Air Quality, Energy and Health Science and Policy Summaries

Accelerating action for clean air, clean energy access and climate change mitigation

Conference discussion papers

to support WHO's Second Global Conference on Air Pollution and Health

World Health Organization

Acknowledgments

The production of this report was supported by funds generously provided by Foreign, Commonwealth and Development Office of the Government of the United Kingdom of Great Britain and Northern Ireland, the Spanish Agency for International Development Cooperation and the Ministry of Foreign Affairs, European Union, and Cooperation of the Government of Spain, the Norwegian Agency for Development Cooperation, the Government of the Netherlands and the Clean Air Fund.

WHO Air Quality, Energy and Health Science and Policy Summaries

Health effects of air pollution – evidence and implications

Technical brief

Key messages

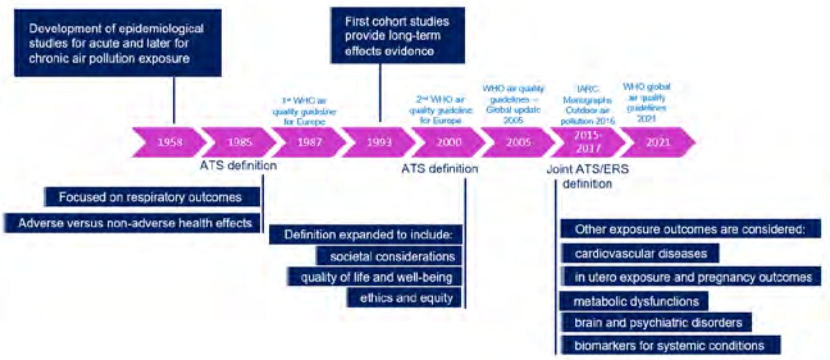
- The health effects of air pollution have been documented and described by the medical community for several decades.
- Air pollution can reach almost all organs and systems of the body, impacting respiratory, cardiovascular, cerebrovascular, reproductive and metabolic systems, amongst others.
- Children, pregnant women, older people, people living with chronic disease, and those living in the lowest socioeconomic groups are most at risk.
- Air pollution is the leading environmental health risk factor causing about 6.4 million deaths globally every year.
- Close to 84% of air pollution related deaths are from noncommunicable diseases (NCDs), including heart disease, stroke, chronic obstructive pulmonary disease (COPD) and lung cancer.
- Air pollution burden remains underestimated and is likely to increase, due to population ageing and emerging links with additional diseases and conditions (e.g. low birth weight, neurological and psychiatric diseases, metabolic diseases, cancer other than lung).
- There are substantial inequalities in air pollution levels and health burden globally, closely interlinked with social and economic disparities.
- Ensuring health data are available, reliable and that air pollution exposure is linked with relevant health outcomes using available coding for recording, reporting and monitoring diseases is critical for disease surveillance, impact assessment and prioritization of interventions.
- With the enormous health evidence at hand, we must act now to ensure clean air for all and speed up actions for those who are most affected and most vulnerable.

Overview

Health effects of air pollution – a long history

Evidence on air pollution effects on health has been well documented over the last six decades. Important milestones over the years are marked by key epidemiological studies, the first World Health Organization (WHO) reports in the 1950s *(1)*, and the publication of the first edition of the WHO global air quality guidelines in 1987 *(2)*, which provided recommendations for thresholds of air pollutants safe for health. Over the last 40 years, significant statements have been made by medical societies on the definition of what constitutes an adverse health effect of air pollution, which have evolved with mounting scientific evidence from toxicology and epidemiology *(3,4)* (Fig. 1).

Fig. 1. Timeline of selected air pollution and health milestones



Notes: ATS: American Thoracic Society; ERS: European Respiratory Society; IARC: International Agency for Research on Cancer.

Air pollution exposure pathways and physiological impacts

While the WHO air quality guidelines series cover a wide range of air pollutants, this summary will focus on the health effects of a subset of pollutants. Particulate matter (PM) is a good indicator of air pollution as it arises from multiple sources, and it is ubiquitous in our environment. PM consists of a complex mixture of solid particles and liquid droplets of varying size, shape and composition. It is the pollutant for which there is the largest body of evidence on health impacts.

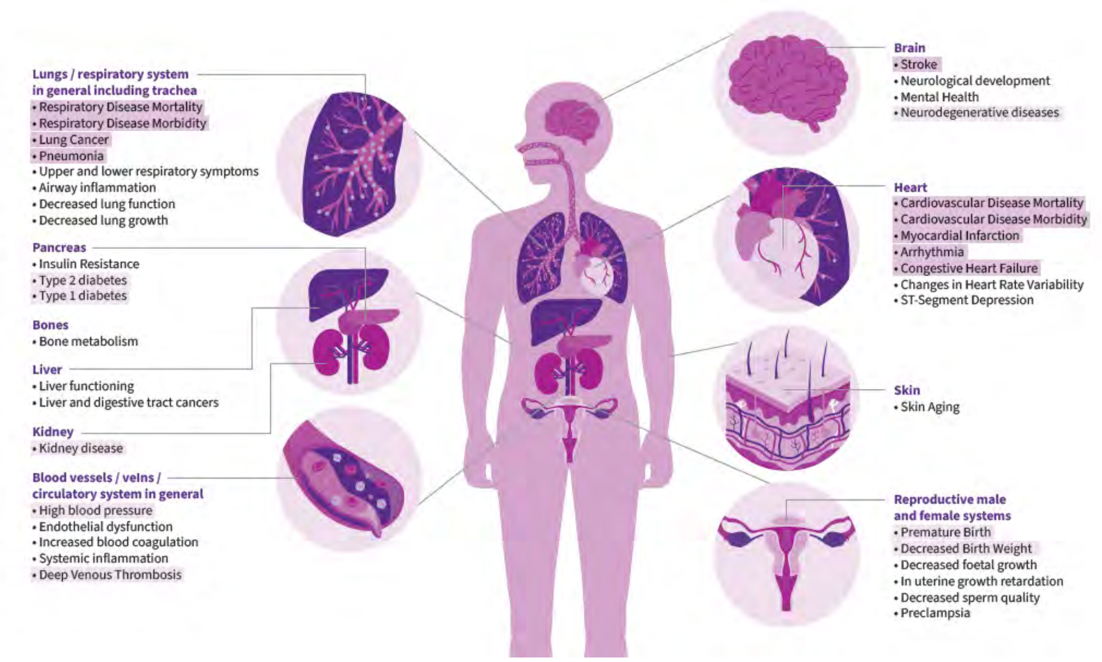
Other main air pollution are nitrogen dioxide and ground-level ozone, which are gases that originate from various sources and lead to substantial adverse health impacts, though not comparable in magnitude with PM *(5)*.

See SPS[1]: *Exposure to health damaging air pollutants*

While inhalation is the main pathway of exposure to air pollutants, there are other routes of human exposure, such as dermal absorption, ocular exposure and ingestion.

When inhaled, health-damaging pollutants including small particulates can penetrate deep into the respiratory system and enter the blood stream, allowing them to reach almost all organs within the body (Fig. 2), including but not limited to cardiovascular, reproductive and metabolic systems, brain, liver and kidneys. Many of these damaging effects on the cells and tissues within the human body may not be reversible. Furthermore, air pollution causes oxidative stress, inflammation, immune response, DNA problems, skin damage and direct damage to parts of the body like eyes, nose, throat, lungs, gut, neurons, bones and blood cells.

Fig. 2. Organs and systems affected by air pollution – list of diseases



Source: Adapted from Thurston et al. *(3)*. Disease outcomes highlighted reflect the ATS/ERS assessments of established air pollution adverse effects. It also includes those diseases currently included in WHO assessments (highlighted in pink) as well as noting those for which evidence of an association with air pollution and/or adverse outcomes is emerging *(6)*.

[1] Science and Policy Summary

Short- and long-term exposure to air pollutants and impact on health

Impact of air pollution episodes on all-cause mortality and more

Short-term, day-to-day exposure to high peaks in air pollution over several minutes (e.g. cycling or walking on very busy streets), hours (e.g. longer commutes in a polluted city) or days (e.g. air pollution episodes in the cities during winter months) presents a significant burden that can cause mild symptoms in healthy people such as runny nose and eyes, cough, headaches or trigger even more severe exacerbations of diseases in chronic lung and heart patients, leading to symptoms that require medication use, doctor visits, hospitalizations, sick days, productivity losses and overall reduced quality of life, or even death.

There are numerous studies investigating effects of air pollution on all-cause (non-accidental and natural) mortality. Short-term exposure to air pollution peaks can trigger sudden death, and the latest analyses of temporal trends show that despite reductions in air pollution, the effects on health remain high *(7)*. This may be due to multiple factors such as different chemical composition, toxicity and sources of air pollution, as well as socioeconomic determinants or changes in population distribution and susceptibility.

Long-term exposure: the real threat

It is well established that air pollution shortens lives, with life lost ranging from months to years. Longer term exposures over several years, decades or a lifetime increases the risk of premature mortality and can pose greater risks than acute exposure, even at low levels *(8)*. The updated 2021 WHO global air quality guidelines *(6)* clearly state that the association between air pollution and mortality is even stronger now *(9)*, even at lower pollutant levels. This led to the significant lowering of the annual guidelines value to 5 $\mu g/m^3$ for $PM_{2.5}$ and 10 $\mu g/m^3$ for nitrogen dioxide.

Strong associations were also reported in a European multi-city, multi-country study that examined low-level exposure to $PM_{2.5}$ *(10)*, (approaching 2.5 $\mu g/m^3$) and findings suggest that health risks are not linear and there are stronger effects at low exposure levels. These findings are in line with other results from around the globe *(11,12)*. More recently, analyses from WHO 2024 project Health Risks of Air Pollution in Europe-2 (HRAPIE-2), shows even stronger associations of $PM_{2.5}$ with mortality due to various diseases *(13)*.

In some regions, despite the reduction of air pollution, the population becomes more susceptible as it ages and hence the air pollution attributable burden on mortality can increase. With more high-quality studies, our understanding of the strength and the shape of the exposure-risk relationship is improved with the latter information being crucial for informing decision-making such as choosing acceptable levels for the population.

Besides leading to premature mortality, long-term exposure to air pollution globally contributes to the disease morbidity, including the development of new disease in millions of people as well as millions of people living with chronic diseases, both of which have debilitating impacts on productivity and quality of life. A recent review concluded that there is sufficient evidence to support the link of long-term exposure to air pollution with the incidence of asthma in children and adults, acute lower respiratory infections (ALRI) in children, autism spectrum disorder in children, COPD, ischaemic heart disease, stroke, hypertension, diabetes, dementia and lung cancer *(14)*.

Air pollution: a major risk factor for health

Long-term exposure to air pollution (PM_{10} and/or $PM_{2.5}$) is a risk factor for the development of all major NCDs. This section focuses on the morbidity (incidence of disease) outcomes selected by the recent WHO Estimating the Morbidity from Air Pollution and its Economic Costs (EMAPEC) *(15)* project, based on a comprehensive review of evidence on long-term exposure to air pollution and morbidity. We refer below to the analyses for the outcomes for long-term effects identified in this project *(14)*.

Respiratory system

The respiratory tract is the first entry point for air pollutants. Exposure to air pollution can adversely affect lungs throughout one's entire lifetime including before birth. Typical health effects of air pollution include a suppressed immune system, inflammation and oxidative stress, impaired lung growth in children, and lung function decrements in children and adults. Long-term exposure to air pollution in healthy people increases the risk of development of a range of respiratory diseases, such as asthma in children *(16)* and adults *(17),* COPD *(18)*, ALRIs in children *(17),* and an increased risk of premature death due to respiratory diseases *(8).* Furthermore, air pollution presents a substantial burden in the daily life of respiratory disease patients, where exposure to short-term air pollution peaks triggers exacerbations of pre-existing disease, such as cough, shortness of breath, difficulties in breathing, asthma attacks, COPD, increased use of medication, emergency room visits, hospitalizations, and even death.

Cardiovascular system

A wealth of evidence summarized by the American Heart Association in 2010 *(4,19),* the European Society of Cardiology in 2015 *(20)* and the World Heart Federation *(21)* links air pollution to increased cardiovascular disease morbidity. These statements marked the point when air pollution was recognized as a risk factor for cardiovascular disease. There is now sufficient evidence to conclude that long-term exposure to air pollution is linked to the incidence of ischaemic heart diseases *(22),* stroke *(23)* and hypertension *(24),* as well as premature mortality from cardiovascular diseases *(8).* Short-term exposure to air pollution also presents a significant burden to patients with heart disease and can trigger severe exacerbations leading to hospitalization and/or death.

Lung cancer

There is clear evidence of a link between long-term exposure to air pollution and incidence *(25)* and mortality *(8)* from lung cancer. Outdoor air pollution and PM were classified in 2013 as carcinogenic to humans based on evidence of air pollution and lung cancer incidence and mortality by the International Agency on Research for Cancer *(26,27).* Other relevant IARC evaluations have also classified diesel engine exhaust (as well as some PM constituents) *(28)* and household burning of coal as a carcinogen to the human lung *(29).*

Metabolic effects

A plausible biological mechanism of air pollution promoting diabetes was provided by Sun et al. *(30)* showing that exposure to particulate air pollution caused increased blood glucose, inflammation in adipose tissue and insulin resistance in high-fat-diet mice. This led to a surge in epidemiological studies on long-term exposure to air pollution and type 2 diabetes, and there is suggestive evidence of a causal relationship between air pollution and type 2 diabetes incidence *(31).*

Nervous system

Long-term exposure to air pollution can have detrimental effects on the brain via inflammatory reactions and oxidative stress of the brain's nerve cells, which can lead to neurological damage and disease, impairing cognitive development in children and promoting cognitive decline in adults *(32).*

There are ongoing investigations to assess the evidence that air pollution can contribute to autism spectrum disorder in children *(33)* and dementia incidence in adults *(34)*.

Reproductive male and female systems

Numerous studies have linked air pollution to reproductive functions, pregnancy outcomes, fertility, and fetal health. Beyond suggestive links with birth weight and neonatal deaths *(35),* air pollution also has been shown to have deleterious effects such as reduced intrauterine growth, premature birth, stillbirth, birth defects, as well as cause pre-eclampsia, gestational diabetes and hypertension in pregnant women. Air pollution can negatively impact human reproduction in both males and females, by increasing time to conceive and decreasing fertility with decreased sperm and egg production.

Emerging evidence

There are ongoing reports on air pollution and a number of mortality and morbidity health outcomes for which evidence is awaiting further epidemiological studies. There is biological evidence showing the direct connection between air pollution exposure and its effects on cells, DNA and the body. Evidence points to linkages between air pollution and COVID-19 morbidity and mortality *(36).* Air pollution has been linked to allergic sensitization and increased risk of allergic diseases, including eczema, allergic rhinitis and food allergies.

See SPS: *Climate change, air pollution, pollen and health*

There is now evidence showing that air pollution's adverse effects extend beyond ischaemic heart disease and stroke to increased risk of heart failure and atrial fibrillation. Similarly, research in adults shows possible links with breast, brain, stomach, thyroid, colon, liver, bladder, kidney, leukaemia, lymphoma and pancreatic cancers, as well as leukaemia and brain tumours in children. Other outcomes that are under scrutiny to air pollution include type 1 diabetes, skin diseases (eczema, skin cancer), eye diseases (conjunctivitis), worsening of rare lung diseases such as cystic fibrosis, chronic kidney diseases, fatty liver diseases, dementia, Alzheimer's, Parkinson's disease, multiple sclerosis, and psychiatric outcomes, including depression, anxiety and suicide.

Children's health and other at-risks groups

Although everyone is exposed to air pollution, not everyone is affected equally, and several groups are particularly susceptible and/or vulnerable to its harmful effects. Exposure to air pollution induces adverse health effects, which can vary widely depending on the type, level and duration of exposure, as well as individual factors such as gender, age, vulnerability, education level and socioeconomic status.

See SPS: *Air pollution and children's health*

Key definitions: high-risk groups

Susceptible groups: People with physical predispositions increasing the risks resulting from air pollution exposure. These include age, life stage and pre-existing diseases.
Vulnerable groups: People with increased exposure to air pollution due to external factors such as socioeconomic status, place of residence, occupational exposure, precarious living conditions and polluted energy at home.

Children are more susceptible to air pollution than adults due to several factors: their lungs, brains, and immune systems are still developing, children breathe faster and inhale more air per unit of body weight than adults, and they are more active and spend more time outdoors *(37,38)*.

Pregnant women are also more susceptible to air pollution due to the special physiological, mental and behavioural factors associated with pregnancy compared with non-pregnant women. Children and adults with chronic diseases, like asthma, cardiovascular and respiratory diseases are also more susceptible to the adverse effects of air pollution, as well as those with weakened immune systems, reduced lung function, impaired cognitive function, weakened circulatory systems and multiple chronic diseases related to ageing. People with the lowest socioeconomic status are also vulnerable to air pollution as they are often more exposed than those with higher socioeconomic status. This can result from various factors, for example, low-income residential areas typically have poorer housing conditions and are often situated in closer proximity to pollution sources increasing their exposure levels. Additional vulnerability factors impacting poorer populations include higher prevalence of other health risks (e.g. higher rates of smoking, obesity and lower rates of physical activity), less access to education and preventive health care and higher likelihood of comorbidities. Outdoor workers, athletes and recreational sports people who spend a lot of time outdoors, especially in polluted environments, are also more vulnerable to air pollution due to the duration and levels of exposure chronically experienced by these populations.

Current exposure levels and health burden

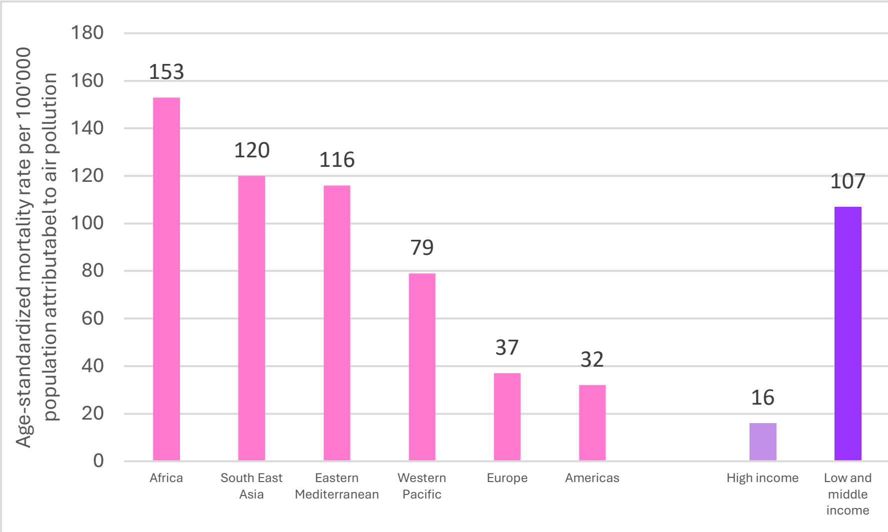
There are large differences in air pollution levels and trends around the globe, and despite the decreasing trends of air pollution exposure in some countries *(39),* air pollution continues to worsen in many low- and middle-income countries (LMICs).

Significant disparities in air pollution levels exist globally, with up to tenfold differences between the cleanest countries in Northern and Western Europe and some of the most polluted ones in Asia *(5)*.

Because of the links with multiple diseases and the ubiquitous nature of the exposure (99% of the world´s population is exposed to levels above the WHO guideline for $PM_{2.5}$ of 5 µg/m^3), air pollution (all air pollutants combined, including indoor air pollution) is ranked as the second leading risk factor for mortality in 2021, ahead of tobacco smoke and dietary risks *(40)*. Air pollution from PM-attributable deaths – as currently reported under Sustainable Development Goal Indicator 3.9.1 – account for 6.4 million deaths in 2021, including causes causally linked to air pollution: ischaemic heart disease, stroke, COPD, ALRI and lung cancer *(41)*. Additionally, type 2 diabetes and neonatal deaths are considered in the comparative risk assessment of the Global Burden of Disease *(40)*. In total, NCDs account for nearly 84% of the total deaths from air pollution from ambient and household air pollution *(41)*.

The health effects currently considered in global disease burden analyses have a strong evidence base, but those estimates of impacts do not consider health outcomes with emerging evidence such as neurocognitive development in children, neurodegenerative diseases including dementia and Parkinson's disease, psychiatric disorders, cancers other than lung, chronic kidney diseases, eye and skin diseases, etc. Inhaled air pollution has the capacity to move into the blood and to organs around the body. For example, air pollution particles have been found in cells in the human placenta. Thus, the current global assessments are likely an underestimate of the true air pollution related disease burden, which is also expected to increase, with new studies showing stronger effects of air pollution on health than previously known and at lower levels. It is also striking that the attributable disease burden is unevenly distributed around the world. With an annual rate of around 107 deaths per 100 000 attributed to $PM_{2.5}$, low-income countries have a greater disease burden than high-income countries, with a rate of 16 deaths per 100 000. The distribution shown in Fig. 3 indicates a considerably high burden in the WHO African, South-East Asia and Easter Mediterranean regions *(41)*.

Fig. 3. Global $PM_{2.5}$ attributed age-standardized mortality rates per 100 000 people, by WHO region, 2021



Health risks from low levels of air pollution exposure

Air pollution levels have been decreasing over recent decades in Canada, Europe and the United States, as a result of successful air pollution legislation and/or the implementation of air quality standards (e.g. legal limit values) leading to the introduction of cleaner fuels, regulation of industrial emissions and the implementation of pollution control technologies. This development has generated interest in the health effects of air pollution at low levels, even below legal limit values, in these parts of the world, which has driven additional research. This research has been important to help evaluate whether the current legislation in Canada, Europe, the United Kingdom of Great Britain and Northern Ireland and the United States etc. adequately protect human health, and whether revisions of current legislation are needed, and has influenced recent revisions of air quality standards in the European Union (EU) and United States. On the other hand, in the other parts of the world, such as South-East Asia, North Africa, the Middle East and Latin America, where air pollution levels are much higher and have been stable or increasing, there is, in general, less stringent or even lack of regulation and/or monitoring programmes. These countries also often lack the research infrastructure and capacity for monitoring pollution levels and sources and studying the health effects of air pollution, presenting major obstacles to translating local research results into successful policies for air pollution reduction.

Source-specific health effects and composition of PM

$PM_{2.5}$ is a mixture of different chemical components reflecting the contributions of different sources. While there is consensus among the scientific studies about the main sources and sectors of $PM_{2.5}$ *(42,43)* their contributions vary across studies and locations, which may be due to different models using dissimilar emission rates, meteorology and physicochemical atmospheric processes. The major global sources of ambient $PM_{2.5}$, including primary emissions and emission of precursors, are: dust (34%), households (17%), industry (12%), power plants (7%), agriculture (13%), transport (10%) and waste (35%) *(44,45)*.

See SPS: *Understanding the health impacts of sand and dust storms*
See SPS: *Agriculture – sectoral solutions for air pollution and health*

See SPS: *Transport – sectoral solutions for air pollution and health*

The relative importance of these sources differs from region to region. In the African and Eastern Mediterranean regions, dust, followed by household emissions, are the main sources of air pollution. Household energy combustion is also a significant source in the European and South-East Asia regions. In the Western Pacific Region, industry emissions dominate. In the Region of the Americas, natural dust and transport are the main contributors to $PM_{2.5}$ *(44–46)*.

Household $PM_{2.5}$ pollution is mainly associated with residential cooking, heating and lighting using polluting fuels and technologies in LMICs and is highly connected with energy poverty. Other indoor PM sources are emissions from building materials, resuspension and cleaning and consumer products. The contribution of the outdoor environment to indoor PM varies from 10% to 90% and heavily depends on ventilation rates *(47)*.

See SPS: *Household air pollution and related health effects*

Although there is evidence that $PM_{2.5}$ from different sources can have varying toxicities *(48),* at present there are no clear conclusions to guide regulatory efforts pointing to specific sources of $PM_{2.5}$ as being the specific health effects drivers *(49).*This implies that the current practice of setting air quality standards based on PM size and concentration still remains relevant. A more effective approach to protecting the public that incorporates source-specific $PM_{2.5}$ needs to be considered as it focuses mitigation on those sources with the greatest adverse health effects. Countries or regions that have successfully reduced air pollution and health effects achieved their targets by controlling the sources that contribute most to air pollution with a focus on cost efficiency but without specific regard to the toxicity of sources or $PM_{2.5}$ components.

