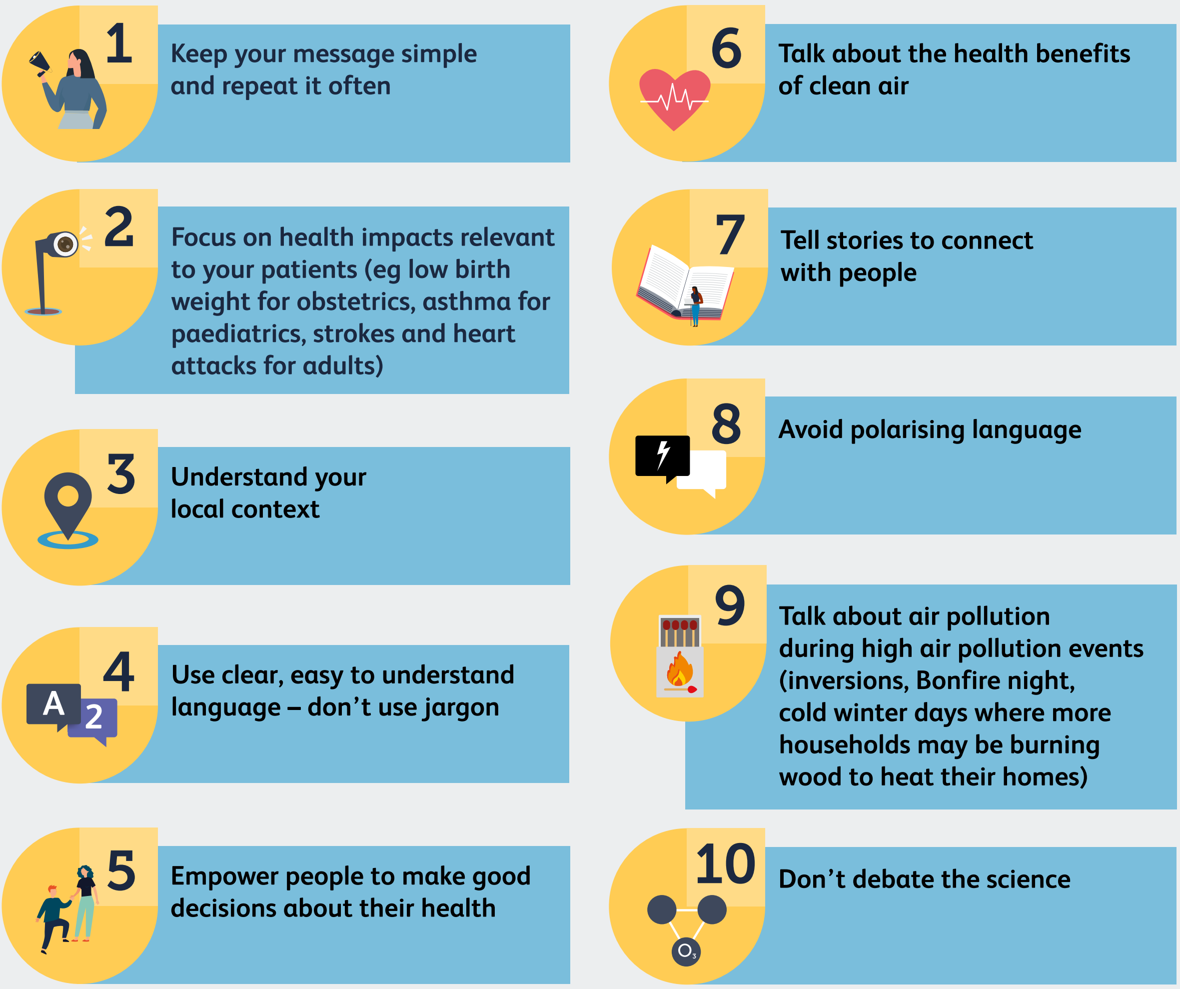

Fig 3.11. Ten top tips for clean air communication.

Adapted from WHO (2024) under CC BY-NC-SA 3.0 IGO.[140]

Table 3.3. Three levels at which clinicians can communicate the benefits of clean air.

Communicating the benefits of clean air	
Personal	Health professionals are seen as role models within our communities. By educating ourselves and following principles that reduce air pollution emissions and exposure, we can encourage others to follow suit.
Professional	In our clinical practice we need to make air pollution conversation 'business as usual'. This includes talking to our patients and colleagues about air pollution.
Political	We are consistently among the most trusted professions. We should use this power to advocate for air quality to be seen as a health issue and for policies that reduce air pollution at local, regional and national levels.

Adapted from the WHO Air pollution and health training toolkit for health workers.[137]

It is vital for health professionals to make the case that air pollution is a health issue. Indeed, the RCP, RCOG and RCPCH all called on the UK government[141] to meet the World Health Organization's (WHO) 2005 legal limits on particulate matter in the Environment Act 2021, expressing disappointment when the final target was set at reaching 2005 limit values by 2040.[142] Clinicians and their professional bodies must continue to stress the benefits of clean air and the local and central policy changes needed to achieve it. They should also trust in the ability of their patients to make rational behavioral choices when presented with honest information from trusted clinicians.