Synergies between climate change and air pollution

Climate change and air pollution are intrinsically connected since greenhouse gases and air pollutants share the same source (i.e. fossil fuel combustion). Additionally, global warming, and changing and more extreme weather can aggravate already unhealthy air quality by altering its dispersion capacity, composition and toxicity. Global warming will lead to increases in exposure to ground-level ozone, sand and dust storms, and wildfires, often in combination with extreme heat and droughts, posing additional challenges to health *(50).* Recent reports of significant synergies in the effects of air pollution ($PM_{2.5}$ and nitrogen dioxide) and high temperature in exacerbating risk of respiratory and cardiovascular diseases mortality in cities around the globe illustrate the urgent need for clean air actions to mitigate the effects of climate change as well as joint air pollution and climate change actions for optimal health *(51,52).*

See SPS: *Health and air pollution co-benefits of climate change mitigation*

Research gaps

Although there is ample evidence on the health effects of air pollution, demanding urgent and ambitious actions around the globe to protect human health, there is additional research needed to address important gaps. Much remains to be learned about how different components of $PM_{2.5}$, or their sources, are (or are not) linked to various health outcomes. This may include broad categorical components of $PM_{2.5}$, such as black carbon, ultrafine particles, organic carbon or crustal materials that can be linked to distinctive sources.

There is clear and supportive evidence that exposure to air pollution can lead to increased risk and exacerbation of a range of infectious disease outcomes, and these lead to increases in disease burden.

However, because these linkages remain somewhat uncertain, it is important to understand how air pollution exacerbates infectious disease so that its true contribution to the global disease burden is fully accounted for. There is a need for a better understanding of the synergistic effects of air pollution and climate change on health, including the interaction of air pollutants with heat. Finally, targeted policy-oriented research in LMICs on air pollutants and health outcomes would catalyse understanding and build local capacities to enable policy-makers to integrate health evidence into air quality management actions.

Success stories: reducing air pollution improves health

There are several success stories of air pollution reduction as a result of the implementation of regulation/air quality standards or specific measures or policies. Air quality standards in the United States (USA National Ambient Air Quality Standards [NAAQS]) and EU (EU Ambient Air Quality Directive [AAQD]) have led to decreases in air pollution levels in the last few decades. Recent increases in evidence on the health effects of air pollution at low levels *(6)* have led to revisions and strengthening of US NAAQS and EU AAQD to align them closer to WHO 2021 global air quality guidelines and further protect health. Similar reductions and successful policies are increasingly seen in areas beyond the EU and North America, with China as an example. These illustrate that substantial air pollution reduction can be achieved in a short amount of time with bold and targeted actions and strategies *(53)*.

For example, air pollution levels have been remarkably reduced in China in the last decade since the Air Pollution Prevention and Control Action Plan (2013–2017), Three-Year Action Plan for Blue Skies (2018–2020) and the ongoing Action Plan for Continuous Improvement of Air Quality (2023) were implemented. Air quality monitoring networks have been established nationwide, which have resulted in reductions in anthropogenic emissions in key sectors (e.g. industry, energy and transportation) with restrictive control policies implemented at all levels in various government sectors. However, ambient ozone levels remain to be ~~monitored~~ reviewed because their slight increase across different regions, suggests a future need to understand the sources and source-specific health effects to prioritize monitoring-based pollution control regulatory activities *(54,55)*.

Still, many areas and countries in the world, most of them with considerable air pollution problems, lack air quality regulation and/or monitoring.

Effective policies and actions reducing air pollution and related health burden

There are a number of examples of policies and actions that can lead to a reduction in air pollution and health benefits. Banning household coal burning in Irish cities in the 1990s contributed to a reduction in respiratory disease mortality *(56)*. Similar benefits can be seen in Krakow, Poland, when authorities banned household coal and wood burning in 2019 *(57)*. The closure of coal power plants in the eastern United States led to significant reductions in air pollution and related mortality *(58,59)*. Another area of growing interest is policies targeting the reduction of private vehicle traffic and promoting active transportation, such as cycling, walking and using public transport, that are increasingly part of cities' clean air, sustainable transport and climate change action plans. London implemented a congestion charge zone (CCZ) in 2003, and 10 years later introduced an ultra-low emission zone (ULEZ), covering all London boroughs, becoming the world's largest clean air zone, *(60)*. The health benefits of LEZs in cities in Germany, Milan, Tokyo and London have been shown for cardiovascular diseases, while CCZs reduced rates of respiratory infections in London *(61)*. The Superblock model is an innovative urban planning strategy implemented in Barcelona *(62)* – by restricting traffic in several city blocks to streets surrounding the superblock, while within the superblock, car traffic is banned and public space is transformed into green areas, playgrounds, sports facilities, etc. The superblock model makes significant improvements to air quality, reduced noise levels and increased green areas *(63).*

Reductions in air pollution bring health benefits

It can be difficult to isolate and examine the effects of a specific action on air pollution and health, as improvements in air quality usually result from a combination of legislation and policy measures, technological advancements and individual actions/changes in behaviour. In a systematic review of the reduction in air pollution in 27 LMICs during COVID-19 *(64),* the authors found that there was a mean percentage change of -30.6 % in $PM_{2.5}$. Despite the majority of global urban growth occurring in LMICs, there are distinct geographical gaps in air pollution data, but where available, health improvements associated with this reduction were reported.

Studies from Switzerland showed that a reduction in PM_{10} helped improve lung function *(65)* and reduce lung symptoms *(66)* in adults. A study in the United States investigated the effects of policy-driven air quality improvements on children's respiratory health in southern California *(67)* and found that a decline in nitrogen dioxide and $PM_{2.5}$ between 1993 and 2014 led to fewer cases of asthma and bronchitis. Recent studies from 2023 and 2024 showed that improvements in air quality in Stockholm, Sweden, between 2002 and 2019, from around 8 to 5 µg/m^3, contributed to improved lung function *(68)* and fewer asthma cases in children (*69).* These Swedish studies have been central to the debate on new EU air pollution threshold values, as they show that air quality improvements are effective and contribute to better health, even where air pollution is very low, i.e. around the WHO global air quality guidelines value. Overall, the health benefits of improved air quality remain underexplored.

Way forward

Implement air quality standards and increased sectoral collaboration

Overall, air pollution poses an enormous health burden on people but also huge financial costs to families, health systems and society as a whole. There is ample evidence on the unacceptable health burden of air pollution to support urgent and ambitious actions around the globe for cleaner air, protection of human health and mitigation of climate change. Air quality regulation around the globe should be revised and aligned with the science-based 2021 WHO global air quality guidelines, to provide public health protection. Implementing air quality standards and monitoring programmes are urgently needed in countries/cities without any, starting with the WHO global air quality guidelines or interim values. Reduction in air pollution is a complex task requiring a mix of policies and actions across a number of sectors, including transport, energy production, residential heating and cooking, agriculture, industry, waste management and urban planning. The best results are achieved through intersectoral collaboration – involving the health sector – between state governments, regional governments and cities/municipalities, as well as international collaborators.

Strengthen the health sector role in advocacy and data surveillance

For the health sector, there is an urgent need to educate and empower the health workforce to understand and communicate the health risks of air pollution, advise vulnerable groups, engage in multisectoral collaboration (including on health impact assessment of policies) and research, as well as advocate for clean air. Another often overlooked piece of the puzzle is the availability and reliability of health data, which are critical for both programmatic planning, impact assessment, prioritization of interventions and research purposes. Strengthening health data surveillance, civil registration, vital statistics and cause of deaths is therefore critical. The use of the International Classification of Diseases (ICD) codes for exposure to air pollution for recording, reporting and monitoring diseases should be further disseminated and used, so as to strengthen links with major diseases associated with air pollution.

Take sector-specific actions
Within the transport sector, actions include expanding and improving public transport, expanding cycling and pedestrian-friendly infrastructure, limiting car traffic, promoting carpooling and carsharing, electrifying transport and reducing emissions from ships and aircraft/airports.

See SPS: *Transport – sectoral solution for air pollution and health*

Within the energy production and residential energy use sectors, key actions include transitioning away from fossil fuels (coal, oil) towards renewable (wind, solar) energy production, shifting away from polluting fuels and technologies for cooking to clean alternatives, expanding and improving in district/central heating, promoting replacements for gas, oil and biomass heating with district heating, solar heating systems and heat pumps, and supporting energy retrofitting to promote energy efficiency and green buildings.

See SPS: *Phasing out coal-fired electric power generation – implications for public health: Canada: a success story – sectoral solution for air pollution and health*
See SPS: *Clean household energy – sectoral solution for air pollution and health*

Within the agriculture sector, it is imperative to reduce air pollutant emissions, via controlling agricultural waste burning via regulations and initiatives, and providing support for sustainable agriculture practices.

See SPS: *Agriculture – sectoral solution for air pollution and health*

Urban planning in the cities should promote green city development, including parks, street planting, green roofs and walls.

See SPS: *Green spaces – sectoral solution for air pollution and health*

Waste management should include the implementation of waste sorting, recycling and reuse to reduce the amount of waste dumps (mainly in LMICs) and incineration (high-income countries).

See SPS: *Open waste burning – sectoral solution for air pollution and health*

Another important step in clean air strategies can be information, education and empowerment of citizens about air pollution levels, sources and health effects. This will enable them to reduce exposures, minimize their own risk, reduce emissions and empower themselves to demand clean air actions from policy-makers. This can be accomplished by early education of children and youth in schools, training of health professionals on how to assess air pollution in clinical practice, and educating patients to empower them to avoid risk.

Countries should support and pursue ambitious goals in significant international and regional agreements, such as the Gothenburg Protocol under the Convention on Long-Range Transboundary Air Pollution, which sets reduction commitments for various pollutants, and under the International Maritime Organization, which sets emission standards for shipping.

Support international agreements
There are several individual measures that can be taken to reduce exposure to air pollution, such as choosing less polluted streets during commutes, especially when walking and cycling; ventilating homes with windows facing the least polluted streets/backyards; avoiding using wood/coal burning for heating, lighting and cooking. The use of face masks outdoors and air purifiers can help reduce exposure to air pollution, with a note of generally poor evidence on the effectiveness of these measures

and many products on the market. Yet, in the hierarchy of interventions, the most efficient, sustainable and equitable measure to protect health from air pollution remains to reduce emissions at the source.

Methodology for content development

WHO defined the scope of the document and collaborated with its Advisory Groups (Scientific Advisory Group on Air Pollution and Health [SAG]; and the Global Air Pollution and Health – Technical Advisory Group [GAPH-TAG]) members, which cover a wide range of expertise, to prepare the initial draft based on an overview of health effects of air pollution. Evidence for this rapid review was gathered and presented at monthly discussions with experts involved on the development of the document.

WHO staff and consultants from the WHO Air Quality, Energy and Health Unit reviewed the report to ensure alignment with the WHO requirements for the collections of WHO Air Quality, Energy and Health Science and Policy Summaries. This series synthesizes current knowledge and evidence on air quality, energy access, climate change links and health, primarily to inform intergovernmental discussions.

Acknowledgements

The WHO gratefully acknowledges the many individuals and organizations, including those from its advisory groups (Scientific Advisory Group on Air Pollution and Health [SAG] and the Global Air Pollution and Health Technical Advisory Group [GAPH-TAG]), who contributed to the development of this document.

This document was written by Zorana J Andersen (University of Copenhagen, Denmark) and Kari C Nadeau (Harvard University, United States), with contributions from GAPH-TAG members: Claudio Belis (European Commission, Joint Research Centre, Italy); Hanna Boogaard, Aaron Cohen (Health Effects Institute, Boston, United States); Thomas Clasen (Emory University, United States); Philip Hopke (University of Rochester, United States); Sylvia Medina (Santé publique France); Dietrich Plass (German Environment Agency); Xavier Querol (Spanish Research Council, IDAEA-CSIC, Spain); Michelle Turner (Barcelona Institute for Global Health (ISGlobal), Spain); Marialuisa Volta (University of Brescia, Italy) and Jason West (University of North Carolina, United States).

The development to the document was led by Karla Cervantes-Martínez and Sophie Gumy (WHO Department of Environment, Climate change and Health, WHO), with inputs from Heather Adair-Rohani, Pierpaolo Mudu, Samantha Pegoraro, Kerolyn Shairsingh and Cristina Vert (WHO Department of Environment, Climate change and Health).

Declarations of interest

All external experts submitted a declaration of interest to WHO disclosing potential conflicts of interest that might affect, or might reasonably be perceived to affect, their objectivity and independence in relation to the subject matter of the report. WHO reviewed each of the declarations and concluded that none could give rise to a potential or reasonably perceived conflict of interest related to the subjects covered by the report.

References[2]

1. Evolution of the WHO air quality guidelines: past, present and future. Copenhagen: WHO Regional Office for Europe, Copenhagen; 2017 (https://iris.who.int/handle/10665/341912).
2. Air quality guidelines for Europe. Copenhagen: WHO Regional Office for Europe; 1987 (https://iris.who.int/handle/10665/107364).
3. Thurston GD, Kipen H, Annesi-Maesano I, Balmes J, Brook RD, Cromar K al. A joint ERS/ATS policy statement: what constitutes an adverse health effect of air pollution? An analytical framework. Eur Respir J. 2017;49(1) (DOI: 10.1183/13993003.00419-2016).
4. Brook RD, Rajagopalan S, Pope 3rd CA, Brook JR, Bhatnagar A, Diez-Roux AV et al. Particulate matter air pollution and cardiovascular disease: an update to the scientific statement from the American Heart Association. Circulation. 2010;121(21): 2331-78 (DOI: 10.1161/CIR.0b013e3181dbece1).
5. State of global air 2024. Special report. Boston, MA: Health Effects Institute; 2024 (https://www.stateofglobalair.org/resources/report/state-global-air-report-2024).
6. WHO global air quality guidelines. Particulate matter (PM2.5 and PM10), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide. Geneva: World Health Organization; 2021 (https://iris.who.int/handle/10665/345329). Licence: CC BY-NC-SA 3.0 IGO.
7. Liu C, Chen R, Sera F, Vicedo-Cabrera AM, Guo Y, Tong S et al. Ambient particulate air pollution and daily mortality in 652 cities. N Engl J Med. 2019;381(8):705-715 (DOI: 10.1056/NEJMoa1817364).
8. Chen J, Hoek G. Long-term exposure to PM and all-cause and cause-specific mortality: a systematic review and meta-analysis. Environ Int. 202;143:105974 (DOI: 10.1016/j.envint.2020.105974).
9. Hoek G, Krishnan RM, Beelen R, Peters A, Ostro B, Brunekreef B et al. Long-term air pollution exposure and cardio-respiratory mortality: a review. Environ Health. 2013;12(1):43 (DOI: 10.1186/1476-069X-12-43).
10. Schwarz M, Peters A, Stafoggia M, F de'Donato F, Sera F, Bell ML et al. Temporal variations in the short-term effects of ambient air pollution on cardiovascular and respiratory mortality: a pooled analysis of 380 urban areas over a 22-year period. Lancet Planet Health. 2024;8(9):e657-e665 (DOI: 10.1016/S2542-5196(24)00168-2).
11. Stak M, Weinmayr G, Rodopoulou S, Chen J, de Hoogh K, Andersen ZJ et al. Long term exposure to low level air pollution and mortality in eight European cohorts within the ELAPSE project: pooled analysis. Br Med J. 2021; 374(1904) (DOI: 10.1136/bmj.n1904).
12. Stafoggia M, Oftedal B, Chen J, Rodopoulou S, Renzi M, Atkinson RW et al. Long-term exposure to low ambient air pollution concentrations and mortality among 28 million people: results from seven large European cohorts within the ELAPSE project. Lancet. Planet Health. 2022;6(1):e9-e18, 2022 (DOI: 10.1016/S2542-5196(21)00277-1).
13. Orellano P, Kasdagli ML, Pérez-Velasco R, Samoli E. Long-term exposure to particulate matter and mortality: an update of the WHO global air quality guidelines systematic review and meta-analysis. Int J Public Health. 2024;69(1607683) (DOI: 10.3389/ijph.2024.1607683).
14. Forastiere F, Spadaro JV, Ancona C, Andersen ZJ, Cozzi I, Gumy S et al. Choices of morbidity outcomes and concentration-response functions for health risk assessment of long-term exposure to air pollution. Environ Epidemiol. 2024;8(4):e314 (DOI: 10.1097/EE9.0000000000000314).
15. Estimating the morbidity from air pollution and its economic costs. Geneva: World Health Organization; 2025 (https://www.who.int/activities/estimating-the-morbidity-from-air-pollution-and-its-economic-costs).
16. Khreis H, Kelly C, Tate J, Parslow R, Lucas K, Nieuwenhuijsen M. Exposure to traffic-related

[2] Accessed 26 March 2025.

air pollution and risk of development of childhood asthma: a systematic review and meta-analysis. Environ Int. 2017;100:1-31 (DOI: 10.1016/j.envint.2016.11.012).

17. Systematic review and meta-analysis of selected health effects of long-term exposure to traffic-related air pollution. HEI special report 23. Boston, MA: Health Effects Institute; 2022 (https://www.healtheffects.org/publication/systematic-review-and-meta-analysis-selected-health-effects-long-term-exposure-traffic).
18. Park J, Kim H-J, Lee C-H, Lee CH, Lee HW. Impact of long-term exposure to ambient air pollution on the incidence of chronic obstructive pulmonary disease: a systematic review and meta-analysis. Environ Res. 2021;194(110703) (DOI: 10.1016/j.envres.2020.110703).
19. Kaufman JD, Elkind MSV, Bhatnagar A, Koehler K, Balmes JR et al. Guidance to reduce the cardiovascular burden of ambient air pollutants: a policy statement from the American Heart Association. Circulation. 2020;142(23):e432-e447 (DOI: 10.1161/CIR.0000000000000930).
20. Newby DE, Mannucci PM, Tell GS, Baccarelli AA, Brook RD, Donaldson K et al. Expert position paper on air pollution and cardiovascular disease. Eur Heart J. 2015;36(2):83-93 (DOI: 10.1093/eurheartj/ehu458).
21. Miller RM, Di Cesare M, Rahimzadeh S, Adeoye M, Perel P, Taylor S et al. Clearing the air to address pollution's cardiovascular health crisis. Glob Heart. 2024;19(1):82 (DOI: 10.5334/gh.1364).
22. Zhu W, Cai J, Hu Y, Zhang H, Han X, Zheng H et al. Long-term exposure to fine particulate matter relates with incident myocardial infarction (MI) risks and post-MI mortality: a meta-analysis. Chemosphere. 2021;267(128903) (DOI: 10.1016/j.chemosphere.2020.128903).
23. Yuan S, Wang J, Jiang Q, He Z, Huang Y, Li Z et al. Long-term exposure to PM2.5 and stroke: a systematic review and meta-analysis of cohort studies. Environ Res. 2019;177(108587) (DOI: 10.1016/j.envres.2019.108587).
24. Qin P, Luo X, Zeng Y, Zhang Y, Li Y, Wu Y et al. Long-term association of ambient air pollution and hypertension in adults and in children: a systematic review and meta-analysis. Sci Total Environ. 2021;796(148620) (DOI: 10.1016/j.scitotenv.2021.148620).
25. Yu P, Guo S, Xu R, Ye T, Li S, Sim MR et al. Cohort studies of long-term exposure to outdoor particulate matter and risks of cancer: a systematic review and meta-analysis. Innovation. 2021;2(3):100143 (DOI: 10.1016/j.xinn.2021.100143).
26. Loomis D, Grosse Y, BLauby-Secretan B, El Ghissassi F, Bouvard V et al. The carcinogenicity of outdoor air pollution. Lancet Oncol. 2013;14(13):1262-3 (DOI: 10.1016/s1470-2045(13)70487-x).
27. Outdoor air pollution. IARC monographs on the evaluation of carcinogenic risks to humans. Volume 109. Lyon: International Agency for Research on Cancer; 2015 (https://publications.iarc.fr/Book-And-Report-Series/Iarc-Monographs-On-The-Identification-Of-Carcinogenic-Hazards-To-Humans/Outdoor-Air-Pollution-2015).
28. Diesel and gasoline engine exhausts and some nitroarenes. IARC monographs on the evaluation of carcinogenic risks to humans. Volume 105. Lyon: International Agency for Research on Cancer; 2013 (https://publications.iarc.fr/Book-And-Report-Series/Iarc-Monographs-On-The-Identification-Of-Carcinogenic-Hazards-To-Humans/Diesel-And-Gasoline-Engine-Exhausts-And-Some-Nitroarenes-2013).
29. Household use of solid fuels and high-temperature frying. Volume 95. IARC monographs on the evaluation of carcinogenic risks to humans. Lyon: International Agency for Research on Cancer; 2010 (https://publications.iarc.fr/Book-And-Report-Series/Iarc-Monographs-On-The-Identification-Of-Carcinogenic-Hazards-To-Humans/Household-Use-Of-Solid-Fuels-And-High-temperature-Frying-2010).
30. Sun Q, Yue P, Deiuliis JA, Lumeng CN, Kampfrath T et al. Ambient air pollution exaggerates adipose inflammation and insulin resistance in a mouse model of diet-induced obesity.

Circulation. 2009;119(4):538-46 (DOI: 10.1161/CIRCULATIONAHA.108.799015).

31. Yang B-Y, Fan S, Thiering E, Seissler J, Nowak D, Dong G-H et al. Ambient air pollution and diabetes: a systematic review and meta-analysis. Environ Res. 2020;180(108817) (DOI: 10.1016/j.envres.2019.108817).
32. Roy R, D'Angiulli A. Air pollution and neurological diseases, current state highlights. Front Neurosci. 2024;18(1351721) (DOI: 10.3389/fnins.2024.1351721).
33. Lin L-Z, Zhan X-L, Jin C-Y, Liang J-H, Jing J, Dong G-H. The epidemiological evidence linking exposure to ambient particulate matter with neurodevelopmental disorders: a systematic review and meta-analysis. Environ Res. 2022;209(112876) (DOI: 10.1016/j.envres.2022.112876).
34. Cheng S, Jin Y, Dou Y, Zhao Y, Duan Y, Pei H, Lyu P. Long-term particulate matter 2.5 exposure and dementia: a systematic review and meta-analysis. Public Health. 2022;212:33-41 (DOI: 10.1016/j.puhe.2022.08.006).
35. Gosh R, Causey K, Burkart K, Wozniak S, Cohen A, Brauer M. Ambient and household PM2.5 pollution and adverse perinatal outcomes: a meta-regression and analysis of attributable global burden for 204 countries and territories. PLOS Med. 2021;18(11):e1003852 (DOI: 10.1371/journal.pmed.1003718).
36. Brunekreef B et al. Air pollution and COVD-19. Brussels: European Parliament; 2021 (https://www.europarl.europa.eu/RegData/etudes/STUD/2021/658216/IPOL_STU(2021)658216_EN.pdf).
37. Air pollution and children's health. Copenhagen: European Environment Agency; 2023 (https://www.eea.europa.eu/publications/air-pollution-and-childrens-health).
38. Pereira F, Nadeau K. Climate change, fossil-fuel pollution, and children's health. New Engl J Med. 2022;386(24):2303-2314 (DOI: 10.1056/NEJMra2117706).
39. Air pollution data portal. Global Health Observatory. Geneva: World Health Organization; 2025 (https://www.who.int/data/gho/data/themes/air-pollution).
40. GBD 2021 Risk Factors Collaborators. Global burden and strength of evidence for 88 risk factors in 204 countries and 811 subnational locations, 1990–2021: a systematic analysis for the Global Burden of Disease Study 2021. Lancet. 2024;403(10440):2162-2203 (DOI: 10.1016/S0140-6736(24)00933-4).
41. SDG 3.9.1: preliminary updates for the year 2021. Geneva: World Health Organization; 2025 (link).
42. Karagulian F, Belis CA, Dora CFC, Prüss-Ustün AM, Bonjour, S Adair-Rohani H et al. Contributions to cities' ambient particulate matter (PM): a systematic review of local source contributions at global level. Atmos Environ. 2015;120:475-483 (DOI:10.1016/j.atmosenv.2015.08.087).
43. Hopke PK, Dai Q, Li L, Feng Y. Global review of recent source apportionments for airborne particulate matter. Sci Total Environ. 2020;740(140091) (DOI: 10.1016/j.scitotenv.2020.140091).
44. Romanello M, Walawender M, Hsu S-C, Moskeland A, Palmeiro-Silva Y, Scamman D et al. The 2024 report of the Lancet Countdown on health and climate change: facing record-breaking threats from delayed action. Lancet. 2024;404(10465):1847-1896 (DOI: 10.1016/S0140-6736(24)01822-1).
45. McDuffie EE, Martin RV, Spadaro JV, Burnett R, Smith SJ et al. Source sector and fuel contributions to ambient PM2.5 and attributable mortality across multiple spatial scales. Nat Commun. 2021;1(1)3594 (DOI: 10.1038/s41467-021-23853-y).
46. Belis CA, Van Dingenen R. Air quality and related health impact in the UNECE region: source attribution and scenario analysis. Atmos Chem Phys. 2023;23(14):8225-8240 (DOI: 10.5194/acp-23-8225-2023).
47. Saraga DE, Querol X, Duarte RMBO, Aquilina NJ, Canha N, Alvarez EG et al. Source

apportionment for indoor air pollution: current challenges and future directions. Sci Total Environ. 2023;900(165744) (DOI: 10.1016/j.scitotenv.2023.165744).

48. Hopke P, Hidy G. Changing emissions results in changed PM2.5 composition and health impacts. Atmosphere. 2022;13(2):193 (DOI:10.3390/atmos13020193).
49. Lippmann M, Chen LC, Gordon T, Ito K, Thurston GD. National Particle Component Toxicity (NPACT) Initiative: integrated epidemiologic and toxicologic studies of the health effects of particulate matter components. HEI research report 177. Boston, MA: Health Effects Institute; 2013 (https://www.healtheffects.org/publication/national-particle-component-toxicity-npact-initiative-integrated-epidemiologic-and).
50. Chowdhury S, Hänninen R, Sofiev M, Aunan K. Fires as a source of annual ambient PM2.5 exposure and chronic health impacts in Europe. Sci Total Environ. 2024;922(171314) (DOI: 10.1016/j.scitotenv.2024.171314).
51. Rai M, Stafoggia M, de'Donato F, Scortichini M, Zafeiratou S, Fernandez LV et al. Heat-related cardiorespiratory mortality: effect modification by air pollution across 482 cities from 24 countries. Environ Int. 2023;174(107825) (DOI: 10.1016/j.envint.2023.107825).
52. Stafoggia M, Michelozzi P, Schneider A, Armstrong B, Scortichini M, Rai M et al. Joint effect of heat and air pollution on mortality in 620 cities of 36 countries. Environ Int. 2023;181(108258) (DOI: 10.1016/j.envint.2023.108258).
53. Li C, van Donkelaar A, Hammer MS, McDuffie E, Burnett RT, Spadaro JV et al. Reversal of trends in global fine particulate matter air pollution. Nat Commun. 2023;14(1):5349 (DOI: 10.1038/s41467-023-41086-z).
54. Song C, Wu L, Xie Y, He J, Chen X, Wang T. Air pollution in China: status and spatiotemporal variations. Environ Pollut. 2017;227:334-347 (DOI: 10.1016/j.envpol.2017.04.075).
55. Silver B, Conibear L, Reddington CL, Knote C, Arnold SR, Spracklen DV. Pollutant emission reductions deliver decreased PM2.5-caused mortality across China during 2015–2017. Atmos Chem Phys. 2020;20(20:11683-11695 (DOI: 10.5194/acp-2019-1141).
56. Dockery DW, Rich DQ, Goodman PG, Clancy L, Ohman-Strickland P, George P et al. Effect of air pollution control on mortality and hospital admissions in Ireland. Research report 176. Boston, MA: Health Effects Institute; 2013 (https://www.healtheffects.org/system/files/Dockery-176.pdf).
57. European Green Capital Award Good Practices - Kraków - air protection. Brussels: European Commission; 2023 (https://environment.ec.europa.eu/topics/urban-environment/european-green-capital-award/inspiration/krakow-air-protection_en).
58. Fan M, Wang Y. The impact of PM2.5 on mortality in older adults: evidence from retirement of coal-fired power plants in the United States. Environ Health. 2020;19(1):28 (DOI: 10.1186/s12940-020-00573-2).
59. Henneman L, Choirat C, Dedoussi I, Dominici F, Roberts J, Zigler C. Mortality risk from United States coal electricity generation. Science. 2023;382(6673):941-946 (DOI: 10.1126/science.adf4915).
60. Kelly JW, PA Media. London air quality improved by ULEZ and LEZ - report. BBC News, 2 November 2023 (https://www.bbc.com/news/uk-england-london-67288327).
61. Chamberlain RC, Fecht D, Davies B, Laverty AA. Health effects of low emission and congestion charging zones: a systematic review. Lancet Public Health. 2023;8(7):e559-e574 (DOI: 10.1016/S2468-2667(23)00120-2).
62. Nieuwenhuijsen M, de Nazelle A, Pradas MC, Daher D, Dzhambov A, Echave C et al. The superblock model: a review of an innovative urban model for sustainability, liveability, health and well-being. Environ Res. 2024;251(1):118550 (DOI: 10.1016/j.envres.2024.118550).
63. Mueller N, Rojas-Rueda D, Khreis H, Cirach M, Andrés D, Ballester J et al. Changing the urban design of cities for health: the superblock model. Environ Int. 2020;134:105132

(DOI: 10.1016/j.envint.2019.105132).

64. Navaratnam AMD, Williams H, Sharp SJ, Woodcock J, Khreis H. Systematic review and meta-analysis on the impact of COVID-19 related restrictions on air quality in low- and middle-income countries. Sci Total Environ. 2024;908:168110 (DOI: 10.1016/j.scitotenv.2023.168110).
65. Downs SH, Schindler C, Liu LJS, Keidel D, Bayer-Oglesby L, Brutsche MH et al. Reduced exposure to PM10 and attenuated age-related decline in lung function. New Engl J Med. 2007;357(23):2338-47 (DOI: 10.1056/NEJMoa073625).
66. Schindler C, Keidel D, Gerbase MW, Zemp E, Bettschart R, Brändli Oet al. Improvements in PM10 Exposure and Reduced Rates of Respiratory Symptoms in a Cohort of Swiss Adults (SAPALDIA). Am J Respir Criti Care Med. 2008;179(7) (DOI: 10.1164/rccm.200803-388OC).
67. Gilliland F, Avol E, McConnell R, Berhane K, Gauderman WJ, Lurmann F et al. The effects of policy-driven air quality improvements on children's respiratory health. HEI research report 190. Boston, MA: Health Effects Institute; 2017 (https://www.healtheffects.org/publication/effects-policy-driven-air-quality-improvements-childrens-respiratory-health).
68. Yu Z, Merid SK, Bellander T, Bergström A, Eneroth K, Georgelis A et al. Associations of improved air quality with lung function growth from childhood to adulthood: the BAMSE study. Eur Respir J. 2023;61(5):2201783 (DOI: 10.1183/13993003.01783-2022).
69. Yu Z, Merid SK, Bellander T, Bergström A, Eneroth K, Merritt AS et al. Improved air quality and asthma incidence from school age to young adulthood: a population-based prospective cohort study. Ann Am Thorac Soc. 2024;21(10) (DOI: 10.1513/AnnalsATS.202402-200OC).

WHO Air Quality, Energy and Health Science and Policy Summaries

Exposure to health damaging air pollutants

Technical brief

Key messages

Exposure to air pollution has significant adverse health effects, responsible for nearly 1 in every 8 deaths globally. Air pollution affects all age groups, from unborn children to older people, in both high- and low-income nations.

Exposure is the contact between people and polluted air, which is influenced by how much time people spend breathing air pollution at different concentrations. Exposure to air pollutants affects the respiratory, cardiovascular and other organ systems, increasing the risk of morbidity and mortality. Adverse health effects are related to exposure to the mixture of pollutants, with well-established evidence for fine and coarse particulate matter (PM), nitrogen dioxide, sulfur dioxide, ozone and carbon monoxide; ultrafine particles (UFPs) and components of PM such as black carbon and some metals are also understood to adversely impact health.

Large geographic differences exist in ambient air pollution concentrations at global, regional and local scales, and across urban and rural areas, with important contributions from anthropogenic sources such as transportation, industry, power generation, residential sources, waste burning and agriculture. Non-anthropogenic sources of air pollutants such as sea salt and dust, wildfires and volcanoes also contribute greatly and explain the natural variability across regions. On average, low- and middle-income countries (LMICs) have higher levels of ambient air pollution than high-income countries (HICs). Yet, even within individual cities or countries, socioeconomically marginalized groups are often exposed to higher concentrations of air pollutants.

Understanding air pollutant concentrations and their sources is important for informing policy actions and reducing population exposures, as the relative importance of a source as well as other factors (such as topography and meteorology) may vary by city or region. However, that understanding is poor in some of the most polluted cities and countries in the world because of a lack of air quality and source apportionment measurements. New tools, including satellite observations, improved air quality models and data fusion methods, are helping to better quantify air pollution and its sources across all scales.

Enough is known about the factors that determine exposure, vulnerability and health effects, and about sources, for countries to take action to reduce pollutant emissions and the disease burden from air pollution. Air quality has improved significantly in the past 30 years in some regions and nations including China, Europe and the United States of America. These reductions have been shown to bring substantial health benefits including increased life expectancy. The actions taken in these countries to improve air quality, including setting air quality standards and implementing controls on emissions from large industries, energy production facilities and transportation, are helpful in informing air quality actions in LMICs, although the importance of different sources and effectiveness of actions in individual countries and cities may differ. In that context, nations should consider adopting the World Health Organization (WHO) air quality guidelines (AQG), or interim targets (IT), as air quality standards. In addition to reducing air pollutant emissions, actions to reduce greenhouse gas emissions, including moving towards a clean energy transition, will have direct and indirect benefits for air quality and health.

Key definition
Exposure: The contact between individuals and air pollution, capturing both how polluted the air is and how much time people spend in different environments with different levels of pollution. This contact can be short or prolonged and it can happen indoor or outdoor. The extent of exposure is affected by daily activities, and depends on factors such as the age, occupation, and other characteristics of individuals. Exposure can be characterized using concentration data from ground monitoring stations, satellite observations and computer models, which estimate concentrations spatially to observe how they vary over a population. Other techniques such as personal sampler devices and biological monitoring can provide measures of an individual's personal exposure from their activities throughout the day and offer insights into the extent and effects of air pollution exposure in the human body.

Overview

Exposure to air pollution – both ambient and household – is recognized as the most important environmental risk factor for global public health leading to one in every eight deaths annually, with 6.7 million deaths worldwide *(1).* Currently, over 95% of the world's population is exposed to concentrations of ambient $PM_{2.5}$ and ozone that exceed the annual WHO AQG *(2).* However, 159 countries have surpassed WHO IT1 for $PM_{2.5}$ (35 mg/m^3) with 45 of these nations achieving IT4 (10 mg/m^3). Many countries have seen progress in the last decade as an increasing percentage of their populations live in areas where ambient $PM_{2.5}$ levels meet the various interim targets proposed in the WHO AQG. For example, 18 more countries have met IT3 for $PM_{2.5}$ (15 mg/m^3) with 7 of these countries reaching IT4. While some regions are making more progress than others, nearly all regions have concentrations exceeding WHO AQG – a problem for high- and low-income nations alike.

Air pollutants that impact health

Health effects of air pollution have been established for both long-term (years) and short-term (hours, days) exposures. The effects of exposure can vary among people based on age, sex, physical condition, medical history, socioeconomic position, external environment and other factors. WHO updated its health-based air quality guidelines for major air pollutants in 2021, because the current scientific consensus is that for most regulated air pollutants, and even for some not yet regulated, adverse health risks still exist at concentrations well below current AQG *(3)* (see Table 1). This was informed by key findings in several epidemiological studies that air pollution concentration-response functions are continuous and without a threshold. As such, improvements in air quality are expected to result in benefits for public health both where concentrations are high and where they are low.

Air pollutants have exposure patterns, biological mechanisms and health impacts that differ depending on the pollutant. PM refers to solid and liquid particles that exist in a wide range of different sizes and have different chemical and biological composition reflecting contributions from a variety of sources. The gaseous pollutants are specific chemical compounds, including ozone, sulfur dioxide, nitrogen dioxide and carbon monoxide (Table 1).

Exposure to air pollution has been linked with adverse human health effects affecting nearly every organ system, but the strongest evidence exists for respiratory and cardiovascular diseases, even if there is growing evidence for other systems. Increased risk of outcomes in metabolic, respiratory, nervous, cardiovascular systems and maternal and child health have been thoroughly documented in studies globally.

See SPS[1] *Health effects of air pollution – evidence and implications*

Particle size matters for PM-related health effects. The largest particles, such as dust, may be trapped in the upper airways, where they are removed by coughing or relocated to the gastrointestinal tract. Fine particles (measured as PM with aerodynamic diameter less than 2.5 µm, or $PM_{2.5}$) are particularly damaging to health because they are inhaled deeper into the lung and are more widely distributed in outdoor air. Among components of $PM_{2.5}$, there is evidence that black carbon, coming from outdoor and household combustion of wood, diesel fuel and coal, may be particularly detrimental to health. Ultrafine particles, whose main sources are motor vehicles and industry, can also be formed in the atmosphere, comprise particles smaller than 0.1 µm and may be damaging to health because of their ability to reach the deepest regions of the lung and be transported directly into the bloodstream.

The health effects attributed to PM exposure are substantial and have been studied in countries around the world. Evidence for these health effects, including mortality, cardiovascular disease, cancer, and effects on the respiratory and nervous systems, is well established through authoritative reviews by organizations including WHO, United States Environmental Protection Agency and the International Agency for Research on Cancer (IARC). For instance, in 2013, the IARC classified outdoor air pollution as carcinogenic to humans *(3,4).*

Ozone is known to cause several health effects, largely to the respiratory system. Other gases, including sulfur dioxide, nitrogen dioxide and carbon monoxide, also have well-established health effects, reflected in the WHO AQG. These gases are also important because they participate in reactions that form $PM_{2.5}$ and ozone. Some volatile organic compounds (VOC) such as benzene are understood to be toxic, and toxic elements, including lead, mercury, cadmium, arsenic, vanadium and nickel, can affect the development of the brain and nervous system, especially in children, and cause cancer.

The 2021 WHO AQG revisions made the guidelines for PM and nitrogen dioxide in particular much stricter than before. The revision also included best practice statements for some emerging pollutants including UFPs and black carbon. For these pollutants, there was insufficient evidence to develop quantitative guidelines due to lack of routine monitoring, but enough evidence to be concerned, and to motivate reductions in emissions and exposure, as well as more routine monitoring. For UFPs, there is strong toxicological evidence and growing epidemiological evidence suggesting that exposures greater than 10 000 particles/cm^3 over a 24-hour period may be harmful.

Table 1. Air pollutant sources and WHO guidelines

Pollutant	**Major sources**	**Relevant WHO guidelines**[a]
PM_{10} (fine and coarse particulate matter)	Primary emissions from: - Transport - Industry - Construction - Agriculture - Biomass burning	Annual average 15 mg/m^3 24-hour average 45 mg/m^3
$PM_{2.5}$ (fine particulate matter)	Primary emissions from: - Residential combustion - Transport - Industry	Annual average 5 mg/m^3 24-hour average 15 mg/m^3

[1] Science and Policy Summary.

	- Energy production - Biomass burning - Agriculture - Waste - Natural sources Secondary $PM_{2.5}$ is formed from emissions of SO_2, NO_X, VOCs and NH_3	
O_3 (ozone)	Not directly emitted from sources but formed from emissions of NO_X and VOCs from: - Transport - Industry - Energy production - Biomass burning - Agriculture - Waste - Natural sources	6-month average of 8-hour daily maximum 60 μg/m^3 8-hour average100 μg/m^3
NO_2 (nitrogen dioxide)	Primary and secondary emissions from: - Transport - Industry - Energy production - Biomass burning - Residential combustion	Annual average 10 mg/m^3 24-hour average 25 mg/m^3
SO_2 (sulfur dioxide)	Primary emissions from: - Industry - Energy production - Natural sources	24-hour average 40 mg/m^3 10-minute average 500 mg/m^3
CO (carbon monoxide)	Primary emissions from: - Transport - Industry - Energy production - Biomass burning - Residential combustion	24-hour average 4 mg/m^3 1-hour average 35 mg/m^3

Note: [a] See WHO (2021) for a full list of air quality guidelines and how they are specified *(3).*
NH_3 ammonia; NO_x nitrogen oxides.

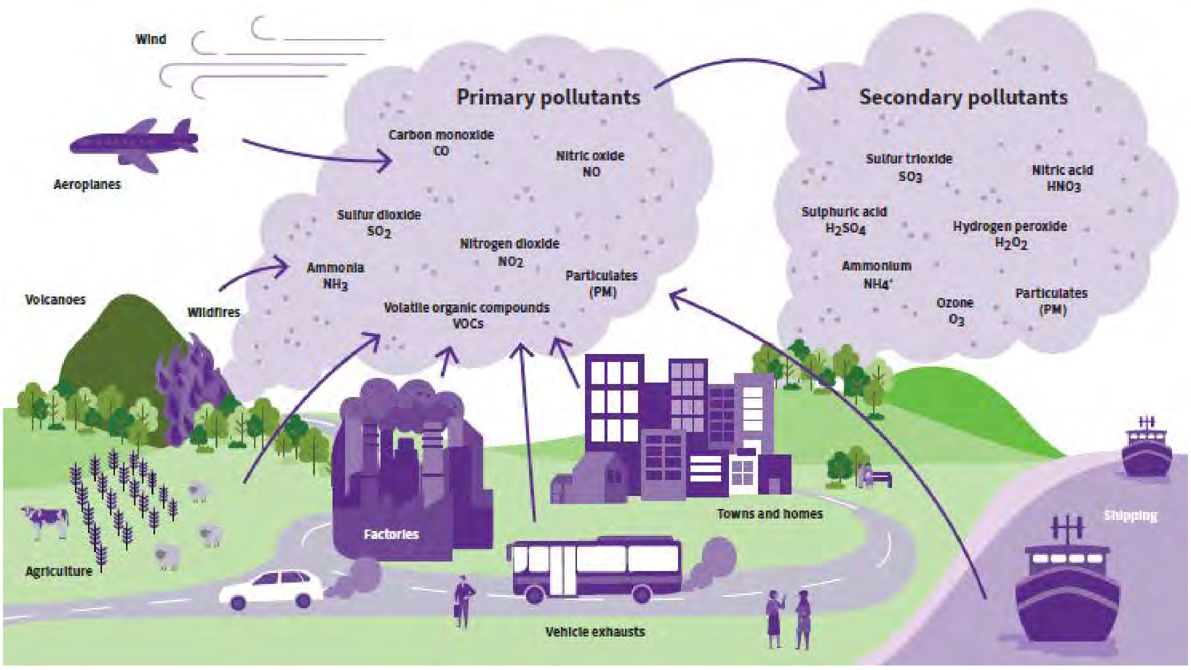
Pollutant characteristics and mixtures

Exposure to air pollutants comes from a complex mixture of gases and particles, reflecting contributions from a variety of sources. PM is a complex mixture of different sized particles from many compounds. Since its composition varies from place to place and over time, PM is not as clearly defined as individual gases. Some PM is directly emitted as particles into the atmosphere, such as in smoke from fires and soot from diesel engines, known as "primary" PM. Other PM forms in the atmosphere by chemical reactions of gases, including sulfur dioxide and nitrogen oxides, VOCs and ammonia, and is known as "secondary" PM. In many polluted regions, secondary PM contributes the majority of $PM_{2.5}$ *(5).* Among gaseous air pollutants, ground-level ozone is entirely secondary – it is not directly emitted, but is formed in the atmosphere in the presence of sunlight through chemical reactions of nitrogen oxides, VOCs, carbon monoxide and methane. Note that ground-level ozone is different from ozone in the stratosphere, which protects against harmful ultraviolet radiation from the sun.

The concentrations and mixtures of pollutants vary widely at global, regional and micro scales. Pollutants such as $PM_{2.5}$ and ozone can move over hundreds of kilometres, vary in their chemical composition with atmospheric transport and contribute to transboundary air pollution; so a city's pollution can affect regions downwind, and upwind regions can influence a city's pollution. Each of the components of an air pollutant mixture might have contributions from different sources, such as power generation, industry, transport, agriculture and residential solid fuel use. For example, in large cities in many HICs, air pollution is characterized by PM, nitrogen dioxide, ozone, carbon monoxide and much lower concentrations of sulfur dioxide, with PM being mainly composed of organic matter, secondary inorganic aerosols, mineral matter and black carbon. In cities in LMICs, the proportion and levels of mineral matter, black carbon and secondary inorganic aerosols in PM are often higher, as are concentrations of sulfur dioxide, carbon monoxide and ozone (in some cases). In cities, the mixture of pollution is highly affected by road traffic, industrial and residential emissions, while in towns and peri-urban areas, arid regions and rural areas, residential emissions, dust and agricultural emissions may contribute to PM and its precursors. Inside cities, the concentrations of nitrogen dioxide, UFPs, black carbon and carbon monoxide tend to be much higher at short distances from road traffic. Consequently, strategies to abate pollution may differ among nations and cities.

Traditionally, regulations address concentrations of individual gases and mixtures of PM (measured as $PM_{2.5}$ and PM_{10}), supported by evidence of health effects associated with these pollutants. However, some components of the PM mixture may be more damaging to health than others. This may be due to the different chemical composition and size distribution such as for black carbon and UFPs, which has led the WHO to issue best practice statements for these pollutants. There is also research underway to try to understand whether mixtures of air pollutants from specific sources (e.g. coal burning, traffic, sand and dust storms, wildfires) are more damaging to health than from other sources. However, there is no clear consensus on which sources or particle components are more damaging for particular health outcomes, and so bulk PM_{10} and $PM_{2.5}$, which have clear detrimental health impacts, are the indicators that are widely measured and regulated.

Fig. 1. Major sources of air pollution



Notes: Primary pollutants are emitted directly into the atmosphere. Secondary pollutants are formed in the atmosphere from chemical reactions involving primary gaseous pollutants. Air pollutants can move and impact populations downwind of their sources.
Source: Amazing World of Science website (https://www.mrgscience.com/ess-topic-63-photochemical-smog.html). Human silhouettes obtained from Freepik Company, S.L.

In addition to being exposed to multiple contaminants in the air pollution mixture, exposure can coincide with other meteorological or physical conditions that together may synergistically increase health risk. Certain hazards, such as sand and dust storms, heatwaves or wildfires, can intensify exposure to PM and gaseous pollutants such as ozone. This heightened exposure impacts not only the populations near the origins of these events but can extend to areas thousands of kilometres away. The synergistic effect of these co-occurring exposures should be considered for overall health effects, and air quality actions should consider variable sources that contribute to episodes of poor air quality.

See SPS *The impacts of wildfire smoke on health*
See SPS *Understanding the health impacts of sand and dust storms*
See SPS *The synergies of heat stress and air pollution and its health impacts*

Exposure

Exposure to air pollution occurs when humans come into contact with contact polluted air and inhale or ingest it. Exposure is dependent on both pollutant concentration and the amount of time spent in environments where that pollutant is present. This includes exposures that occur outdoors, as well as in indoor environments. Personal activities, such as participating in vigorous exercise, can increase the amount of pollution inhaled because of increased respiratory rate, which in turn, increases the delivery of air pollutants into a person's lungs. As such, where people spend their time and for how long, what activities they engage in, and what concentrations of air pollutants they inhale, are critical to understand in order to mitigate exposure, especially for vulnerable populations (e.g. children, pregnant people, older people, unhoused, certain occupational groups). Exposure is often highly variable across time and space, with some individuals or communities receiving higher exposures than others.

Understanding exposure requires an assessment of concentration of the pollutant over the time of exposure. While exposure is not the same as concentration, air quality studies usually use concentrations from fixed-site monitoring, personal monitoring, modelling or remote sensing as a proxy for exposure *(6).*

While spending time outdoors in polluted air certainly contributes to exposure, most people spend the majority of their time in indoor environments. Outdoor air pollution infiltrates to indoor environments, and indoor environments often have their own sources of air pollution. In some LMICs where solid fuel combustion for cooking and heating are large contributors to exposures, indoor air pollutant concentrations can often be higher than outdoor. Factors related to housing quality and integrity, and how well buildings and residences are maintained and ventilated, also influence how much occupants are exposed to outdoor air, as well as how much indoor air is vented to the outdoors.

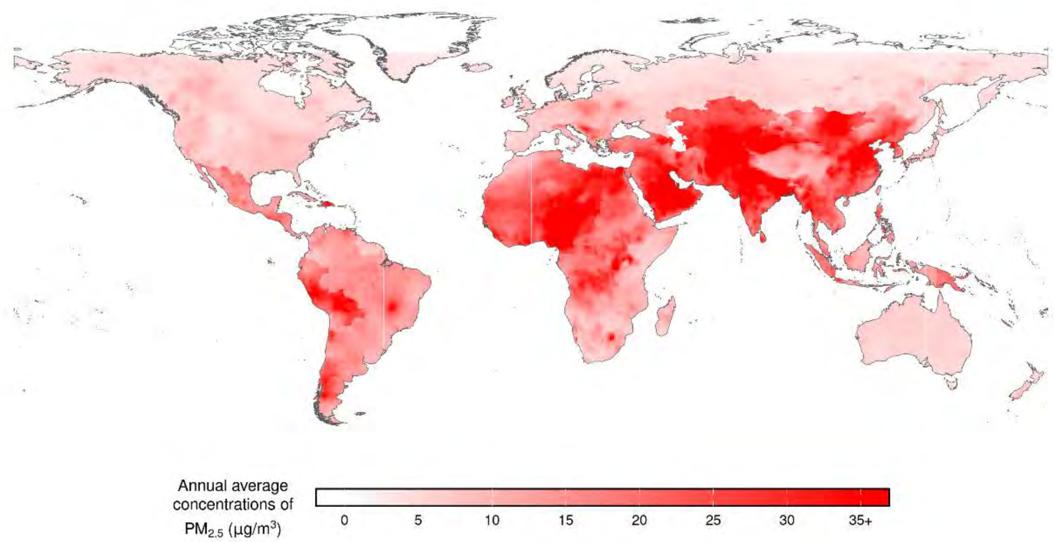
See SPS *Indoor air pollution – how to protect human health in our homes*
See SPS *Household air pollution and related health effects*

In general, reductions in air pollution exposures can lead to reductions in adverse health outcomes. The most effective strategy for lowering exposure is by implementing approaches that reduce ambient air pollution concentrations by reducing emissions of air pollutants at their sources, especially in communities or groups where exposures are high. Personal interventions may be a useful option for at-risk individuals to reduce their exposure, such as wearing face masks, using indoor air purifiers, or modifying behaviours. However, these actions may not reach target audiences because they are costly, pose a burden on individuals who implement them, can sometimes be ineffective if poorly utilized, and can lead to inequities. While personal interventions can reduce short-term exposures for individuals, particularly for those most at risk, a more effective, sustainable and equitable long-term government strategy is to focus on reducing pollutant emissions at their source.