Examples of good medical practice

Here are some examples of good medical practice that have led to successful change to inspire clinicians to take action:

1. The Mobilising Primary Care on Air Pollution project in 2022 successfully demonstrated that GPs are effective emissaries for information on air pollution, both to their colleagues and members of the public, including patient groups vulnerable to the health harms of air pollution. This small study trained 40 GPs, 88% of whom reported that the training had helped them to talk to patients about outdoor air pollution.[143]
2. In 2022 Great Ormond St Hospital for Children in London introduced an alert in its Electronic Medical Record (EMR) system Epic™[144] This was based on modelled annual average $PM_{2.5}$ and NO_2 data based on UK postcodes from Imperial College London. This triggered warnings in the chart to clinicians when patients' home postcodes exceeded WHO 2021 limits. In addition to then providing resources and links for clinicians as part of their workflow it supported advocacy to local government on their behalf. This system has since been installed in several other London hospitals, including Guy's and St Thomas', King's and the Brompton spreading its reach outside of paediatrics and to much a broader clinician and patient group. Alongside this, at Great Ormond Street Hospital, a pre-written letter with generic advice on the impacts of air pollution, actions to take to reduce exposure and where to go for more information is available to all clinicians within the Epic electronic health record system and increases capabilities of those who are less confident.[144] One outcome of this work has been questions from clinicians about how to talk to patients and when it is appropriate or indeed ethical, given the widely held view that there is little patients can do about their situation. While this is an understandable concern, it does not seem to be supported by patient surveys that demonstrate an unmet need for individualised information and support from clinicians to improve prevention and treatment of air pollution's impact. A recent initiative by the European Academy of Paediatrics may bring some much-needed clarity to the ethics of the situation.[145]
3. In February 2024 an alert system developed by the London Air Quality and Health Programme Office – which includes the Mayor of London, NHS England, UK Health Security Agency, and Office for Health Improvement and Disparities was launched.[146] New alerts will directly notify clinicians in GP practices and emergency departments across the capital via email about high and very high pollution episodes. Advice includes 'In future, consider having conversations with your patients about how air pollution could impact them, and any steps they can take to reduce their risk of harm. This can be done routinely as part of long-term condition management, so patients learn how to self-manage. Remind patients to continue to follow their asthma/COPD plans, take their preventer inhaler or controller medications as prescribed, carry their reliever inhaler and to arrange a review after every exacerbation. People can continue physical activity during air pollution episodes. Children do not need to be kept from school or prevented from taking part in games. However, during high air pollution episodes, older people, and those with cardiac or respiratory conditions may need to reduce vigorous physical activity, particularly if they experience symptoms.' This type of collaboration across traditional boundaries is to be congratulated and hopefully rolled out nationally.
4. A request for guidance on whether air pollution should be listed on death certificates was raised in 2023 given that 'government advice is provide on the inclusion of smoking, alcohol, and occupational exposures, but not on when to include air pollution'.[147] While the relative merits of death certification may be debated, it certainly calls into question whether current data collection in the NHS for morbidity and mortality adequately addresses the known impact of air quality and clinical management. The introduction of the medical examiner system in 2023 represents an opportunity to bridge the gap between clinicians, relatives and the certification system. It offers a unique opportunity to train a small group of engaged and knowledgeable clinicians on the current impact air pollution has on many of the causes of deaths, which they will then use to guide certifying doctors.

5. NHS services are a major contributor to air pollutant emissions, with healthcare related activities estimated to account for ~5 % of road traffic in England in 2019.[148] NHS service providers and leadership teams can adopt actions to reduce air pollutant emissions across NHS estates and related services, with potential benefit for patients, staff visitors and residents. Research undertaken by the University of Birmingham in partnership with University Hospitals Birmingham NHS Foundation Trust demonstrated the importance of senior management support for air quality management within healthcare organisations, generating a shortlist of actions to mitigate air pollutant emissions and a practical checklist to support assessment of local air quality using low-cost methods.[149,150] The effectiveness of a framework approach to air quality management and value of tracking progress was also demonstrated in a study of the Clean Air Hospital Framework self-assessment tool and measures to monitor effectiveness undertaken at Newcastle-Upon-Tyne Hospitals NHS Foundation Trust.[151] More recently the Integrated Care Systems Clean Air Framework produced by Global Action Plan provides a practical framework intended to support systemic air quality actions across a range of healthcare services, linking to mandated requirements of NHS green plans and the NHS Standard Contract.[135]

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Air pollution is the largest environmental health risk globally, causing loss of healthy years of life and premature death. This report provides new insights into why urgent action is needed to improve air quality across the country. It presents the latest evidence on the impacts of air pollution on health and health inequalities, the economic costs and policy solutions fit for the future. A set of 19 recommendations set out the much-needed action required from governments and other stakeholders to clean up the air that we are all so dependent upon for our health and wellbeing.

Led by the RCP's special adviser on air quality, Professor Sir Stephen Holgate CBE, the report was developed with the help of 30 clinical and academic experts and approved by RCP Council.

A summary for policymakers can be downloaded from the RCP website:

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