Geographical distribution and inequities

The spatial distribution of air pollutants is highly variable at global, regional and municipal scales. While some pollutants are more spatially variable than others, increases in ground measurements and improvements in satellite observations and models, provide a clearer picture of global air quality patterns (see Fig. 2).

Fig. 2. Global distribution of population-weighted annual average $PM_{2.5}$ in 2023 (µg m^{-3})

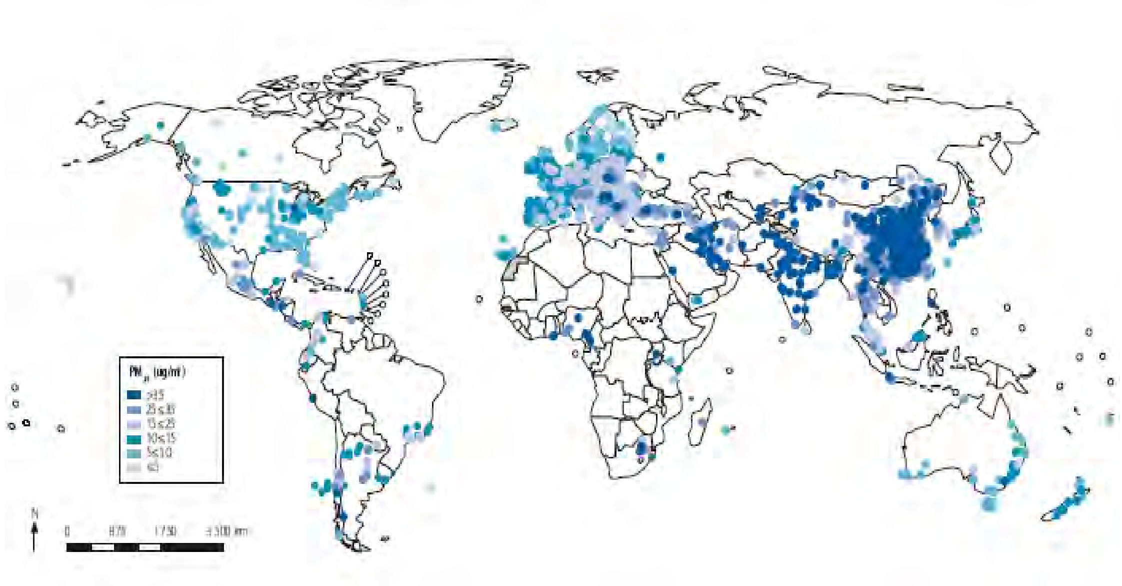


Source: Preliminary SDG 11.6.2 modelled estimates from the Data Integration Model for Air Quality *(7).*

Within countries and cities, pollution can also vary depending on factors such as proximity to sources, topography and meteorology, with some cities experiencing air pollution levels 10 times higher than others. Globally, air pollution is often higher in LMICs. But it is also the case that within individual countries or cities, socioeconomically marginalized people often have greater exposure to air pollution. This is thought to be a result of important structural factors, social inequities and policies that have historically led to greater placement of polluting sources (e.g. major roads and industries) in areas where socially disadvantaged populations live, including racial and ethnic minority groups, immigrant and refugee populations, and lower income communities. Further, people with lower incomes have fewer resources to move to less polluted neighbourhoods. These chronically elevated exposures often impact populations with greater vulnerability (e.g. poor access to health care, pre-existing health conditions, chronic stress and discrimination), contributing to persistent health disparities.

In addition, the availability, spatial coverage and quality of monitoring data and of emissions inventories still lag in certain regions of the world, creating important gaps in our understanding of exposure patterns and health risks, especially at more local scales and critically so in LMICs *(8).* Some of the most polluted regions have the fewest monitors. As of 2022, only 118 nations regularly monitored air quality, with many nations in sub-Saharan Africa lacking monitors entirely (see Fig. 3) *(9).* Other countries have many times fewer monitors per million people than is the case in Brazil, China, Europe, Japan and the United States of America *(10).* Further, since monitoring networks are typically oriented towards polluted cities, we have less understanding of air pollution levels affecting rural populations. These large data gaps contribute to increased uncertainty in estimating air pollution levels in these regions, leading to less confident assessments of air pollution exposure and disease burden, and of the actions that could be taken to reduce air pollution.

Fig. 3. Human settlements with reference-grade air quality monitoring

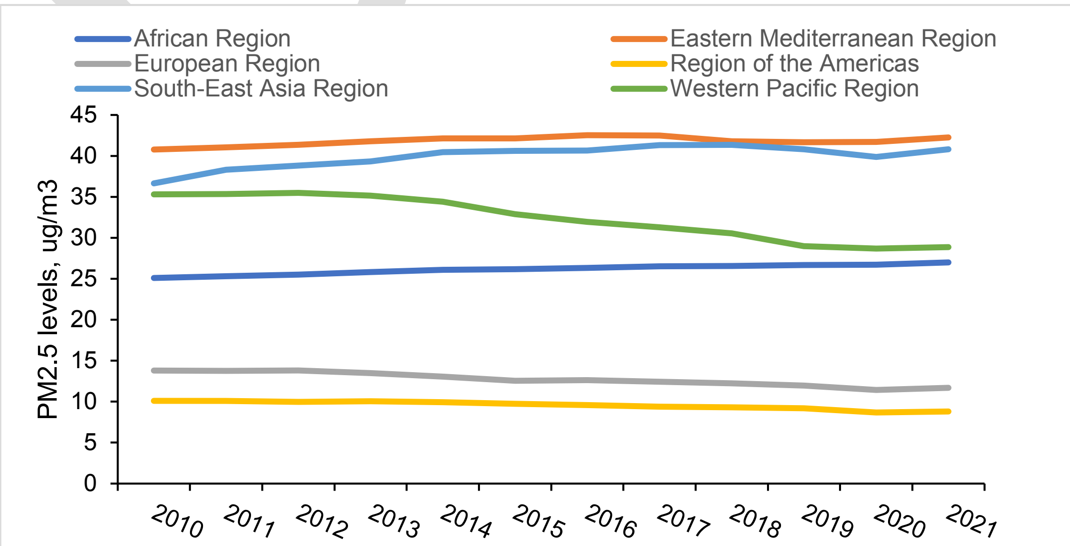


Notes: There is a large disparity in monitoring density in different regions of the world with particular gaps in parts of Africa, Latin America and Asia.
Source: WHO Ambient Air Quality Database *(8).*

Trends and sources in world regions

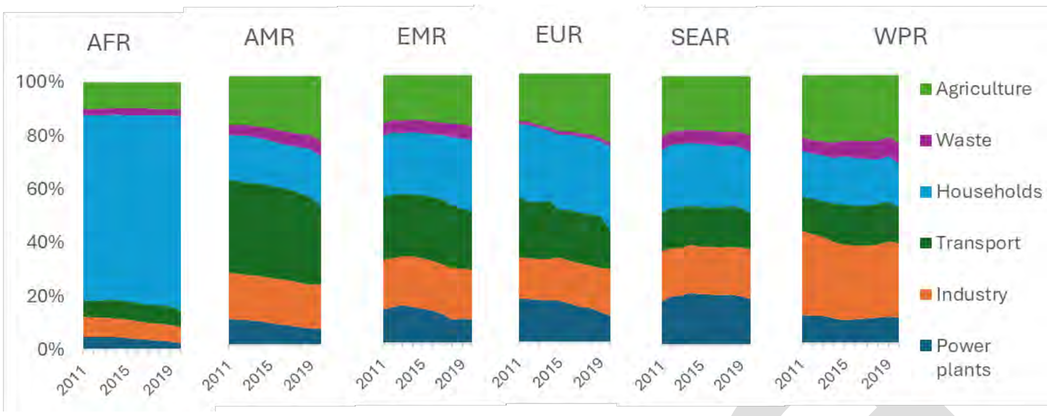
From 2010 to 2021, concentrations of $PM_{2.5}$ showed diverse trends across the regions, with levels decreasing in the WHO European, American and Western Pacific regions (see Fig. 4).

Fig. 4. Trends of $PM_{2.5}$ (annual average) ambient population-weighted concentrations as an indicator for exposure in the six WHO world regions, 2010 to 2021



Source: Romanello et al., 2024 *(11).*

Fig. 5. Relative contributions of human-generated emissions from different sectors to $PM_{2.5}$ (population-weighted) in the six WHO world regions from 2010 to 2021



Note: The impact of natural sources is not included.
Source: Romanello et al., 2024 *(11).*

In Africa, household fuel use is the greatest source of anthropogenic $PM_{2.5}$ and its levels have increased in the last 10 years. Household fuel use is also a main contributor to $PM_{2.5}$ in South-East Asia and Europe. In South-East Asia the contribution of the agriculture sector to $PM_{2.5}$ is almost as high as household sources, and has increased over the decade. In the Eastern Mediterranean Region, households are the main source of $PM_{2.5}$ followed by transport. In the Western Pacific, industry followed by agriculture emissions are the main contributors to $PM_{2.5}$ concentrations with industries showing a decreasing trend while agriculture has increased over the decade. For the Region of the Americas, transport has the greatest contribution to $PM_{2.5}$ followed by agriculture (see Fig. 5). While not shown in Fig 5, natural sources (e.g. desert dust) is the main component of $PM_{2.5}$ concentrations in the Americas, Africa and Eastern Mediterranean regions. Individual cities and countries may have contributions to emissions that differ strongly from these regional averages. Therefore, it is important to use source apportionment and emissions inventories to quantify the contributions of different local sources, as well as more distant transboundary sources, to inform air pollution abatement actions.

Changes in long-term trends in concentrations are not only influenced by policy actions but also by climate change. Climate change can affect meteorology, which impacts the emissions, formation, propagation and removal of pollutants, including through increased emissions from wildfires and windblown dust. As such, climate change may counteract the benefits of some emission reductions from human actions. The extent and rate of air quality improvements can be advanced/fast-tracked through policies and programmes that aim to reduce anthropogenic and non-anthropogenic emissions.

Way forward

Poor air quality is bad for health. We know enough about the sources of air pollution, transformation and transport in the atmosphere, and health effects, to support significant action to control emissions at the source. We understand well that air pollution imposes significant impacts on health across the globe, although we do not know with certainty the concentrations to which people are exposed throughout the world. Actions have been taken to improve air quality in many countries, bringing significant health benefits, including lengthening life expectancy and improving the quality of life. Much is known about how to reduce air pollution. The sooner action is taken, the more lives will be saved.

Utilize the WHO Air Quality Guidelines

To improve air quality, nations are encouraged to use the WHO AQG and interim targets to set air quality standards *(3)*, since these guidelines are based on the current global understanding of the health effects of air pollutants. The severity of air pollution, major sources and feasibility of solutions can vary widely across countries. Acknowledging that any reduction in air pollution contributes to improvements in air quality and human health, WHO Member States are encouraged to set air quality standards – ensuring they are embedded in their legislation to make them legally binding – and to identify the major sources of pollution and implement sectoral policies that are most relevant for their context.

See SPS *Air quality legislation and its implications for health*

Focus on local, regional and international airshed management: Cities with severe air pollution should take action on their own air pollutant sources. However, cities are also impacted by transboundary sources in other countries or jurisdictions. As air pollution moves across boundaries, regional and international cooperation is essential steps toward improving air quality. For example, the Convention on Long-Range Transboundary Air Pollution has been an important mechanism by which agreements to reduce emissions have been reached among European and neighbouring nations. Similarly, in Southeast Asia, the ASEAN Agreement on Transboundary Haze Pollution has enabled regional governments to coordinate action on air pollution. Governments, and more specifically the health sector, can play an important role acting as convenor between multiple stakeholders, bringing together academia, private industry, communities impacted by air pollution and relevant government agencies *(12).*

See SPS *Transboundary conventions for air pollution and the role of the health sector*

Design policies to reduce emissions at source

Many nations that have already improved their air quality provide examples and lessons learned for those now beginning to manage their own air quality. Although the mixtures of air pollutants and sources, and feasibility of different control measures may differ between locations, where air quality has improved, it has overwhelmingly been by reducing emissions at their sources. Actions to remove pollution from outdoor air (e.g. smog towers or mist cannons) are not effective, and actions to reduce exposure such as indoor air filtration can be helpful in limiting health impacts but have generally been left to individual choices and affordability and not government interventions or mandates. As such, regulations on emission sources and the establishment and enforcement of air quality standards have been important steps towards cleaner air. Brazil, for example, has recently approved the National Air Quality Policy, offering a clear vision and timeline for air quality management. In Europe, adoption of the Ambient Air Quality Directive not only brings European Union member states closer to meeting WHO AQG but also includes rules for access to justice and compensation for people whose health was impacted by air pollution. In 2024, the United States Environment Protection Agency also revised its National Ambient Air Quality Standards for $PM_{2.5}$ to levels lower than WHO IT4. With increased knowledge of air pollution management options, and newly available clean energy and low emission technologies, nations should adopt stringent emissions controls with a vision of a future with cleaner air.

National and local governments have a range of actions they can take to reduce emissions and improve air quality and health. These include smokestack controls on power plants and large industries; tailpipe controls on motor vehicles, such as implemented through vehicle emission standards, and electric vehicles; promotion of public transport and non-motorized transport; electrification of homes and businesses; efficient waste management practices to reduce waste burning and improve waste collection and disposal; and promoting good practices in agriculture and land-use management. In many cases, stronger enforcement of air quality regulations is necessary (see sectoral SPS below). Many cities and nations have important contributions from multiple emission sectors, suggesting it is necessary to develop policies to address more than one sector. Since the sources of air pollutants vary in different locations, governments can prioritize actions based on the prevalence and type of air pollution sources, as well as resources, time and availability.

See SPS *Clean household energy – sectoral solutions for air pollution and health*
See SPS *Open waste burning – sectoral solutions for air pollution and health*
See SPS *Land use planning – sectoral solutions for air pollution and health*
See SPS *Transport – sectoral solutions for air pollution and health*
See SPS *Agriculture – sectoral solutions for air pollution and health*

Invest in building and expanding air quality monitoring and science

Our current understanding of air pollutant concentrations is limited in many regions due to a lack of air pollutant monitors. Often, regions with severe air pollution problems have few or no air pollutant monitors. In nations or cities without monitors, obtaining reference-grade instruments and developing monitoring infrastructure can be important steps forward, and international initiatives and financing may help toward this goal. While low-cost and passive sensors are not suitable to replace reference-grade monitors, they can be combined with reference monitors and satellite data to provide important information on the levels of pollutants and their spatial distributions as well as to enhance the quality of the air quality forecasts *(13)*. These sensors can also be used for measuring personal exposures and fostering citizen science and community engagement. Where pollution is severe and monitoring is present, it is important to also communicate air quality levels to the public, such as distributing information alongside air quality forecasts.

In addition to understanding the distribution of pollutants, it is important to understand the sources of air pollution. How much of $PM_{2.5}$ in a city, for example, comes from industry vs transportation? How much is from the city itself vs upwind regions? How effective would different emissions control actions be? Measurements can help address these questions by observing the composition of $PM_{2.5}$, for example. But models can also be instrumental in addressing these questions, allowing exploration of policy scenarios. Efforts to improve the accuracy of air pollution forecasts for a region need to be developed together with implementation of measurements and development of emissions inventories and source apportionment studies.

Plan to jointly address multiple air pollutants and climate change

It is important to recognize that much of $PM_{2.5}$ is not directly emitted, and therefore authorities should control emissions of the gas precursors of $PM_{2.5}$ (e.g. sulfur dioxide, nitrogen oxides, VOCs and ammonia), in addition to controlling direct emissions of $PM_{2.5}$. To control ozone, it is necessary to reduce emissions of nitrogen oxides, VOCs and carbon monoxide, which may come from a variety of sources. Modelling tools can help on the understanding of these dependencies among pollutants and quantify the improvement in concentrations from actions to control emissions of each pollutant.

In addition, the major sources of air pollution are also often sources of greenhouse gases. Consequently, many actions that move toward clean energy sources can reduce emissions of both air pollutants and greenhouse gases, addressing both local air pollution and global climate change simultaneously. Integrated assessment modelling can support decision-makers in identifying cost-effective measures to reduce both air pollution and greenhouse gas emissions, as well as quantify the costs and benefits of actions.

See SPS *Health and air pollution co-benefits of climate change mitigation*

Quantify the health, economic, and equity benefits of actions

Studies across multiple nations have found that the economic benefit of improved health through changes in air quality outweigh the costs of emissions controls, although this conclusion depends on both the type of emissions control and the value placed on health benefits. Evaluating the economic or monetized health benefits of reducing emissions, in comparison with costs, can bolster the case for taking action. In addition, it is important to consider how communities may be differentially impacted by air pollution or actions to reduce emissions. Actions to improve air quality will not necessarily relieve air pollution exposure inequality unless they are designed to achieve that goal.

See SPS *Phasing out coal-fired electric power generation – implications for public health*
See SPS *The economic costs of the health effects of air pollution*

Support research on source-specific burden of air pollution

Finally, while we know enough currently to take action, continued research on the health effects of specific sources of air pollution is important to better understand and reduce impacts. Continued research can help to identify more clearly the components of air pollutants and PM mixtures, as well as the sources of pollution, that are most important for impacting health, allowing air pollution controls to be more specific and effective. Further, research can help identify vulnerable populations and interventions that can help reduce ultimate health effects.

Methodology for content development

WHO defined the scope of the document and collaborated with its Advisory Groups (Scientific Advisory Group on Air Pollution and Health, SAG; and the Global Air Pollution and Health – Technical Advisory Group, GAPH-TAG) members, which cover a wide range of expertise, to prepare the initial draft based on an overview of exposure to health damaging air pollutants, supplemented by expert advice. This consisted of exploring the most recent evidence and selecting key documents as a reference for the development of the SPS, prioritizing systematic reviews and metanalysis.

The draft underwent peer review by specialists from various research institutes, universities, public organizations, WHO Collaborating Centres, and UN agencies. Additionally, an early version of the document was presented for peer-review at the Technical Advisory Group and Scientific Advisory Group on Air Pollution and Health meeting. And feedback was addressed by the main contributors. Finally, WHO staff and consultants from the WHO Air Quality, Energy and Health Unit reviewed the report to ensure alignment with the WHO requirements for the collections of WHO Air Quality, Energy and Health Science and Policy Summaries. This series synthesizes current knowledge and evidence on air quality, energy access, climate change links and health, primarily to inform intergovernmental discussions.

Acknowledgements

The WHO gratefully acknowledges the many individuals and organizations, including those from its Advisory Groups (SAG and GAPH-TAG), who contributed to the development of this document.

This document was written by Dayana Agudelo Castañeda (Universidad del Norte, Colombia); Tim Barzyk (United States Environmental Protection Agency); Claudio A Belis (European Commission, Joint Research Centre, Italy); Sagnik Dey (Indian Institute of Technology Delhi, India); Rima Habre (University

of Southern California, United States); Ali Al-Hemoud (Kuwait Institute for Scientific Research, Kuwait); Gerard Hoek (Utrecht University, the Kingdom of the Netherlands); Phil Hopke (University of Rochester, United States); Kenza Khomsi (General Directorate of Meteorology, Morocco); Aminata Mbow (Ministry of Environment and Ecological Transition, Senegal), Lidia Morawska (Queensland University of Technology, Australia); Christian Nagl (Environment Agency Austria); Zhi Ning (Hong Kong University of Science and Technology, China, Hong Kong SAR); Pallavi Pant (Health Effects Institute, United States); Richard Peltier (University of Massachusetts, United States); Ajay Pillarisetti (University of California Berkeley, United States); Xavier Querol (Spanish Research Council, IDAEA-CSIC, Spain); Jennifer Richmond-Bryant (North Carolina State University, United States); Marialuisa Volta (University of Brescia, Italy); J Jason West (University of North Carolina, United States); Steve HL Yim (Nanyang Technological University, Singapore).

Peer-reviewers included Kalpana Balakrishnan (Sri Ramachandra Medical College and Research Institute, India); Sara Basart and Paolo Laj (World Meteorological Organization); Praveen Kumar (Boston College, United States); Julian Marshall (University of Washington, United States); and Horacio Riojas (Instituto Nacional de Salud Pública, Mexico).

Additionally, an early version of this SPS was presented for peer-review at the Technical Advisory Group and Scientific Advisory Group on Air Pollution and Health meeting in Beijing, China, in October 2024.

The development of this document was led by Kerolyn Shairsingh, Sophie Gumy and Pierpaolo Mudu (WHO Department of Environment, Climate Change and Health) with inputs and review from Karla Cervantes and Cristina Vert (WHO Department of Environment, Climate Change and Health).

Declarations of interest

All external experts submitted a declaration of interest to WHO disclosing potential conflicts of interest that might affect, or might reasonably be perceived to affect, their objectivity and independence in relation to the subject matter of the report. WHO reviewed each of the declarations and concluded that none could give rise to a potential or reasonably perceived conflict of interest related to the subjects covered by the report.

References[2]

1. Sustainable Development Goal Indicator 3.9.1: mortality attributed to air pollution. Geneva: World Health Organization; 2024 (https://iris.who.int/handle/10665/379020). Licence: CC BY-NC-SA 3.0 IGO.
2. State of global air 2024. Health Effects Institute; 2024 (https://www.stateofglobalair.org/resources/report/state-global-air-report-2024).
3. WHO global air quality guidelines. Particulate matter (PM2.5 and PM10), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide. Geneva: World Health Organization; 2021 (https://apps.who.int/iris/handle/10665/345329). Licence: CC BY-NC-SA 3.0 IGO.
4. Air pollution and cancer. Lyon: International Agency for Research on Cancer; 2013 (https://www.iarc.who.int/wp-content/uploads/2018/07/AirPollutionandCancer161.pdf).
5. Striving for clean air: air pollution and public health in South Asia. Washington: World Bank; 2023 (https://www.worldbank.org/en/region/sar/publication/striving-for-clean-air).

[2] Accessed 14 February 2025.

6. Overview of methods to assess population exposure to ambient air pollution. Geneva: World Health Organization; 2023 (https://iris.who.int/handle/10665/373014). Licence: CC BY-NC-SA 3.0 IGO.
7. Global Health Observatory. Geneva: World Health Organization; 2024 (https://www.who.int/data/gho).
8. WHO ambient air quality database, 2024 update. Geneva: World Health Organization; 2024 (https://www.who.int/publications/m/item/who-ambient-air-quality-database-(update-jan-2024)).
9. Shairsingh K, Ruggeri G, Krzyzanowski M, Pierpaolo M, Malkawi M, Castillo J et al. WHO air quality database: relevance, history and future developments. Bull World Health Organ. 2023;101: 800-807 (http://dx.doi.org/10.2471/BLT.23.290188).
10. Brauer M, Guttikunda S, Nishad K, Dey S, Tripathi S, Weagle C et al. Examination of monitoring approaches for ambient air pollution: a case study for India. Atmospheric Environ. 2019;216 (https://doi.org/10.1016/j.atmosenv.2019.116940).
11. Romanello M, Walawender M, Hsu S-C, Moskeland A, Palmeiro-Silva Y, Scamman D et al. The 2024 report of the Lancet Countdown on health and climate change: facing record-breaking threats from delayed action. Indicator 3.2.1, Mortality from ambient air pollution by sector. Lancet. 2024;404:10465 (https://doi.org/10.1016/S0140-6736(24)01822-1).
12. Improving the capacity of countries to report on air quality in cities: users' guide to the repository of United Nations tools. Geneva: World Health Organization; 2023 (https://iris.who.int/handle/10665/373134). Licence: CC BY-NC-SA 3.0 IGO.
13. Integrating low-cost sensor systems and networks to enhance air quality applications. Geneva: World Meteorological Organization; 2024. (https://library.wmo.int/records/item/68924-integrating-low-cost-sensor-systems-and-networks-to-enhance-air-quality-applications)).

WHO Air Quality, Energy and Health Science and Policy Summaries

Health and air pollution co-benefits of climate change mitigation

Technical brief

Key messages

Many sources of greenhouse gas (GHG) emissions, particularly fossil fuel combustion, are also major sources of air pollutants, both indoors and outdoors. Thus, actions to address climate change through reducing GHG emissions can also reduce exposures to harmful air pollutants resulting from those same sources (e.g. particulate matter [PM], nitrogen oxides). The term co-benefits refers to the positive consequences for public health and the environment of reducing GHG emissions. Furthermore, actions focused on reducing short-lived climate pollutants (SLCPs) can also lead to improved air quality as ground-level ozone and black carbon are health-damaging air pollutants.

Key climate change mitigation actions that can reduce air pollution are taken in many sectors including energy production, transport, agriculture and industry. Some examples include decreasing energy use; transitioning energy sources from fossil fuels, such as coal, to cleaner and renewable energy sources; improving energy security; and transitioning households away from polluting fuels such as biomass to electricity or other clean-burning forms of energy. Other actions that benefit both climate change mitigation and air quality include promoting cleaner transportation, reducing waste burning and reducing the likelihood and severity of wildfires.

With reductions of GHG and SLCP emissions, the resulting climate benefits occur globally and over long-term scales, but the resulting air quality improvements will be observed locally and immediately where and when the emissions are reduced. Policies to reduce atmospheric carbon dioxide will have a global benefit; however, near-term health and air pollution benefits to people and their environments are considerable and should be considered in policy formulation. The estimated economic benefits, assessed by modelling, associated with reduced health impacts, can be comparable with or exceed the costs of implementing the climate change mitigation measures. In other words, the mitigation actions “pay for themselves” in the economic value they return from the lives they save and, beyond that, some actions also generate economic returns, making them feasible and beneficial to implement in national economies. Quantifying and communicating these health and economic co-benefits of climate change mitigation action can help build public support and provide stronger incentives for policy-makers to pursue ambitious climate policies. Promoting public health as a policy goal not only improves individual well-being but also enhances community resilience to climate change.

Key points:

- The health benefits of climate change mitigation measures may be more significant and tangible to local communities than the climate benefits of the measures themselves, as some health benefits accrue quickly and locally. Actions to mitigate climate change have global impacts, but the concomitant reductions in air pollution occur at regional and local levels and provide direct benefits to the communities taking the climate actions.

- Reductions in SLCPs can rapidly reduce climate change (even more quickly than reductions in carbon dioxide). Policies to reduce SLCPs can also reduce the disease burden from air pollution as some SLCPs are health-damaging air pollutants.
- The health sector should support climate change mitigation measures and call for accelerated action. Equally, it should advocate based on the evidence on co-benefits for the triple wins of such measures: for the economy, for public health and for environmental health.

Overview

According to the Intergovernmental Panel on Climate Change (IPCC), the main sectors that contribute to GHG emissions are energy generation (34%), industry (24%), agriculture, forestry and other land use (22%) and transport (15%) *(1)* (see Fig. 1). When comparing these sectors with the top five sectors responsible for death from air pollution (agriculture, industry, households, power generation, transport), the connection between the sources of local air pollution and the emissions that drive climate change is very clear *(2).*

See SPS[1] *Exposure to health-damaging air pollutants*

A recent Lancet summary showed that significant health co-benefits can be gained from climate change mitigation actions that reduce air pollution, with major benefits estimated for transitioning to clean cookstoves *(3).* Reducing emissions of GHGs or SLCPs, such as black carbon and ozone, reduces harmful air pollutants that cause respiratory and cardiovascular illnesses and deaths. However, not all actions to reduce GHGs will decrease the emissions of air pollutants harmful to health and result in co-benefits. Specific consideration of health benefits, both direct and indirect, is needed as climate actions are considered *(4).* With regard to indirect benefits, climate change mitigation actions across various sectors (e.g. transport, agriculture, household, energy, industry) can have health co-benefits by creating environments more conducive to physical activity, increasing access to healthier diets, and reducing gender inequality *(3,5,6).*

Numerous studies support that:

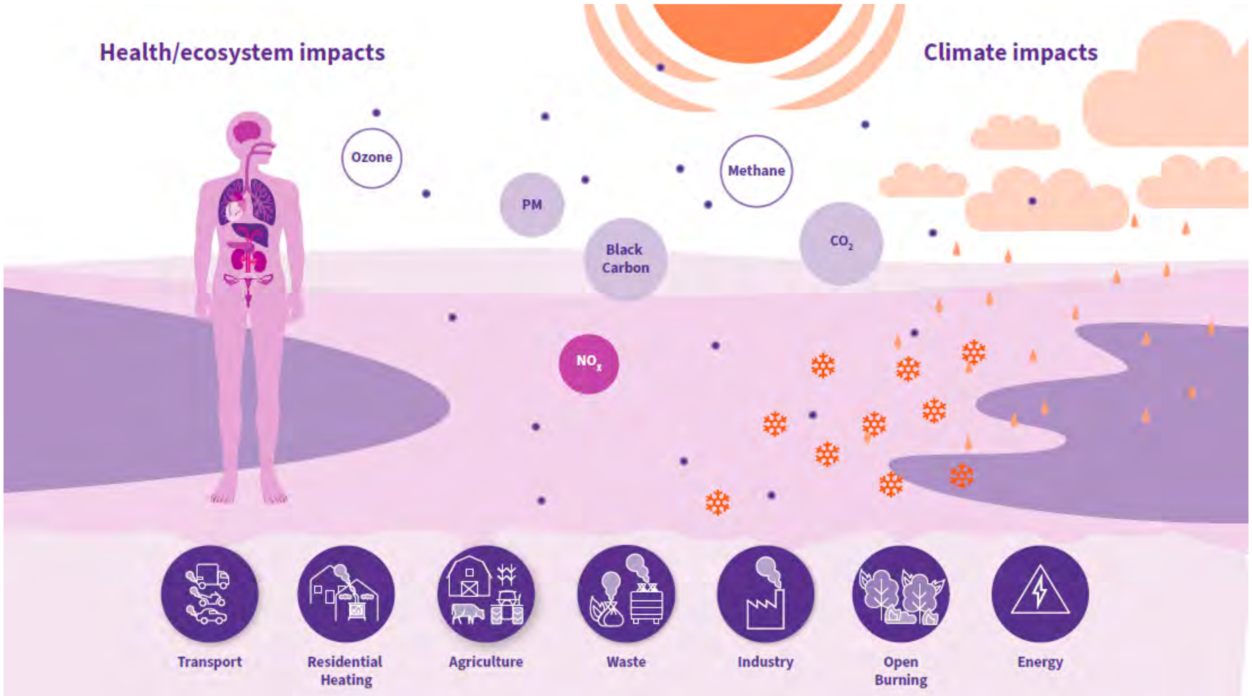
- actions to reduce GHG emissions and SLCPs can reduce air pollutant emissions; and
- air pollutant emission reductions benefit health *(2–6).*

The climate change mitigation measures that provide health co-benefits are described below and are divided into actions that reduce GHGs and those that reduce SLCPs. The decisions about which actions provide the strongest benefits for health and climate will be location dependent, and that prioritization is beyond the scope of this document.

The purpose of this SPS is to highlight mitigation actions that are mutually beneficial to climate change and air pollution through the lens of health.

[1] Science and Policy Summary

Fig. 1. Sectoral sources of GHG and air pollutant emissions and their health and the climate impacts



Notes: Sources of emissions shown to impact health (blue side) and climate (red side). Waste includes both landfill methane emissions and waste incineration and includes emissions from livestock. Open burning includes burning of agricultural land, waste and wildlands.

Source: Adapted from *Impacts of short-lived climate forcers on Arctic climate, air quality, and human health: summary for policy-makers.* Arctic Monitoring and Assessment Programme; 2021 *(7).*

Climate change mitigation measures that reduce GHGs can have health co-benefits

Fossil fuel use for diverse purposes accounts for approximately 70% of GHG emissions across all sectors *(6).* This major source of GHG emissions also emits health-damaging air pollutants such as fine particulate matter ($PM_{2.5}$) and nitrogen oxides amongst others *(3,8).* Several studies have shown that millions of premature deaths can be attributed to air pollution from fossil fuel burning *(2,9,10).*

Mitigation actions to reduce GHGs including reducing energy demand, increasing energy efficiency or replacing coal-fired electric power plants with cleaner energy sources, reduce harmful air pollutants from energy generation, benefiting the climate, air quality and health. A recent summary showed that the largest reductions of GHG emissions come from actions in the energy sector, and these actions had substantially higher health co-benefits for low- and middle-income countries (LMICs) when compared with high-income settings *(11).*

The potential total magnitude of the health co-benefits from improving air quality is estimated at 6.7 million premature deaths avoided worldwide annually, with people in Asia and Africa standing to benefit most from health improvements associated with ambitious climate actions, as these regions are densely populated with elevated levels of air pollution *(12).*

Climate change mitigation measures that reduce SLCPs have health co-benefits

In addition to actions that reduce GHG emissions over the long term, other climate change actions focus on SLCPs such as methane, ground-level ozone and black carbon. SLCPs are pollutants that affect the climate system and have relatively short lifespans – ranging from a few days to a few decades – substantially shorter than the lifetime of carbon dioxide, which is roughly a 100 years. Reducing emissions of some SLCPs is attractive for addressing climate change, since the climate will respond relatively quickly to a change in these emissions, as opposed to the longer timescale for carbon dioxide.

Furthermore, SLCPs can directly and indirectly adversely impact human health. Exposure to black carbon and ozone can harm the cardiovascular and respiratory systems, respectively, with injury inflicted on both and contributing to premature mortality *(13–15).* Reducing methane has been shown to produce substantial indirect health benefits via ozone reductions *(16,17).*

Black carbon is released from the open burning of domestic and agricultural waste, wildfires and household cooking, heating and lighting with polluting fuels such as coal and biomass. It is also emitted from vehicles that burn diesel and brick production *(18).* Climate change mitigation measures that reduce open burning will not only reduce SLCPs such as black carbon and ozone, but will also generate health co-benefits by preventing the release of $PM_{2.5}$ and toxic heavy metals. Further, actions to reduce personal vehicle use and expand public transport benefit climate change and air quality and also offer additional environmental and health co-benefits through increased physical activity.

Ozone is not emitted directly, but formed by photochemical reactions involving nitrogen oxides (nitric oxide and nitrogen dioxide), volatile organic compounds, methane and carbon monoxide. Ozone production increases with temperature so that reducing warming and extreme heat events will reduce exposure to the combination of higher levels of ozone and temperatures that are dangerous to health. Turning to the short-term timeframe, reducing ground-level ozone requires lowered emissions of ozone precursors, which are released primarily from combustion processes, but also from oil and gas extraction in some settings. However, with the complex and diverse chemical reactions involved in the formation of ozone, reduction of a particular precursor may not result in reduction of ozone generation. For example, despite current mitigation measures in Europe, modelling of future scenarios in Europe shows that emissions of precursors, particularly methane, from outside of the region could drive ozone related mortality upwards from 2020 to 2050 *(19).* Similarly, during the COVID-19 lockdowns, many cities experienced a reduction of nitrogen dioxide emissions, but ground-level ozone concentrations increased *(20).* Ozone reduction would bring co-benefits directly for health and indirectly improve agricultural yields in many parts of the world.

See SPS *Exposure to health-damaging air pollutants*

See SPS *Agriculture – sectoral solutions for air pollution and health*

Since 2020, more countries are including SLCPs in their nationally determined contributions (NDCs), 31 additional countries (47 countries in total), acknowledging the importance of reducing these pollutants along with GHG emissions. Furthermore, 20 of these NDCs include quantitative information on SLCP and/or air pollutant reductions, a substantial jump from two countries pre-2020 *(21).*

Tools to estimate health co-benefits

Models are the key tools that support decision-makers in designing climate change policies and in assessing air quality and health co-benefits. Integrated assessment modelling (IAM) combines information from many scientific disciplines to generate useful scenarios and estimates for decision-making, e.g. comparisons of various climate change mitigation measures that improve air quality and reduce GHGs emissions. Results of IAM can be applied in the design of policies for both climate and air quality and support the development of comprehensive strategies that simultaneously tackle climate change and air pollution *(22).*

Fig. 2 presents an example framework for modelling health and economic co-benefits from climate action. The framework includes a high-level overview of the methods used in each model, followed by the model inputs and outputs. Note that some models may only address part of the framework and multiple modelling tools are usually required.

Fig. 2. Modelling framework to undertake the health impact assessment of Colombia's NDC

Tool	LEAP	Integrated Benefits Calculator (IBC)	Carbon-H
Methods	• GHG, SLCP and air pollutant emission quantification • Scenario and projection analysis	• Gridding emissions • Emissions to PM exposure estimate	• Population weighted exposure to PM • Quantification of morbidity and morality outcomes • Economic valuation of health outcomes
Inputs	• Activity for energy demand, and supply sectors, industrial production, livestock and crop production, and waste generation • Emission Factors • Projections of key socioeconomic drivers	• GEOS-Chem adjoint coefficient sensitivities parameterised for Colombia • Rest of the world emission estimates from ECLIPSE dataset • LEAP emission outputs	• Exposure response functions • Baseline disease incidence rates • Population
Outputs	• National total historical (2010—2014) GHG, SLCP and air pollution emission estimates from energy, IPPU, AFOLU and waste • Projected (2015—2010) emissions of GHGs, SLCPs and air pollutants from all sectors	• Population-weight ed annual average PM concentrations for Colombia	• Avoided pre-mature mortality from PM • Economic benefits expressed in millions of US$, 2019 nominal prices

Source: *Health benefits of raising ambition in Colombia's nationally determined contribution (NDC)*. WHO technical report. WHO; 2023 *(23).*

The main WHO tool for estimating health co-benefits from climate change action is Climate Change Mitigation, Air Quality and Health (CLIMAQ-H), which assesses health benefits due to effects on air pollution of reducing carbon emissions *(24).* CLIMAQ-H is an updated replacement for the previous Excel-based WHO tool, Carbon Reduction Benefits on Health (CaRBonH). CLIMAQ-H can guide countries in maximizing the benefits of tackling climate change and air pollution together. It can be used to estimate the health and related economic gains achieved by reduced emissions from climate actions. While emissions reductions can be modelled for the WHO European Region, other countries require additional models to derive the emission reductions from implementing climate-driven policies. The pollutants considered in the CLIMAQ-H model include $PM_{2.5}$, sulfur dioxide, nitrogen oxides and ammonia. Additional tools that can evaluate the effectiveness of emission reduction strategies and their health co-benefits are summarized in the review by Abdala et al., 2024. Based on the findings of this systematic review, the authors emphasize the need for implementing cost–benefit analyses, standardizing methods and increasing research in regions with limited assessments *(25).*

Monetizing health co-benefits

There are many different economic valuation methods and metrics to quantify the health and other co-benefits of climate change mitigation actions (in monetary terms), such as using the monetary values of averted deaths and averted cases of injury and disease and applying the monetary value per tonne carbon dioxide emission averted or other GHGs averted. Where these economic valuations have been used to monetize health effects, the economic benefits from health loss averted due to air pollution averted alone have been shown to be comparable to or exceed the costs of mitigation actions, suggesting no costs or even return on investment *(26).* A global study monetizing lives saved using value of mortality risk reductions found that the global loss of lives averted from reduced air pollution alone were 1.4 to 2.45 times the costs of the GHG reduction actions to meet the temperature targets of the Paris Agreement of limiting climate change to 2°C and 1·5°C *(27).* A regional example in the United States using monetary value per tonne CO_2 averted showed that eliminating 1 tonne of carbon dioxide is estimated to return between US$ 8 and US$ 430 (in 2022 US$) in health benefits, with the value of air pollution health benefits outweighing the costs of GHG mitigation actions in most studies *(8).*

Many economic analyses and evaluations of climate change mitigation actions only assign a monetary value to reductions in mortality risks from the actions, often using the value per statistical life or value of a life year. Many studies, however, value (in monetary terms) neither reductions in morbidity risks (e.g. risk of an incident clinical case of ischaemic heart disease, stroke, or lung cancer or stroke), nor quality of life loss averted (e.g. restricted activity days averted), nor health care costs averted (e.g. number of hospitalizations averted), which will underestimate the full economic benefit from health loss averted due to climate change mitigation actions *(8).* Globally, removing fossil fuel subsidies and introducing a fossil fuel tax (at the rate of value added tax or general services tax) in 2019 is estimated to save 1.57 million lives in 2030 and have net economic benefits of US$ 8.7 trillion (in 2021 US$) or 7.2% of global GDP in the same year, capturing economic benefits from deaths averted, carbon dioxide emissions averted, impacts on economies, and government expenditure forgone (subsidies) and government revenue collected (tax) *(28).*

WHO has also produced global estimates of the health effects of selected climate mitigation actions that comprise health benefits from reductions in air pollution, as part of the WHO global investment case, 2025–2028 *(29).* These WHO estimates suggest that global scale up of cleaner household energy sources will save 0.1 million lives per year and that efficiently pricing fossil fuels by removing subsidies and adding taxes for these fuels will save an estimated 1.2 million lives per year, attributable to reductions in air pollution alone *(29).* Box 1 highlights how the health workforce can support climate change mitigation action.

Box 1. The role of the health sector in climate change mitigation

The health sector can play a pivotal role in climate change mitigation through several key actions:

1. **Advocacy for health-inclusive policies:** Health professionals and organizations are uniquely positioned to influence climate policies by highlighting the direct and immediate health benefits of mitigation efforts. By framing climate change within the context of public health and clinical care, they can gather broader support for action and drive policy changes that prioritize both environmental sustainability and human health and well-being.
2. **Implementation of low-carbon practices in health care:** The health care sector contributes approximately 5% of global GHG emissions. Health care facilities can address this contribution by adopting sustainable practices such as energy-efficient infrastructure, renewable energy sources and waste reduction strategies.
3. **Promotion of health co-benefits across sectors:** Mitigation efforts in sectors such as transport, energy and agriculture can yield substantial health benefits. For example, promoting active transport, such as walking and cycling, reduces GHG emissions and increases physical activity, leading to improved cardiovascular health. Additionally, transitioning to plant-based diets can lower GHG emissions and decrease the risk of chronic diseases.

By embracing these strategies, the health sector not only reduces its impact on the environment but also plays a crucial role in promoting public health in the face of climate change *(30).* Specific tools that can support these efforts include:

- Climate change and health vulnerability and adaptation assessment *(31).*
- Communicating on climate change and health: toolkit for health professionals *(32).*
- Safe, climate-resilient and environmentally sustainable health care facilities: an overview *(33).*

Country examples on the health co-benefits of climate action

Several case studies are described below for country-specific climate change mitigation measures that are of benefit in slowing climate change and in protecting public health. These examples include NDCs and local level actions that complement national-level programmes. To date, 65 countries now include specific mitigation measures within their NDCs, which can simultaneously reduce exposures to air pollutants as well as limiting GHGs *(21).*

Colombia

Colombia's NDC outlined its aim to reduce GHG emissions by 51% by 2030, and to reduce black carbon emissions and SLCPs by 40% by 2030, as compared with 2014 emission levels. Most notably, Colombia committed to ambitious black carbon and GHG reduction targets, which required technical analyses such as health impact assessments, and the engagement of multiple international and national institutions: the World Health Organization (WHO) and Pan American Health Organization, Colombia's Ministry of Health and Social Protection, and the Ministry of Environment and Sustainable Development and leadership from the Presidency *(23).*

Under a high ambition scenario, GHG emissions reductions would be accompanied by significant air quality improvements that could prevent more than 3800 premature deaths annually from ambient air pollution by 2030 and provide an annual economic benefit of US$ 1.9 billion (in 2017 US$), equivalent to 0.64% of Colombia's projected GDP in 2030.

Pakistan

Pakistan's NDC has set a conditional target of 20% reduction of projected emissions by 2030 to support the global efforts in combating climate change. To reach this target, Pakistan will increase power generation from renewable energy, electric vehicles sales, access to household electricity and upgrade fuel standards to EURO5 upgrade by 2030, while completely banning imported coal.

Under a high ambition scenario, the Government of Pakistan can significantly improve air quality and prevent more than 65 000 annual deaths from ambient air pollution in 2030. In addition, these health gains would be equivalent to 1.5% of Pakistan's projected GDP in 2030 *(34,35).*

European Union

The European Union, seeking to be a global leader in the fight against climate change, is moving ahead with ambitious policies to reduce GHG emissions. In particular, the ambition is for the European Union to become climate neutral by 2050 with the goal of cutting GHG emissions by at least 55% by 2030. The Fit for 55 package (FF55) is a set of proposals to revise and update EU legislation, to ensure that policies are in line.

Using Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS), the European Monitoring and Evaluation Programme IAM model estimates were made for how climate change mitigation policies will improve air quality and health co-benefits based on reductions of $PM_{2.5}$ (using both CaRBonH-HRAPIE (WHO Europe Health Risk functions for Air Pollution In Europe and FASST-GBD [Global Burden of Disease health risk functions]). The results suggest benefits of billions of euros from avoided morbidity and mortality by 2050 *(36).*

Nigeria

Nigeria's NDC included a pledge to reduce GHG emissions by 47% conditionally by 2030. Nigeria is also a voluntary member of the United Nations Environment's Climate and Clean Air Coalition aiming to reduce SLCPs across 10 high-impact sectors. In 2019, the government endorsed a national action plan featuring 22 specific actions aimed to sustainably reduce SLCPs and achieve health co-benefits. The 2021 update of the NDCs integrates many of those actions into sectoral mitigation measures, projecting reductions in emissions of black carbon (42%) and methane (28%), as well as significant reductions in other harmful pollutants like $PM_{2.5}$ and nitrogen oxides by 2030. In one of the actions, for example, the Nigerian Government plans to transition over 26 million households to liquefied petroleum gas for cooking, aiming to reduce the health and environmental impacts of traditional cooking methods using biofuels that contribute to air pollution and deforestation. This clean cooking initiative is projected to prevent 30 000 premature deaths by 2030 and promote cleaner energy solutions for vulnerable populations *(37).*

Quezon City, the Philippines

Quezon City, Philippines, exemplifies subnational climate action by aligning with the national NDC commitment to reduce GHG emissions by 75% from business-as-usual levels by 2030, while also prioritizing air quality. The city aims for interim GHG reductions of 34% by 2030 and 84% by 2050, which are estimated to prevent nearly 400 annual premature deaths in 2050, saving an estimated PHP$ 4 billion. Using the Pathways-AQ model, it was identified that enhancing on-road transport, transitioning to renewable energy, and improving energy efficiency in manufacturing can create synergies that improve air quality and mitigate climate change, significantly reducing emissions of GHGs, $PM_{2.5}$ and nitrogen oxides *(38).*

The findings of the case studies described above, like most estimates of air pollution co-benefits, are based on modelling, and few quantify the observed health benefits of enacted climate policies. Most evidence that exists comes from high-income countries and represents an underestimate of the global health gains. Studies that evaluate the actual health co-benefits attributable to reduced air pollution that arise from implemented policy packages and/or emission pledges should be prioritized in LMICs.

Way forward

Policy actions, aiming to reduce emissions from critical sources, can be planned to achieve air quality, health and climate emission goals simultaneously, acknowledging the co-benefits of the actions. For actions focused on addressing air pollutant emissions, the climate emission consequences of those actions can also be estimated. Similarly, the consequences of actions focused on reducing GHG emissions can be evaluated for co-benefits for air quality and health. In this framework, the following actions can support decision-making on climate change mitigation.

Integrate climate action planning and air quality management

Climate change mitigation measures can be highly synergistic in reducing air pollution and achieving the associated health benefits. Integrating programmes can facilitate meeting both climate and air pollution goals simultaneously. Climate change mitigation measures should be carefully designed to avoid potential negative impacts to air quality, health, livelihoods and some of the Sustainable Development Goals. A well-designed climate action plan can achieve multiple wins in health, environment, economy and other sustainable development aspects. Examples include frameworks that consider health in national adaption plans or air quality and climate change mitigation planning *(39,40).*

Incorporate health into NDCs to deliver the highest possible health benefits

The NDC renewal in 2025 presents an opportunity for countries to integrate health benefits into their countries' NDCs and gain other (e.g. welfare and economic) benefits. *(41).*

Conduct more accountability studies that monitor air quality impacts of climate change mitigation measures

Huge efficiencies can be gained from integrating air pollution and climate change monitoring systems. Demonstrating that climate change mitigation measures are actually improving air quality and health should increase momentum, and sharing experiences about successes and failures can support decision-making in the future.

Strengthen local capacity for developing and applying tools for technical policy analysis that integrate air quality and health into energy and climate action planning

Developing policies requires serious planning in selecting tools, strengthening local capacity for the sustained use of these tools, data collection procedures, the ability to iterate between modelling and input/review from stakeholders etc.

Engage the health sector in communications about health benefits of climate goals

The health sector should take greater leadership in designing, analysing and communicating health-promoting climate change action, providing insights about health benefits of climate change mitigation and adaptation measures, including also environmental health surveillance and warning systems, and facilitating cross-sectoral policy-maker engagement *(32).*

Allocate funding to climate actions with health benefits

The economic case for climate mitigation actions that reduce air pollution and thereby improve health and attributable economic outcomes is strong. Increasing the allocation of financing that targets reductions in SLCPs and actions with air pollution benefits is important. To motivate increased financial investment, the air pollution benefits will need to be estimated in models, monetized and reported. Tracking the monetized co-benefits is essential for their inclusion in finance allocations.

Consider the timelines for climate change mitigation measures and transitions

For example, policies directed at decarbonization often include reducing the use of fossil fuels for energy production. Although reducing fossil fuel burning is an important climate action that reduces air pollution, not fossil fuels have the same adverse health impacts. This energy transition requires considering a just and inclusive energy transition.

Analysing policy actions

Although these policy actions are a useful starting point in general, the specific policies for a given location will need further analysis, particularly to ensure equitable distribution across different geographies and demographics. For all policy decisions, there are trade-offs and unintended consequences that should be considered before new policies are implemented. Some interventions which reduce GHG emissions could have detrimental impacts on health. For example, when Europe developed policies to encourage diesel as a transportation fuel to increase fuel efficiency, air pollution and related health issues were made worse. Some actions may not deliver equitable outcomes, and climate policies (costs and benefits) may disproportionately impact different societal groups.

Accounting for co-benefits can help governments and other policy stakeholders identify GHG mitigation and air pollution source reduction policies that deliver the greatest possible societal benefits. The ideal approach to identifying high priority policies would maximize societal benefits through rigorous cost–benefit analysis of options. In situation where resources, funding and time are constrained, policy entrepreneurs can use the tools described above to identify policy options that deliver meaningful co-benefits and that are well matched to their political and economic realities and opportunities.

Illustrative climate change mitigation measures

Many climate change mitigation measures are common across the globe; however, some actions will vary by region based on key population and infrastructure characteristics. In some regions, level of development and socioeconomic factors, including income inequality, may pose barriers such as limited access to public transport and inadequate infrastructure in the face of insufficient resources to make needed improvements. The following list of illustrative climate change mitigation measures, separated by sector, can be applied selectively across different geographies and levels of government.

Sector	Illustrative climate change mitigation measures that impact air pollution
Energy	Increase renewable energy (using economic incentives) and transition away from fossil fuels (coal, oil and gas) in energy systems Focus on clean energy sources Reduce demand for energy Increase end use efficiency, reduce electric transmission and distribution losses Reduce variable renewable energy curtailment with appropriate storage capacity See SPS *Phasing out coal-fired electric power generation – implications for public health*
Waste	Reduce waste burning (central waste collection and construction/maintenance of sanitary landfills) Provide waste pickup and enforce a ban on open burning of household waste Compost organic waste and generate biogas Recycle and reuse valuable materials See SPS *Open waste burning – sectoral solutions for air pollution and health*
Agriculture, Forestry, Other Land Use (AFOLU)	Eliminate burning of crop residues Optimize agricultural fertilizer use, runoff and residue Manage land to reduce large, damaging wildfires and desertification Slow deforestation See SPS *Understanding the health impacts of sand and dust storms* See SPS *The impacts of wildfire smoke on health* See SPS *Land use planning – sectoral solutions for air pollution and health* See SPS *Agriculture – sectoral solutions for air pollution and health*
Household	Facilitate affordable, reliable access to clean cooking, lighting, and heating fuels and technologies Connect more households to electricity Use efficient air conditioning, refrigeration, low-energy use appliance Use combined insulation and ventilation to reduce heating and cooling Consider onsite and nearby production and use of renewables See SPS *Household air pollution and related health effects* See SPS *Clean Household energy – sectoral solutions for air pollution and health*
Transport	Reduce demand for private vehicles (through subsidies to public transport, encouraging teleworking options) Promote non-motorized and active transport (i.e. walking and cycling) Improve emission standards and implement vehicle inspections (eliminate high-emitting vehicles) Improve fuel efficiency Increase use of electric vehicles and rail electrification Use clean fuels (low sulfur) Require improved emission control devices (EU VI/6) and particulate filters Control emissions from international shipping Facilitate electric or non-motorized last-mile freight delivery Create pedestrianized zones See SPS *Transport – sectoral solutions for air pollution and health*

Industry	Use clean energy and improve efficiency of cement production Implement post-combustion controls including emission standards for nitrogen oxides Modernize industry (including improved emissions from coke ovens, brick kilns; converting boilers from fossil fuel combustion to electric) Circular material flows Link steel production with cleaner production methods See SPS *Industry – sectoral solutions for air pollution and health*

Acknowledgements

This SPS was coordinated by the World Health Organization (WHO) Air Quality, Energy and Health Unit.

WHO would like to thank the many individuals who contributed to the development of this document. This documents was prepared by: Thomas Clasen (Emory University, United States); Kenza Khomsi (General Directorate of Meteorology, Morocco); Gregor Kiesewetter (International Institute for Applied Systems Analysis, Austria); Frank Pega, Christian Schweizer, Kerolyn Shairsingh (WHO); Helen Petach; Christian Nagl (Environment Agency Austria); Jon Samet (University of Colorado Denver, United States); Marialuisa Volta (University of Brescia, Italy); J Jason West (University of North Carolina, United States).

WHO also recognizes the helpful contributions and comments provided by: Mark Budolfson (University of Texas, United States); Zoe Chafe (C40, United States); Andy Haines (London School of Hygiene & Tropical Medicine, United Kingdom of Great Britain and Northern Ireland); Kari Nadeau (Harvard University, United States); Pallavi Pant (Health Effects Institute, United States); Noah Scovronick (Emory University, United States); George Thurston (Grossman School of Medicine, New York University, United States).

An early version of this SPS was also presented and discussed at the Technical Advisory Group and Scientific Advisory Group on Air Pollution and Health meeting in Beijing, China, on 12 October 2024.

References[2]

1. Dhakal S, Minx J, Toth F, Abdel-Aziz A, Figueroa Meza A, Hubacek K et al. Emissions trends and drivers. In: IPCC, editor. Climate change 2022: mitigation of climate change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press; 2022 (doi:10.1017/9781009157926.004).
2. Romanello M, Walawender M, Hsu S, Moskeland A, Palmeiro-Silva Y, Scamman D, Ali Z et al. The 2024 report of the Lancet Countdown on health and climate change: facing record-breaking threats from delayed action. Lancet. 2024;404(10465):1847-96 (https://doi.org/10.1016/S0140-6736(24)01822-1).
3. Whitmee S, Green R, Belesova K, Hassan S, Cuevas S, Murage P et al. Pathways to a healthy net-zero future: report of the Lancet Pathfinder Commission. Lancet. 2024;403(10421):67-110 (https://doi.org/10.1016/S0140-6736(23)02466-2).

[2] Accessed 10 March 2025.

4. Sampedro J, Markandya A, Rodés-Bachs C, Van de Ven D. Short-term health co-benefits of existing climate policies: the need for more ambitious and integrated policy action. Lancet Planet Health. 2023:7(7):e540-e541 (https://doi.org/10.1016/S2542-5196(23)00126-2).
5. Volta M, Turrini E, Carnevale C, Valeri E, Gatta V, Polidori P et al. Co-benefits of changing diet. A modelling assessment at the regional scale integrating social acceptability, environmental and health impacts. Sci Total Environ. 2021;756:143708 (https://doi.org/10.1016/j.scitotenv.2020.143708).
6. Hamilton I, Kennard H, McGushin A, Höglund-Isaksson L, Kiesewetter G, Lott M et al. The public health implications of the Paris Agreement: a modelling study. Lancet Planet Health. 2021;5(2):e74-e83 (https://doi.org/10.1016/S2542-5196(20)30249-7).
7. Impacts of short-lived climate forcers on Arctic climate, air quality, and human health: summary for policy-makers. Arctic Monitoring and Assessment Programme. Tromsø: Arctic Monitoring and Assessment Programme; 2021 (https://www.amap.no/documents/doc/impacts-of-short-lived-climate-forcers-on-arctic-climate-air-quality-and-human-health.-summary-for-policy-makers/3512).
8. West J, Nolte C, Bell M, Fiore A, Georgopoulos P, Hess J et al. Chapter 14. Air quality. In: Crimmins AR, Avery CW, Easterling DR, Kunkel KE, Stewart BC, Maycock TK, editors. Fifth National Climate Assessment. Washington, DC: U.S. Global Change Research Program; 2023 (https://doi.org/10.7930/NCA5.2023.CH14).
9. Lelieveld J, Haines A, Burnett R, Tonne C, Klingmüller K, Münze T et al. Air pollution deaths attributable to fossil fuels: observational and modelling study. BMJ. 2023;383:e077784 (https://doi.org/10.1136/bmj-2023-077784).
10. McDuffie E, Martin R, Yin H, Brauer M. Global burden of disease from major air pollution sources (GBD MAPS): a global approach. Research report 210. Boston, MA: Health Effects Institute (https://www.healtheffects.org/publication/global-burden-disease-major-air-pollution-sources-gbd-maps-global-approach).
11. Reynolds T, Whitmee S, Green R, Anton B, Haines A. An umbrella review of health co-benefits from actions to reduce greenhouse gas emissions. Lancet Planet Health. 2024;8(Suppl1):S16 (https://doi.org/10.1016/S2542-5196(24)00081-0).
12. Sustainable Development Goal Indicator 3.9.1: mortality attributed to air pollution. Geneva: World Health Organization; 2024 (https://iris.who.int/handle/10665/379020).
13. Integrated Science Assessment (ISA) for particulate matter. (EPA/600/R-19/188). Washington DC: U.S. Environmental Protection Agency; 2019 (https://www.epa.gov/isa/integrated-science-assessment-isa-particulate-matter).
14. Health effects of black carbon. Bonn: WHO Regional Office for Europe; 2012 (https://iris.who.int/handle/10665/352615).
15. Annenberg S, Schwartz J, Shindell D, Amann M, Faluvegi G, Klimont Z et al. Global air quality and health co-benefits of mitigating near-term climate change through methane and black carbon emission controls. Environ Health Perspect. 2012;120(6):831-9 (https://doi.org/10.1289/ehp.1104301).

16. Huangfu P, Atkinson R. Long-term exposure to NO_2 and O_3 and all-cause and respiratory mortality: a systematic review and meta-analysis. Environ Int. 2020:144:105998 (https://doi.org/10.1016/j.envint.2020.105998).
17. West J, Fiore A, Horowitz L, Mauzerall D. Global health benefits of mitigating ozone pollution with methane emission controls. Proc Natl Acad Sci U S A. 2006;103(11):3988-93 (https://doi.org/10.1073/pnas.0600201103).
18. Li J, Zhang Y, Zheng S, Wang J, Dai R, Zhang W et al. Mitigating black carbon emissions: key drivers in residential usage and coke/brick production. Natl Sci Rev. 2024;11(10):nwae283 (https://doi.org/10.1093/nsr/nwae283).
19. Belis C, Van Dingenen R. Air quality and related health impact in the UNECE region: source attribution and scenario analysis. Atmos Chem Phys. 2023;23(14):8225-8240 (https://doi.org/10.5194/acp-23-8225-2023).
20. Amouei Torkmahalleh M, Akhmetvaliyeva Z, Omran A, Darvish Omran F, Kazemitabar M, Naseri M et al. Global air quality and COVID-19 pandemic: do we breathe cleaner air? Aerosol Air Qual Res. 2021;21(4):200567 (https://doi.org/10.4209/aaqr.200567).
21. Malley CS, Lefèvre EN, Kuylenstierna JCI, Haeussling S, Howard IC, Borgford-Parnell N. Integration of short-lived climate pollutant and air pollutant mitigation in nationally determined contributions. Clim Policy. 2022:23(10):1216-1228 (https://doi.org/10.1080/14693062.2022.2125928).
22. Integrated assessment models (IAMs) and energy-environment-economy (E3) models. United Nations Climate Change; 2025 (https://unfccc.int/topics/mitigation/workstreams/response-measures/modelling-tools-to-assess-the-impact-of-the-implementation-of-response-measures/integrated-assessment-models-iams-and-energy-environment-economy-e3-models).
23. Health benefits of raising ambition in Colombia's nationally determined contribution (NDC). WHO technical report. Geneva: World Health Organization; 2023 (https://iris.who.int/handle/10665/366714). Licence: CC BY-NC-SA 3.0 IGO.
24. Climate change mitigation, air quality and health (CLIMAQ-H). Geneva: World Health organization; 2025 (https://www.who.int/europe/tools-and-toolkits/climate-change-mitigation--air-quality-and-health-(climaq-h)).
25. Abdala SA, Khomsi K, Houdou A et al. Emission reduction strategies and health: a systematic review on the tools and methods to assess co-benefits BMJ Open. 2024;14(12):e083214 (https://bmjopen.bmj.com/content/14/12/e083214).
26. Karlsson M, Alfredsson E, Westling N. Climate policy co-benefits: a review. Clim Policy. 2020;20(3):292-316 (https://doi.org/10.1080/14693062.2020.1724070).
27. Markandya A, Sampedro J, Smith S, Van Dingenen R, Pizarro-Irizar C, Arto I et al. Health co-benefits from air pollution and mitigation costs of the Paris Agreement: a modelling study. Lancet Planet Health. 2018;2(3):e126-e133 (https://doi.org/10.1016/S2542-5196(18)30029-9).
28. Black S, Liu A, Parry I, Vernon-Lin N. IMF fossil fuel subsidies data: 2023 update. Working paper. Washington, DC: International Monetary Fund; 2023 (https://www.imf.org/en/Publications/WP/Issues/2023/08/22/IMF-Fossil-Fuel-Subsidies-Data-2023-Update-537281).

29. All for health, health for all: investment case 2025–2028. Geneva: World Health Organization; 2024 (https://iris.who.int/handle/10665/376856). Licence: CC BY-NC-SA 3.0 IGO.
30. Campbell-Lendrum D, Neville T, Schweizer C, Neira M. Climate change and health: three grand challenges. Nat Med. 2023;29:1631-1638 (https://doi.org/10.1038/s41591-023-02438-w).
31. Climate change and health vulnerability and adaptation assessment. Geneva: World Health Organization; 2021 (https://iris.who.int/handle/10665/345968). Licence: CC BY-NC-SA 3.0 IGO.
32. Communicating on climate change and health: toolkit for health professionals. Geneva: World Health Organization; 2024 (https://iris.who.int/handle/10665/376283). Licence: CC BY-NC-SA 3.0 IGO.
33. Safe, climate-resilient and environmentally sustainable health care facilities: an overview. Geneva: World Health Organization; 2024 (https://iris.who.int/handle/10665/379483). Licence: CC BY-NC-SA 3.0 IGO.
34. Health benefits of raising ambition in Pakistan's nationally determined contribution. WHO technical report. Geneva: World Health Organization; 2021 (https://iris.who.int/handle/10665/347767). Licence: CC BY-NC-SA 3.0 IGO.
35. Pakistan's intended nationally determined contribution. Government of Pakistan; 2022 (https://unfccc.int/sites/default/files/NDC/2022-06/Pak-INDC.pdf).
36. Pisoni E, Thunis P, De Meij A, Wilson J, Bessagnet B, Crippa M et al. Modelling the air quality benefits of EU climate mitigation policies using two different PM2. 5-related health impact methodologies. Environ Int. 2023:172:107760 (https://doi.org/10.1016/j.envint.2023.107760).
37. Nigeria's nationally determined contribution. Government of Nigeria; 2021 (https://unfccc.int/sites/default/files/NDC/2022-06/NDC_File%20Amended%20_11222.pdf).
38. Pun V, Coombes T. Air quality and health implications of the Quezon City enhanced local climate change action plan (2021-2050). C40; 2024 (https://c40.my.salesforce.com/sfc/p/#36000001Enhz/a/Vo0000004CCH/xLHpW5y6yZslBKkJ.53F7.GdviOBy7uSvJXl8uVjaxs
39. Clean air, healthy planet: a framework for integrating air quality management and climate action planning. C40; 2021 (https://www.c40knowledgehub.org/s/article/Clean-air-healthy-planet-A-framework-for-integrating-air-quality-management-and-climate-action-planning?language=en_US).
40. Quality criteria for health national adaptation plans. Geneva: World Health Organization; 2021 (https://iris.who.int/handle/10665/339454). Licence: CC BY-NC-SA 3.0 IGO. https://www.who.int/publications/i/item/9789240018983
41. Quality criteria for integrating health into nationally determined contributions (NDCs). Geneva: World Health Organization; 2024 (https://iris.who.int/handle/10665/380214). Licence: CC BY-NC-SA 3.0 IGO.

WHO Air Quality, Energy and Health Science and Policy Summaries

Understanding the health impacts of sand and dust storms

Technical brief

Key messages

Sand and dust storms (SDS) result from turbulent winds that raise large quantities of particles from the ground into the air in emission areas. Emission areas are typically semi-arid and arid with limited vegetation cover, as bare ground is most susceptible to sediment entrainment by the wind. During SDS, large amounts of particles of a broad range of sizes and chemical composition are uplifted from the soil. SDS have significant impacts on the environment, climate, weather, ecosystems and human health. SDS are a significant concern that warrants multisectoral action with public health authorities. SDS are recognized as a climatic impact-driver, meaning that they can be considered as a climate hazard in risk assessments.

SDS activity varies widely depending on geographical location, climate conditions and local environmental factors. Major sources include large deserts in North Africa, the Middle East and Asia. Local sources are disturbed landscapes caused by climate factors (such as drought or ice cover reduction), agricultural practices, overgrazing and deforestation.

Larger sand particles remain relatively close to the ground in the emission area, while finer dust particles can be lifted kilometres high into the atmosphere and potentially travel thousands of kilometres to receptor areas. Receptor areas can be located close to or far away from SDS emission areas. The air in receptor areas contains a mix of dust particles and non-dust particles, which are emitted from both natural and anthropogenic sources, from both receptor and emission areas and during transport of dust air mases. SDS can last over various time periods with particulate matter (PM) concentrations exceeding 10 000 $\mu g/m^3$ during SDS events close to the sources and exceeding 1000 $\mu g/m^3$ in receptor areas.

Studies on the health effects of SDS have associated short-term exposure with increased mortality, as well as a higher incidence of respiratory and cardiovascular diseases, among other health conditions. However, there is a significant gap in understanding the long-term effects, as no studies have focused on chronic exposure. Detailed measurements on the PM concentrations, chemical composition and size distribution are needed for advancing on the assessment of the health impacts of SDS. Standardized research protocols are needed to enhance the consistency and robustness of future studies, particularly in the source regions of the Saharan belt and the Middle East.

Overview

What are sand and dust storms?

In this document, SDS refer to weather and environment related phenomena associated with strong winds that lift large amounts of sand and dust particles from bare, dry soils into the atmosphere. SDS vary in duration and extent based on meteorological and environmental factors. They can last from a few hours to several days, with localized storms covering small areas (*haboobs*) and large-scale events spanning thousands of kilometres (e.g. the Harmattan in the Sahel).

Dust sources are primarily located in arid and semi-arid regions where loose, fine sediments are exposed to strong winds. Major sources include the Sahara Desert (largest global dust contributor), the Middle East, Central Asia (e.g. the Aral Sea basin) and the Gobi Desert in East Asia *(1).* These regions often feature dry lake beds, alluvial plains and deserts with minimal vegetation. Overall, global dust emissions from major sources (i.e. deserts) are approximately 22–29 billion kg per year, with North African source regions contributing roughly 50% *(2).* Human activities such as overgrazing, deforestation and unsustainable land use practices exacerbate dust emissions by disturbing the soil surface and increasing the susceptibility of these areas to wind erosion *(3).* Agricultural areas in Eastern Europe and drying landscapes within the southern United States are also sources of SDS *(4).*

During SDS, large amounts of particles of a broad range of sizes and chemical composition are uplifted from the soil. Sand and dust are categorized by the size of the particles involved in SDS:

- Sand refers to coarse particles (with diameters of ≥ 60 µm).
- Dust refers to finer particles (with diameters of < 60 µm), including silt and clay.

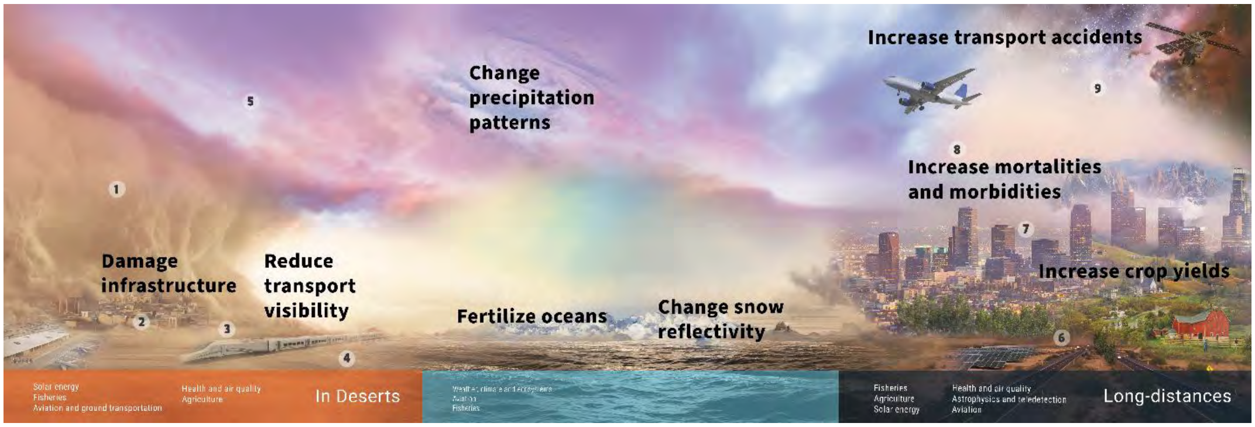
Sand and dust particles are a conglomerate of different components, including large proportions of minerals such as quartz, clay, carbonate, feldspar and iron oxide, and variable proportions of salts such as gypsum. The proportion of different minerals depends on the origin of the dust (i.e. soil source).

SDS can be considered a type of dust event. This is because sand, the larger coarse particle, is mainly found near sources in the emission areas and has a very limited lifetime in the atmosphere. On the other hand, dust, the smaller particle, can remain suspended in the air for extended periods in the emission area and travel long distances to receptor areas. Therefore, SDS contribute to the presence of aerosols (or PM) of different sizes in the air (particularly for particles between 2.5 µm and 10 µm). Dust transport occurs when strong winds lift fine particles into the atmosphere, allowing them to travel thousands of kilometres across continents and oceans. Once airborne, dust interacts with atmospheric processes (see Fig. 1), influencing weather and climate.

Dust particles in the atmosphere interact with sunlight by scattering and absorbing radiation, influencing the Earth's energy balance. Scattering occurs when dust reflects sunlight back into space, which can cool the Earth’s surface and reduce temperatures locally. Conversely, dust absorption traps heat in the atmosphere, contributing to warming at higher altitudes *(5).* The extent of scattering or absorption depends on the size and composition of the dust particles. For example, lighter coloured particles, mainly due to their composition, scatter more light; while darker particles, rich in iron or carbon, absorb more radiation. Moreover, dust affects cloud formation by serving as cloud condensation nuclei or ice nuclei, thereby influencing precipitation patterns and atmospheric dynamics *(6).* In atmospheric chemistry, dust particles act as surfaces for chemical reactions, altering the composition of trace gases and aerosols in the atmosphere.

Dust from deserts, such as the Sahara, also travels across oceans *(7).* Deposited dust fertilizes nutrient-poor regions like the Amazon rainforest and marine ecosystems. However, excessive dust deposition can disrupt local nutrient balances, harming sensitive environments. Dust can also damage vegetation by sandblasting leaves and altering soil chemistry *(8).*

Fig. 1. The impacts of sand and dust storms



Source: inDust website (https://cost-indust.eu/index.php/media-room/resources).

Changes in climatic variables have resulted in more extreme temperatures, prolonged droughts, increased heat waves and evaporation, and intensified aridity in semi-dry and dry regions (i.e. increased desertification). Additionally, anthropogenic changes such as agricultural and forestry practices, desiccation of lakes, land use and water management systems can influence wind erosion, all of which create favourable conditions for dust emissions and increase the likelihood and severity of SDS *(9).* Moreover, climate change is intensifying high-latitude dust activity as warming temperatures accelerate glacial retreat, exposing fine sediments to wind erosion. These newly uncovered dust sources, such as those in Iceland, Greenland, Alaska or Antarctica, contribute to global dust emissions. Climate change is projected to increase desertification, and the synergistic effect of both will reduce the productivity of dryland services (e.g. crops and livestock) and lower ecosystem health, including losses in biodiversity *(10).*

The most recent Intergovernmental Panel on Climate Change reports conclude that SDS are still ranked as a climate factor with low confidence, and there is no agreement about the direction of future changes in dust emissions *(11).* However, changes in land surface properties, like land cover, soil texture and composition, can be influenced by either humans (i.e. land and water management policies) or by climate change. The last few years have recorded exceptional SDS in terms of intensity and extent *(12).* In the Middle East, in the past two decades, the drying up of lakes within the Sistan Plain have increased the frequency of SDS by roughly 40% in the Islamic Republic of Iran *(13).* Overall, dust poses multiple challenges for environmental management, public health and climate adaptation efforts.

What role do SDS play in polluting the air?

One of the most significant environmental effects of SDS is the deterioration of air quality and the associated impacts on human health *(14).* During SDS, levels of PM with aerodynamic diameters of < 2.5 µm ($PM_{2.5}$) and 10 µm (PM_{10}) can rise significantly, although PM_{10} concentrations are particularly increased due to the suspension of larger particles. These concentrations can be orders of magnitude higher than the World Health Organization (WHO) air quality guidelines for PM_{10} (an average of 45 µg/m^3 over a 24-hour period). Close to the emission sources, PM_{10} peaks usually exceed 1000 µg/m^3 *(14–17)* but also, receptor areas can register high PM_{10} concentrations as a consequence of an SDS. An intense dust event in 2023 affected more than 4 million km^2 across Mongolia and China, and even reached the Republic of

Korea and Japan with PM_{10} concentrations exceeding 9000 µg/m^3 in China *(12).* High PM_{10} peaks have also been observed in Europe and the Caribbean during African dust intrusions *(18,19).*

PM composition associated with an SDS varies by source and region, influenced by the type of soil (as mentioned above) and the transport of the air mass. SDS not only directly emit pollutants (i.e. PM) into the atmosphere but can carry biological (e.g. microorganisms, pollen spores) and chemical (e.g. polycyclic aromatic hydrocarbons, metals) pollutants *(20–23).*

See SPS[1] *Climate change, air pollution, pollen and health*

Dust particles also provide surfaces for chemical reactions in the atmosphere, altering the composition of trace gases and aerosols. For instance, they can absorb pollutants like sulfur dioxide and nitrogen oxides, which increases the reactivity/toxicity of PM *(24).* Additionally, particularly close to the emission area, for example in the Middle East and North Africa, deposited dust on the ground may be resuspended by strong winds or road traffic, leading to SDS that also effect air quality levels *(25).*

Overall, the SDS contribution to total PM differs depending on the emission (i.e. soil components) and receptor areas (i.e. concentration, the mixture with other aerosols and atmospheric chemistry processes during dust transport). These factors are directly connected with the physical-chemical characteristics of the PM (i.e. size and chemical composition) and consequently affect the potential PM toxicity. Detailed measurements of the PM concentrations, chemical composition and size distribution are needed to advance the assessment of SDS health effects.

The different combinations of dust and non-dust PM mixtures within emission versus receptor areas calls for the separate evaluation of the health effects of dust storms in emission versus receptor areas, with the effects of dust PM and non-dust PM being assessed independently during dust episodes in receptor sites *(26–28).*

What are the health effects of SDS?

Over the past two decades, research on the health effects of SDS has grown considerably. A scoping review of 204 epidemiological studies summarized the evidence, identified research gaps, and classified exposure assessment methods and associated health effects *(14).* Most studies focused on Asian dust, followed by Saharan and Middle Eastern dust, with only a few studies on American and Australian deserts. These studies have linked SDS to a range of health effects, including both mortality and morbidity outcomes. Respiratory and cardiovascular diseases are most associated with SDS exposure, along with other health conditions such as allergic, eye and infectious diseases. The review also identified significant variability in SDS exposure measurement methods and methodological differences in study designs. The existing body of evidence primarily focuses on short-term health effects, with most studies using time-series and case-crossover designs to assess outcomes during or immediately after a dust storm. No studies are currently available on the long-term health effects of desert dust, such as those occurring months or years after exposure *(14).*

A comprehensive systematic review with meta-analysis of 71 time-series studies found a significant 1.21% increase in the risk of all-cause mortality on dust days compared with non-dust days *(29).* The risk associated with PM_{10} was slightly higher on dust days, while for $PM_{2.5}$ the risk was higher during non-dust days. The review also reported a 2.52% increase in the risk of cardiovascular mortality, with no significant

[1] Science and Policy Summary.

change in respiratory mortality. Additionally, cardiovascular hospital admissions increased by 0.94%, while respiratory admissions exhibited a more pronounced rise of 6.93% during dust days *(29).* Other literature reviews have also reported associations between short-term exposure to SDS and a variety of cardiovascular and respiratory outcomes, also lacking evidence of chronic exposure to SDS *(30–32).*

Moreover, toxicological research provides support for biological plausibility of epidemiological associations between this particulate air pollutant and SDS events including exacerbation of asthma, hospitalization for respiratory infections and seasonal allergic rhinitis *(33).* Other impacts of dust storms are an increase in road accidents, lack of access to health centres as well as the closure of communication routes.

While there is strong evidence of exposure to SDS and a variety of morbidity and mortality outcomes, the variability in the epidemiological approaches makes it difficult to fully assess the level of potential harm. However, developing a standardized research protocol is necessary to harmonize study designs, SDS exposure assessments and health outcome measurements, to ensure more robust and comparable findings *(28).* In addition, the vast majority of the epidemiological studies focused on acute effects by evaluating whether daily peaks in desert dust were associated with concurrent peaks in mortality and morbidity. The current research underscores a significant gap in understanding the long-term health effects of SDS *(34).* Finally, there is a specific need for more research on the effects of SDS in the source regions of the Saharan belt and the Middle East. Improved SDS exposure measurement technologies and increased public awareness efforts could help mitigate the adverse health effects.

From an economic standpoint, the World Bank estimated global welfare losses from dust storms at approximately US$ 3.6 trillion in 2013. At the regional level, East Asia and the Pacific suffered the greatest welfare losses of US$ 1380 billion, with Europe and Central Asia having the second highest estimated losses of US$ 1170 billion *(35, 36).* In the Middle East and North Africa, SDS cost about US$ 140 billion annually which represents over 2.5% of gross domestic product *(35, 36).*

See SPS *The economic costs of the health effects of air pollution*

Box 1. United Nations Coalition to Combat Sand and Dust Storms

The Coalition consists of 19 Members both United Nations (UN) and non-UN agencies, with the Food and Agriculture Organization, UN Convention to Combat Desertification, UN Economic and Social Commission for Asia and the Pacific, UN Economic and Social Commission for Western Asia, UN Development Programme, UN Environment Programme, WHO and the World Meteorological Organization leading specific working groups related to adaptation and mitigation, forecasting and early warning, health and safety, policy and governance as well as mediation and regional collaboration.

The mandate of the Coalition is to ensure coordination and collaboration of the UN-system response to SDS on activities, knowledge exchange, advocacy and funding initiatives as well as capacity-building and preparedness enhancement.

Way forward

Urgent, coordinated actions based on three main pillars are needed at multiple levels to reduce SDS impacts on health, the environment and the economy.

Collect, share and analyse exposure and health data

- Invest in and maintain reliable ground-level monitoring networks (with local and regional representation) for ambient PM (including chemical composition and size distribution, i.e. PM_1, $PM_{2.5}$, PM_{10}) to ensure accurate data collection and assessment.
- Invest in measurement and models for source apportionment to identify dust and non-dust components.
- Enhance health data collection, data sharing and analysis to identify and close existing knowledge gaps and evaluate the effectiveness of control measures to identify those that are most cost effective.
- Conduct further toxicological studies to further our understanding of the effects of SDS on health.
- Ensure standardization of protocols of SDS-related epidemiological studies.
- Design new epidemiological studies on the long-term health effects of SDS.
- Advance the development of impact-based assessment (i.e. long-term effects) and forecasting (i.e. short-term effects) products to feed into early warning systems.

Institutional strengthening

- Ensure multisectoral coordination with ministries of health, meteorology, environment and other sectors that will leverage early warning systems for a timely public health response, facilitate adaptive action withing communities and reduce anthropogenic sources of air pollution during SDS events.
- Develop regional policies to support actions to reduce harm to public health when air pollution alerts are issued at a national level.
- Enhance the skills and knowledge of government agencies to design and implement programmes that reduce or retard desertification and strengthen resilience and response capabilities.
- Ensure a robust civil registration and vital statistics system as well as health surveillance linked with environmental health risks including air pollution and climate change.
- Launch awareness campaigns tailored to specific sectors to educate officials and the public on the risks of SDS and effective strategies to reduce exposure and mitigate SDS occurrences.
- Develop and/or strengthen training programmes for health care workers to respond to SDS events, air pollution episodes and climate change impacts.

Implement science-based interventions

- Promote sustainable agricultural, water and landscape management practices.
- Reduce local anthropogenic emissions of pollutants during SDS episodes.
- Develop and enforce building codes and urban planning guidelines that consider the impacts of SDS, ensuring that infrastructure can withstand dust storms without significant damage.
- Integrate SDS mitigation strategies with broader climate change adaptation plans, recognizing the interconnectedness of these environmental challenges.
- Develop regional cooperations for long-term SDS mitigation, recognizing their transboundary nature.

Methodology for content development

WHO defined the scope of the document and collaborated with its Advisory Groups (Scientific Advisory Group on Air Pollution and Health, SAG; and the Global Air Pollution and Health – Technical Advisory Group, GAPH-TAG) members, which cover a wide range of expertise, to prepare the initial draft based on an overview of the health impacts of SDS, supplemented by expert advice. This consisted of exploring the most recent evidence and selecting key documents as a reference for the development of the SPS, prioritizing systematic reviews and metanalysis.

The draft underwent peer review by specialists from various research institutes and universities. Additionally, an early version of the document was presented for peer-review at the Technical Advisory Group and Scientific Advisory Group on Air Pollution and Health meeting. And feedback was addressed by the main contributors. Finally, WHO staff and consultants from the WHO Air Quality, Energy and Health Unit reviewed the report to ensure alignment with the WHO requirements for the collections of WHO Air Quality, Energy and Health Science and Policy Summaries. This series synthesizes current knowledge and evidence on air quality, energy access, climate change links and health, primarily to inform intergovernmental discussions.

Acknowledgements

The WHO gratefully acknowledges the many individuals and organizations, including those from its Advisory Groups (SAG and GAPH-TAG), who contributed to the development of this document.

This document was written by Ali Al-Hemoud (Kuwait Institute for Scientific Research, Kuwait); Bertrand Bessagnet and Julia C Fussell (Imperial College London, United Kingdom of Great Britain and Northern Ireland); Masahiro Hashziume and Philip K Hopke (University of Rochester, United States); Kenza Khomsi (General Directorate of Meteorology, Morocco); Xavier Querol (Spanish Research Council, IDAEA-CSIC, Spain); Najat A Saliba (American University of Beirut, Lebanon), Massimo Stafoggia (Lazio Region Health Service, Italy); Oriol Teixidó and Aurelio Tobias (Spanish Council for Scientific Research, Spain), Sara Basart (World Meteorological Organization), and Kerolyn Shairsingh (WHO Department of Environment, Climate Change and Health).

Peer-reviewers included Rami Alfarra (Qatar Environment and Energy Research Institute, Qatar); Mostafa Hadei (Kermanshah University of Medical Sciences, Islamic Republic of Iran); and Abbas Shahsavani (Shahid Beheshti University of Medical Sciences, Islamic Republic of Iran).

Additionally, an early version of this SPS was presented for peer-review at the Technical Advisory Group and Scientific Advisory Group on Air Pollution and Health meeting in Beijing, China, in October 2024.

The development of this document was led by Sophie Gumy and Kerolyn Shairsingh (WHO Department of Environment, Climate Change and Health) with inputs and review from Pierpaolo Mudu, Karla Cervantes, and Cristina Vert (WHO Department of Environment, Climate Change and Health).

Declarations of interest

All external experts submitted a declaration of interest to WHO disclosing potential conflicts of interest that might affect, or might reasonably be perceived to affect, their objectivity and independence in relation to the subject matter of the report. WHO reviewed each of the declarations and concluded that none could give rise to a potential or reasonably perceived conflict of interest related to the subjects covered by the report.

References[2]

1. Ginoux P, Prospero JM, Gill TE, Hsu NC, Zhao M. Global-scale attribution of anthropogenic and natural dust sources and their emission rates based on MODIS Deep Blue aerosol products. Rev Geophys. 2012;50:3 (https://doi.org/10.1029/2012RG000388).
2. Kok JF, Adebiyi AA, Albani S, Balkanski Y, Checa-Garcia R, Chin M et al. Contribution of the world's main dust source regions to the global cycle of desert dust. Atmos Chem Phys. 2021;21(10):8169-8193 (https://doi.org/10.5194/acp-21-8169-2021).
3. Global sand and dust storm source base map. Bonn: United Nations Convention to Combat Desertification; 2024 (https://www.unccd.int/resources/brief/global-sand-and-dust-storm-source-base-map).
4. Bessagnet B, Menut L, Colette A, Couvidat F, Dan M, Mailler S, Létinois L et al. An evaluation of the CHIMERE Chemistry Transport Model to simulate dust outbreaks across the Northern Hemisphere in March 2014. Atmos. 2017;8(12):251 (https://doi.org/10.3390/atmos8120251).
5. Li Y, Kang S, Zhang X, Li C, Chen J, Qin X et al. Dust dominates the summer melting of glacier ablation zones on the northeastern Tibetan Plateau. Sci Total Environ. 2023;856:159214 (https://doi.org/10.1016/j.scitotenv.2022.159214).
6. Shi Y, Liu X. Dust radiative effects on climate by glaciating mixed-phase clouds. Geophys Res Lett. 2019;46:6128-6137 (https://doi.org/10.1029/2019GL082504).
7. Prospero JM, Collard F-X, Molinié J, Jeannot A. Characterizing the annual cycle of African dust transport to the Caribbean Basin and South America and its impact on the environment and air quality. Global Biogeochem Cycles. 2014;29:757-773 (https://doi.org/10.1002/2013GB004802).
8. UNEP-WMO-UNCCD Global assessment of sand and dust storms. Nairobi: United Nations Environment Programme; 2016 (https://www.unccd.int/resources/publications/global-assessment-sand-and-dust-storms).
9. Sand and dust storms compendium: information and guidance on assessing and addressing the risks. Bonn: United Nations Convention to Combat Desertification; 2022 (https://www.unccd.int/resources/publications/sand-and-dust-storms-compendium-information-and-guidance-assessing-and).
10. Mirzabaev A, Wu J. Desertification. In: Shukla PR, Skea J, Calvo Buendia E, Masson-Delmotte V, Pörtner HO, Roberts DC et al., editors. Climate change and land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. Intergovernmental Panel on Climate Change; 2019 (https://www.ipcc.ch/site/assets/uploads/2019/11/SRCCL-Full-Report-Compiled-191128.pdf).
11. IPCC Sixth assessment report. Working Group 1: the physical science basis. Intergovernmental Panel on Climate Change; 2021 (https://www.ipcc.ch/report/ar6/wg1/).

[2] Accessed 15 February 2025

12. WMO Airborne Dust Bulletin, 8. Geneva: World Meteorological Organization; 2024 (https://library.wmo.int/idurl/4/68953).
13. Rami A, Hamidi M, Navayi Neya B. Atmospheric analysis of dust storms in Sistan region. J Atmos Sol-Ter Phys. 2022;227:105800 (https://doi.org/10.1016/j.jastp.2021.105800).
14. Lwin KS, Tobias A, Chua PL, Yuan L, Thawonmas R, Ith S et al. Effects of desert dust and sandstorms on human health: a scoping review. Geohealth. 2023;7(3): e2022GH000728 (https://doi.org/10.1029/2022GH000728).
15. Middleton N. Desert dust hazards: a global review. Aeolian Res. 2017;24:53-63 (https://doi.org/10.1016/j.aeolia.2016.12.001).
16. Sarkar S, Chauhan A, Kumar R, Singh RP. Impact of deadly dust storms (May 2018) on air quality, meteorological, and atmospheric parameters over the northern parts of India. Geohealth. 2019;3(3):67-80 (https://doi.org/10.1029/2018GH000170).
17. Shahsavani A, Naddafi K, Jafarzade Haghighifard N, Mesdaghinia A, Yunesian M, Nabizadeh R et al. The evaluation of PM_{10}, $PM_{2.5}$, and PM_1 concentrations during the Middle Eastern Dust (MED) events in Ahvaz, Iran, from April through September 2010. J Arid Environ. 2012;77:72-83 (https://doi.org/10.1016/j.jaridenv.2011.09.007).
18. Cuevas-Agulló E, Barriopedro D, García RD, Alonso-Pérez S, González-Alemán JJ, Werner E et al. Sharp increase in Saharan dust intrusions over the western Euro-Mediterranean in February–March 2020–2022 and associated atmospheric circulation, Atmos Chem Phys. 2024;24(7):4083-4104 (https://doi.org/10.5194/acp-24-4083-2024).
19. Yu H, Tan Q, Zhou L, Zhou Y, Bian H, Chin M et al. Observation and modeling of the historic “Godzilla” African dust intrusion into the Caribbean Basin and the southern US in June 2020. Atmos Chem Phys. 2021;21(16):12359-12383 (https://doi.org/10.5194/acp-21-12359-2021).
20. Griffin DW. Atmospheric movement of microorganisms in clouds of desert dust and implications for human health. Clin Microbiol Rev. 2007;20(3):459-477 (https://doi.org/10.1128/cmr.00039-06).
21. D’Amato G, Holgate ST, Pawanka R, Ledford DK, Cecchi L, Al-Ahmad M et al. Meteorological conditions, climate change, new emerging factors, and asthma and related allergic disorders. A statement of the World Allergy Organization. World Allergy Organ J. 2015;8(1):25 (https://doi.org/10.1186/s40413-015-0073-0).
22. Rodríguez S, Alastuey A, Alonso-Pérez S, Querol X, Cuevas E, Abreu-Afonso J et al. Transport of desert dust mixed with North African industrial pollutants in the subtropical Saharan Air Layer. Atmos Chem Phys. 2011;11(13):6663-6685 (https://doi.org/10.5194/acp-11-6663-2011).
23. Tong D, Gill T, Sprigg W, Van Pelt R, Baklanov A, Barker B et al. Health and safety effects of airborne soil dust in the Americas and beyond. Rev Geophys. 2023;61(2): e2021RG000763 (https://doi.org/10.1029/2021RG000763).
24. Ho KF, Wu K-C, Niu X et al. Contributions of local pollution emissions to particle bioreactivity in downwind cities in China during Asian dust periods. Environ Pollut. 2019;245:675-683 (https://doi.org/10.1016/j.envpol.2018.11.035).
25. Querol X, Tobías A, Pérez N, Karanasiou A, Amato F, Stafoggia M et al. Monitoring the impact of desert dust outbreaks for air quality for health studies. Environ Int. 2019;130:104867 (https://doi.org/10.1016/j.envint.2019.05.061).

26. Miri A, Middleton N. Long-term impacts of dust storms on transport systems in south-eastern Iran. Nat Hazards. 2022;114(1):291-312.
27. Shahsavani A, Tobías A, Querol X, Stafoggia M, Abdolshahnejad M, Mayvaneh F et al. Short-term effects of particulate matter during desert and non-desert dust days on mortality in Iran. Environ Int. 2020;134:105299 (https://doi.org/10.1016/j.envint.2019.105299).
28. Tobías A, Stafoggia M. Modeling desert dust exposures in epidemiologic short-term health effects studies. Epidemiol. 2020;31(6):788-795 (https://doi.org/10.1097/EDE.0000000000001255).
29. Tobias A, Querol X, Roqué M, Suu Lwin K, Yuan L, Ith S et al. Short-term exposure to desert dust and sandstorms and all-cause and cause-specific mortality and morbidity: a systematic review and meta-analysis. Environ Int. 2025;196:109277 (https://doi.org/10.1016/j.envint.2025.109277).
30. Domínguez-Rodríguez A, Baez-Ferrer N, Abreu-Gonzalez P, Rodríguez S, Díaz R, Avanzas P et al. Impact of desert dust events on the cardiovascular disease: a systematic review and meta-analysis. J Clin Med. 2021;10(4):727 (https://doi.org/10.3390/jcm10040727).
31. Hashizume M, Kim Y, Ng CFS, Chung Y, Madaniyazi L, Bell ML et al. Health effects of Asian dust: a systematic review and meta-analysis. Environ Health Perspect. 2020;128:PMC7319773 (https://doi.org/10.1289/EHP5312).
32. Pouri N, Karimi B, Kolivand A, Mirhoseini SH. Ambient dust pollution with all-cause, cardiovascular and respiratory mortality: a systematic review and meta-analysis. Sci Total Environ. 2024;912:168945 (https://doi.org/10.1016/j.scitotenv.2023.168945).
33. Fussell JC, Kelly FJ. Mechanisms underlying the health effects of desert sand dust. Environ Int. 2021;157:106790 (https://doi.org/10.1016/j.envint.2021.106790).
34. WHO global air quality guidelines: particulate matter (PM2.5 and PM10), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide. Geneva: World Health Organization; 2021 (https://iris.who.int/handle/10665/345329). Licence: CC BY-NC-SA 3.0 IGO.
35. World Bank and Institute for Health Metrics and Evaluation. The Cost of Air Pollution Strengthening the Economic Case for Action. Washington, DC: World Bank; 2016. (https://documents1.worldbank.org/curated/en/781521473177013155/pdf/108141-REVISED-Cost-of-PollutionWebCORRECTEDfile.pdf). License: CC BY 3.0 IGO.
36. Sand and dust storms in the Middle East and North Africa (MENA) Region: sources, costs, and solutions. Washington, DC: The World Bank; 2019 (https://documents1.worldbank.org/curated/en/483941576489819272/pdf/SAND-AND-DUST-STORMS-IN-THE-MIDDLE-EAST-AND-NORTH-AFRICA-MENA-REGION-SOURCES-COSTS-AND-SOLUTIONS.pdf).

WHO Air Quality, Energy and Health Science and Policy Summaries

The synergies of heat stress and air pollution and its health impacts

Technical brief

Key message

Projections indicate that climate change will result in more frequent and intense extreme weather events in the coming decades. Among these, an increase in frequency, duration, intensity and magnitude of heatwaves and prolonged excess heat conditions are already being observed globally.

Heat impacts health directly and acutely. Increases in mortality associated with high temperatures, particularly heatwaves, have been documented around the world. Vulnerable population groups include infants, young children, pregnant women, persons with chronic conditions and older people. Additionally, outdoor and manual workers and civil protection personnel are exposed to excessive heat, making them vulnerable to exertional heat stress.

Heat increases the levels of some air pollutants, such as ozone. In addition, recent studies indicate that high levels of fine particulate matter and ozone augment the health impacts of heat. The joint effects of heat stress and air pollution exposures have been documented for all-cause mortality as well as mortality and morbidity due to cardiovascular and respiratory diseases, and for exacerbating noncommunicable and infectious diseases.

Priority actions for short-term health benefits include adaptation measures and protection of the vulnerable; and for long-term health benefits, include reducing ambient air pollution and mitigating the occurrence of extreme heat.

Key definitions

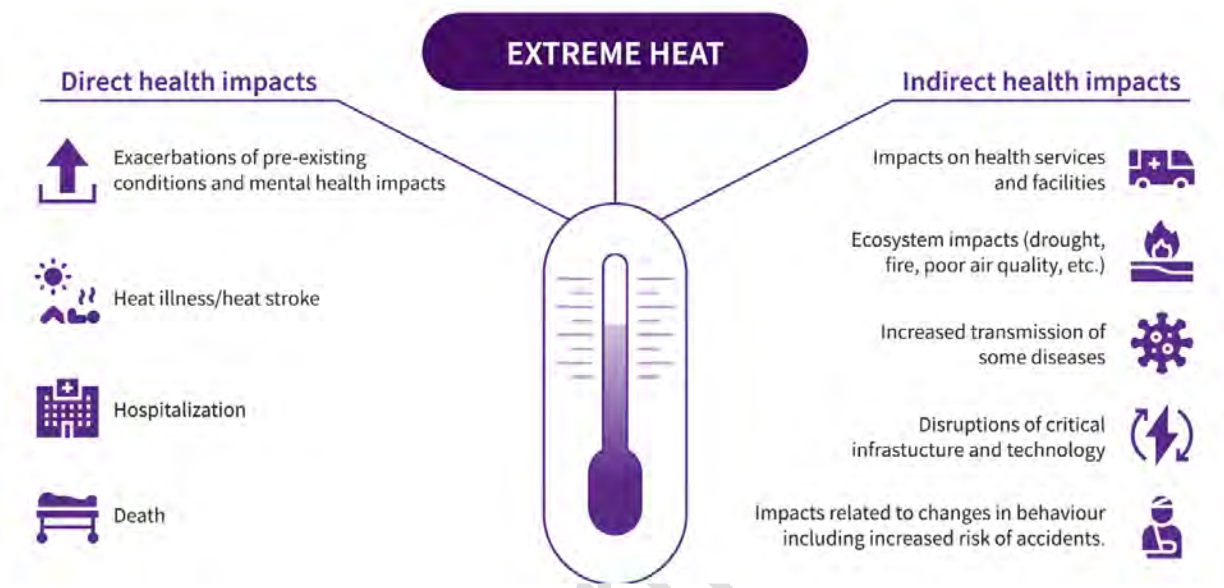
- **Heatwave:** A period where local excess heat accumulates over a sequence of unusually hot days and nights *(1)*.
- **Heat stress:** Occurs when the body cannot effectively eliminate excess heat, leading to an increase in core body temperature and heart rate. It is the leading cause of weather-related deaths and can exacerbate underlying illnesses including cardiovascular disease, diabetes, mental health, asthma, and can increase the risk of accidents and transmission of some infectious diseases *(1)*.

Overview

Current status

Heat impacts health directly and acutely as well as indirectly: Increases in mortality associated with high temperatures and heatwaves have been observed consistently and globally *(2–4)*. Heat increases the risk of heat exhaustion and heatstroke, affecting the heart and kidneys and worsening health risks from pre-existing conditions, especially cardiovascular, mental, respiratory and metabolic-related conditions. As examples, heat can trigger cardiovascular and respiratory deaths. Heat induces kidney injury and counteract the benefit of treatment in the case of hypertension. Heat is also associated with indirect health effects such as impacts on health services and facilities and an increased risk of accidents (Fig. 1).

Fig. 1. Health impacts of heat



Source: WHO; 2024.

The health effects of heat are especially severe among vulnerable population groups, including infants, young children, pregnant women, persons living with diseases and disabilities, and older people *(4, 5)*.

Outdoor and manual workers and civil protection employees are exposed to excess heat because of their work and are also susceptible to exertional heat stress. Additionally, the urban and rural poor face higher heat exposure due to factors such as low-quality housing and lack of cooling. Gender can also affect heat exposure, for example, where women are primarily responsible for cooking indoors during hot weather *(1)*.

The health impacts of heat are expected to increase due to ageing societies and growing urbanization; increased frequency, intensity and duration of heat events; and increasing social inequalities.

Air pollution is a major risk factor for noncommunicable diseases: Air pollution is a complex mixture of gases and particulate matter with clearly demonstrated health impacts, especially regarding fine particles (particles with aerodynamic diameter of 2.5 µm or smaller [$PM_{2.5}$]). Air pollution affects health acutely during hours and days of harmful levels and chronically over years and decades *(6)*. The acute and long-term health impacts are not limited to the lungs, where air pollutants first interact with the human body, but extend to almost all organs, including the heart, brain and reproductive system *(6)*.

See *SPS*[1] *Health effects of air pollution - evidence and implications*

[1] Science and Policy Summary

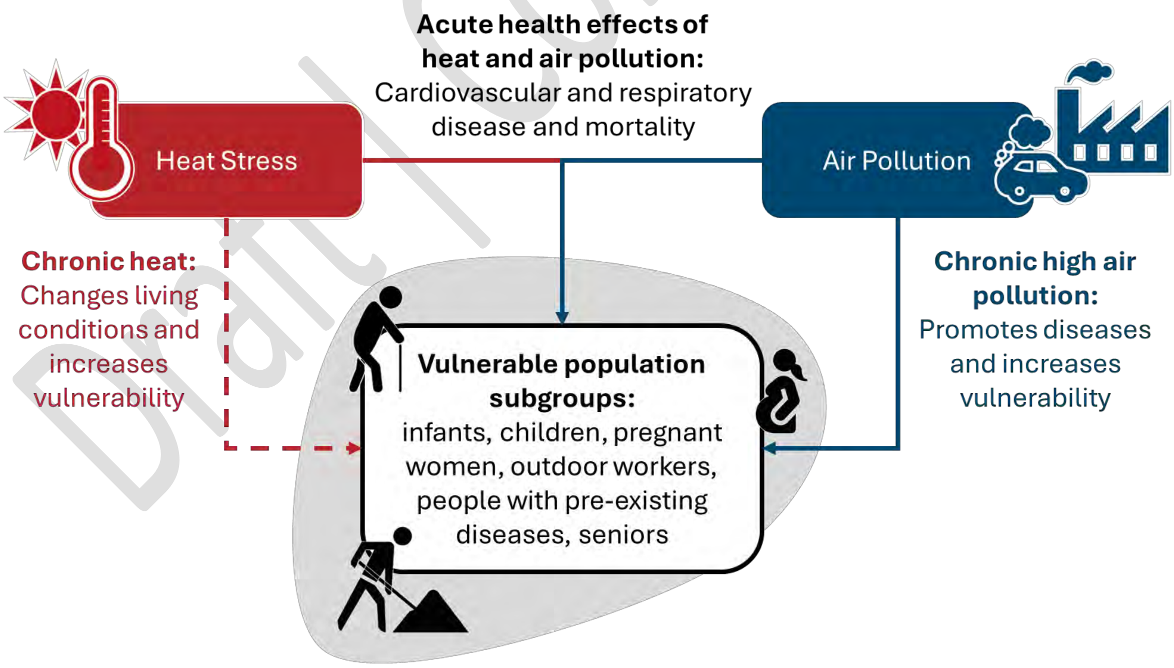
Heat itself increases the levels of some air pollutants: Such pollutants include fine particulate matter (e.g. black carbon) and ozone. During heatwaves or hotter periods, ozone levels are higher because the increased temperature and sunlight accelerate the chemical reactions between ozone precursors (such as methane, carbon monoxide and volatile organic compounds) and nitrogen oxides, leading to higher ozone formation at the ground level. Heatwaves can also significantly increase the risk of wildfires, alter particulate matter formation and properties, and amplify dust storms, as higher temperatures can increase the amount of dust lifted into the atmosphere.

> See *SPS The impacts of wildfire smoke on health* and SPS *Understanding the health impacts of sand and dust storms*

Some air pollutants, such as ozone and black carbon, are known as short-lived climate pollutants (SLCP) as they possess a high warming potential, significantly contributing to climate change. Ozone is also a greenhouse gas.

Heat stress and high levels of fine particulate matter or ozone can amplify health impacts: The joint effects of heat stress and air pollution exposures have been documented for cardiovascular and respiratory disease as well as mortality, with the strongest relative effect of heat on respiratory diseases *(6–9)*. Heat and increased air pollution concentrations jointly trigger the onset of diseases such as acute myocardial infarctions and exacerbate other noncommunicable diseases, leading to death in extreme cases *(10)*. In addition, long-term exposure to air pollution increases heat vulnerability by inducing noncommunicable diseases such as cardiovascular, respiratory and kidney disease (Fig.2).

Fig. 2. Joint health effects of heat stress and air pollution



Barriers, drivers and enablers of action

Barriers: Effectively addressing heat stress and air pollution may be challenging due to the diverse priorities, timelines and approaches of stakeholders across different sectors and organizational levels. This variability can hinder coordination and make it difficult to develop and implement unified, comprehensive strategies. Cities, for example, often experience higher levels of air pollution and heat than rural areas, exposing residents to both risks. Reducing this exposure is challenging due to urban design that fails to minimize heat accumulation, and the use of inappropriate housing materials, inadequate ventilation and insulation.

See *SPS Land use planning - sectoral solutions for air pollution and health*

Drivers: An important driver is the updated World Health Organization (WHO) air quality guidelines that call for improved air quality standard settings around the world. These ambitious goals can only be achieved by reducing the use of fossil fuels and promoting massive usage of renewable energy sources and access to clean energy for all. Such actions would also have co-benefits for climate change mitigation. Other drivers include the increasing attention and funding given to heat-related health impacts, which individuals, health and social care providers and the public directly witness.

Enablers: Enablers are becoming active among intergovernmental and nongovernmental organizations, national and city-level policy-makers, urban planners, funding and research organizations, and patient and health professional organizations. They build on the vast amount of evidence on the joint effects of heat and air pollution that can be used to inform both adaptation plans to climate change and air quality management plans.

Success stories and progress to date

Recent scientific reports such as the Intergovernmental Panel on Climate Change (IPCC) *Sixth Assessment Report (11)* and the 2023 *Report of the Lancet Countdown on health and climate change* (12) highlight the importance of both heat stress and air pollution. Dedicated research projects, e.g. the European Union funded EXHAUSTION project, have elucidated the joint impacts of heat stress and air pollution and developed guidance *(13)*. These results are now considered in updating the guidelines for establishing heat health action plans by the WHO Regional Office for Europe and in the WHO health and climate change country profiles.[2] In China, a new composite air health index (AHI) has been proposed to describe the health risks from co-exposure to high/low temperatures and air pollution simultaneously *(14)*.[3]

Way forward

To achieve joint mitigation of heat stress and air pollution associated health effects, implementation of joint actions from various sectors and stakeholders are needed. Scientific evidence is sufficiently robust to issue policies and build surveillance and impact assessment tools to provide robust evidence on progress at global, national and regional levels. Such assessment includes implementing accurate black carbon measurement, conducting studies of health and air pollution benefits, and cost-effectiveness analysis of policies.

Priority actions for short-term health benefits should focus on adaptation measures and protection of the most vulnerable populations. Heat health action plans need to consider meteorological early warning systems and environmental health surveillance systems for extreme heat and air pollution, effective at regional and local levels, as well as health promotion strategies to protect vulnerable population groups. Health care services should be prepared

---

[2] https://www.who.int/teams/environment-climate-change-and-health/climate-change-and-health/evidence-monitoring/country-profiles
[3] https://www.airhealthindex.org/

structurally and operationally to provide emergency support during extreme events, for example, when heatwaves and wildfires or sand dust storms occur. The construction of heat shelters should avoid co-exposure to air pollution from all sources. Public health surveillance and health monitoring practices to assess health impacts from multiple environmental stressors on a routine basis are missing in many low-, middle- and even high-income countries. Further, health care professionals should consider joint exposure to heat and air pollution as an important factor in providing treatment and lifestyle advice, and advocate for prompt action and management of acute increases in hospitalization associated with heatwaves.

Priority actions for long-term health benefits should consider all possible measures to achieve the ambient air pollution levels recommended by the WHO air quality guidelines in 2021, as well as reducing indoor air pollution. Land use, agricultural and forestry practices need to consider the impact of extreme weather events to avoid wildfires or dust storms during heat episodes.

See *SPS Land use planning - sectoral solutions for air pollution and health* and *Agriculture - sectoral solutions for air pollution and health*

The planning of residential buildings and industrial and service facilities, including the health and social care sectors, should consider protecting against weather extremes, including heat, while simultaneously aiming at reducing their greenhouse gas emissions.

See *SPS Health-care facilities - sectoral solutions for air pollution and health*

All measures that reduce fossil fuel combustion with the goal of mitigating climate change will have co-benefits and reduce the combined harms of heat and air pollution.

- **WHO** works to address climate change – imperative to limiting the magnitude and costs of extreme heat. WHO will continue to develop and report evidence on the risks and solutions to address extreme heat. This should be integrated into WHO's guidance documents and support for air pollution reduction. WHO partners with the World Meteorological Organization on the development of heat health warning systems; and will continue working with the health sector to enhance governance, preparedness and response to the acute impacts of heatwaves, including developing heat action plans, early warning systems, advisories and emergency response plans that identify risks, vulnerable populations and available resources.

- **Member States** should integrate the topic into their heat health action plans and associated early warning systems. Emergency response plans need to be developed and updated that map the risks, vulnerable populations, available capacities and resources for heat, air pollution and other extreme weather events. Health surveillance should consider the joint impacts of heat stress and air pollution. Technical solutions used for heat adaptation of populations, vulnerable subgroups and health services should consider the importance of air pollution reduction. Updates of national and subnational climate change adaptation plans should incorporate Health in All Policies. Land use and urban and rural development projects should consider the joint impacts and future projections. As indicators of progress, experts on the field suggest indicators developed as part of the Lancet Countdown monitoring *(12)*.

- **Academia/researchers** should further substantiate the findings on interlinkages between heatwaves and air quality levels, and close the existing knowledge gap with respect to the impacts of joint long-term exposure to heat stress and air pollution, for example, by adding evidence for less studied health outcomes. While certain medications can increase the health impacts of heat *(15),* potential interactions with air pollution are unknown. There is a need to improve health impact assessment of non-optimal temperatures *(16)* and to develop approaches for health impact assessment of joint effects, develop training courses on the health effects of heat and air pollution, and conduct implementation research highlighting the benefits of actions jointly reducing heat stress and air pollution. An example of the latter would be to work with practitioners and policy-makers to test real-life interventions that might mitigate the risks of these joint exposures.

- **The medical and public health community** should develop guidance on how to treat vulnerable patients, protect vulnerable subgroups, train the current and next-generation medical and public health professionals, alter existing and design future health care infrastructures considering the joint impacts, implement smart workforces as responders to heat and air pollution emergencies, and aim to reduce greenhouse gas emissions from the health system.[4]

Methodology for content development

WHO defined the scope of the document and collaborated with its Advisory Groups (Scientific Advisory Group on Air Pollution and Health, SAG; and the Global Air Pollution and Health – Technical Advisory Group, GAPH-TAG) members, which cover a wide range of expertise, and prepared the initial draft – led by a key expert on the field of air pollution, heat stress and health – based on an overview of the health impacts of heat stress and air pollution, supplemented by expert advice. This consisted of exploring the most recent evidence and selecting key documents as a reference for the development of the SPS, prioritizing systematic reviews and metanalysis.

The draft underwent peer review by specialists from various research institutes, universities, public organizations and UN agencies. And feedback was addressed by the main contributors. Finally, WHO staff and consultants from the WHO Air Quality, Energy and Health Unit reviewed the report to ensure alignment with the WHO requirements for the collections of WHO Air Quality, Energy and Health Science and Policy Summaries. This series synthesizes current knowledge and evidence on air quality, energy access, climate change links and health, primarily to inform intergovernmental discussions.

Acknowledgements

The WHO gratefully acknowledges the many individuals and organizations, including those from its Advisory Groups (the Scientific Advisory Group on Air Pollution and Health, SAG; and the Global Air Pollution and Health – Technical Advisory Group, GAPH-TAG) and its Collaborating Centres who contributed to the development of this document.

This document was written by Annette Peters (Helmholtz Zentrum München – German Center for Environmental Health, Neuherberg, Germany; Medical Faculty, Ludwig-Maximilian Universität,

[4] WHO Member States and other stakeholders are involved with the Alliance for Transformative Action on Climate and Health (ATACH), which aims to build climate resilient and sustainable health systems.

Munich, Germany. Member of the WHO Scientific Advisory Group on Air pollution and Health), Susanne Breitner-Busch (Medical Faculty, Ludwig-Maximilian Universität, Munich, Germany), Susanne Göttlicher (Helmholtz Zentrum München – German Center for Environmental Health, Neuherberg, Germany), Eva Franziska Matthies-Wiesler (Helmholtz Zentrum München – German Center for Environmental Health, Neuherberg, Germany), and Alexandra Schneider (Helmholtz Zentrum München – German Center for Environmental Health, Neuherberg, Germany).

Peer-reviewers included members from the WHO GAPH-TAG: Rima Habre (Keck School of Medicine of USC, United States), Masahiro Hashizume (University of Tokyo, Japan), Wei Huang (Peking University, China), and Haidong Kan (Fudan University, China); members from the WHO Collaborating Centre for Research and Training in Environmental Epidemiology: Magali Hurtado (Instituto Nacional de Salud Pública, Mexico); and Heba Safi (WHO Regional Office for the Eastern Mediterranean).

The development of this document was led by Cristina Vert (WHO Department of Environment, Climate Change and Health) and Sophie Gumy (WHO Department of Environment, Climate Change and Health) with inputs and review from Kerolyn Shairsingh, Pierpaolo Mudu, Karla Cervantes, and Heather Adair-Rohani (Department of Environment, Climate Change and Health, WHO).

Declarations of interest

All external experts submitted a declaration of interest to WHO disclosing potential conflicts of interest that might affect, or might reasonably be perceived to affect, their objectivity and independence in relation to the subject matter of the report. WHO reviewed each of the declarations and concluded that none could give rise to a potential or reasonably perceived conflict of interest related to the subjects covered by the report.

References

1. Heat and health. Geneva: World Health Organization; 2024 (https://www.who.int/news-room/fact-sheets/detail/climate-change-heat-and-health).
2. van Daalen KR, Tonne C, Semenza JC, Rocklov J, Markandya A, Dasandi N et al. The 2024 Europe report of the Lancet Countdown on health and climate change: unprecedented warming demands unprecedented action. Lancet Public Health. 2024 (https://doi.org/10.1016/S2468-2667(24)00055-0).
3. Ebi KL, Capon A, Berry P, Broderick C, de Dear R, Havenith G, et al. Hot weather and heat extremes: health risks. Lancet. 2021;398(10301):698-708.
4. Heat and health in the WHO European Region: updated evidence for effective prevention. Copenhagen: WHO Regional Office for Europe; 2021. https://iris.who.int/handle/10665/339462 Licence: CC BY-NC-SA 3.0 IGO.
5. Singh N, Areal AT, Breitner S, Zhang S, Agewall S, Schikowski T et al. Heat and cardiovascular mortality: an epidemiological perspective. Circ Res. 2024;134(9):1098-112.
6. Thurston GD, Kipen H, Annesi-Maesano I, Balmes J, Brook RD, Cromar K et al. A joint ERS/ATS policy statement: what constitutes an adverse health effect of air pollution? An analytical framework. Eur Respir J. 2017;49(1).
7. Stafoggia M, Michelozzi P, Schneider A, Armstrong B, Scortichini M, Rai M et al. Joint effect of heat and air pollution on mortality in 620 cities of 36 countries. Environ Int. 2023;181:108258.

8. Rai M, Stafoggia M, de'Donato F, Scortichini M, Zafeiratou S, Vazquez Fernandez L et al. Heat-related cardiorespiratory mortality: effect modification by air pollution across 482 cities from 24 countries. Environ Int. 2023;174:107825.
9. Zhang S, Breitner S, Rai M, Nikolaou N, Stafoggia M, De' Donato F et al. Assessment of short-term heat effects on cardiovascular mortality and vulnerability factors using small area data in Europe. Environ Int. 2023;179:108154.
10. Zanobetti A, Peters A. Disentangling interactions between atmospheric pollution and weather. J Epidemiol Community Health. 2015;69(7):613-5.
11. Pörtner HO, Roberts DC, Tignor M, Poloczanska ES, Mintenbeck K, Alegría A et al. (eds). Climate change 2022: impacts, adaptation, and vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC; 2022 (https://www.ipcc.ch/report/ar6/wg2/).
12. Romanello M, Napoli CD, Green C, Kennard H, Lampard P, Scamman D et al. The 2023 report of the Lancet Countdown on health and climate change: the imperative for a health-centred response in a world facing irreversible harms. Lancet. 2023;402(10419):2346-94.
13. Aunan K, Aaheim HA, Andersen MS, Bojariu R, Breitner S, Chowdhury S et al. EXHAUSTION White Paper. Exposure to heat and air pollution in Europe: important findings and recommendations. European Union; 2024 (https://www.exhaustion.eu/resources/exhaustion-white-paper).
14. Zhang Q, Chen R, Yin G, Du X, Meng X, Qiu Y et al. The establishment of a new air health index integrating the mortality risks due to ambient air pollution and non-optimum temperature. Engineering. 2022;14(7):156-62.
15. Heat and medications – guidance for clinicians. United States Centers for Disease Control and Prevention; 2024 (https://www.cdc.gov/heat-health/hcp/clinical-guidance/heat-and-medications-guidance-for-clinicians.html).
16. GBD 2021 Risk Factors Collaborators. Global burden and strength of evidence for 88 risk factors in 204 countries and 811 subnational locations, 1990-2021: a systematic analysis for the Global Burden of Disease Study 2021. Lancet. 2024;403(10440):2162-203.

WHO Air Quality, Energy and Health Science and Policy Summaries

Climate change, air pollution, pollen and health

Technical brief

Key messages

Air pollution and climate change, by enhancing health impacts of allergens such as pollen and airborne biological particles, exacerbate inflammatory and allergic conditions. Key take away messages include:

- The effects of air pollution on inflammatory allergic conditions, such as asthma, are well-known.
- Air pollution and its health effects are exacerbated by climate change, which impacts levels and distribution of outdoor air pollutants such as ground-level ozone and particulate matter.
- Climate change also increases carbon dioxide levels and raises temperatures, which result in an earlier start to the growing season of plants, longer pollen seasons and higher pollen production, increasing overall pollen exposure, which contribute to more severe allergy symptoms.
- Particulate matter alters the pollen surface, increasing its allergenicity.
- Both air pollution and higher allergen levels, influenced by climate change, contribute to increased inflammation and respiratory diseases such as asthma and allergic rhinitis.
- These factors place a greater burden on health care systems and reduce the quality of life for individuals with allergies or respiratory conditions.

Future priority actions

- **Continue monitoring pollen** globally to help health systems prepare for increases in allergy, asthma and immune-related diseases.
- **Implement environmental justice policies** to protect vulnerable populations in polluted regions, reducing their risk of severe allergic reactions and enhancing their capacity to adapt to climate change.
- **Establish health impact information** on pollen and create early warning systems for weather- and climate-related pollen risks.
- **Educate patients** on how to check pollen and air quality levels and provide strategies for reducing exposure to bioaerosols.
- **Public awareness –** promote education campaigns on air pollution, climate change, and their effects on respiratory and allergic diseases.
- **Integrated policy and cross-sector collaboration –** strengthen partnerships across the health care, urban planning, agriculture and environmental sectors to develop comprehensive policies that incorporate health considerations into climate action plans. Support emissions reduction, public transportation and green infrastructure initiatives.
- **Research and One Health approach –** continue studying climate change's health impacts and integrate One Health to address human, animal and environmental health connections.

- **Global cooperation and data sharing:** Enhance efforts by sharing data, best practices and funding initiatives to combat air pollution and protect health.

In summary, climate change and air pollution are amplifying the severity and frequency of allergies, often increasing the duration of the allergy season and making allergies a growing public health concern worldwide.

Key definitions

Pollen: Pollen is a fine yellowish powder (smaller than the width of a human hair) that is released by plants and transported by the wind, by birds, by insects or by other animals. The spread of pollen helps to fertilize plants *(1).*

Allergy: An allergic reaction is an overreaction by our immune system to normally harmless substances *(2).*

Overview

Impact of air pollution on allergic disease

More than 2000 studies have been published between 2000 to 2024 on the effects of air pollution on various inflammatory allergic conditions, including allergic rhinitis, atopic dermatitis, asthma, allergic conjunctivitis and anaphylaxis in adults and children. These effects have been observed even with short-term exposure, such as during wildfire smoke exposure *(3–10).*

See SPS:[1] *Health effects of air pollution – evidence and implications*

Air pollution and its health effects are exacerbated by wildfires, sandstorms and heat waves, which have increased in frequency and intensity with climate change. The changing climate has altered weather patterns, which have, in turn, impacted the levels and distribution of outdoor air pollutants, such as ground-level ozone and fine particulate matter *(11).*

Role of climate change on air pollution and pollen production

One of the consequences of climate change is increased carbon dioxide levels and rising temperatures. These changes in climate are expected to lead to higher levels of certain airborne allergens, such as pollen, resulting in an increase in asthma episodes and other allergic conditions *(11).*

An increase of 1.5°C is expected to have major consequences for human health, including a higher prevalence and severity of allergic disease due to increased pollen and air pollutants predominantly caused by increases in sand and dust storms and wildfires *(12).* These effects are further exacerbated by climate-driven changes in pollen patterns, such as a longer pollen season, increased spread, higher concentrations and enhanced allergenicity, all of which contribute to a greater pollen burden *(13,14).* For example, between 1995 and 2011 the length of pollen season for ragweed, a type of grass, increased by as much as 11 to 27 days in parts of Canada and the United States *(15).*

[1] Science and Policy Summary

Increased carbon dioxide concentrations, together with raising temperatures and altering precipitation patterns, promote and extend the growing season of plants that release pollen, enhance both the quantity and allergenicity of pollen (i.e. a measure of how much particular allergens, such as pollen, affect people), and broaden the geographical spread of pollen *(11)*, leading to earlier flowering *(16).* In some regions, such as the Mediterranean, pollen seasons are already shifting, sometimes by more than a month. Climate change is shifting the timing of seasonal events like flowering, leading to earlier and unpredictable pollen exposure throughout the year *(16).*

Effects on pollen production: Climate change may alter the production of pollen, contributing to the severity and prevalence of allergic diseases in humans *(11)*. Pollen production varies by species and is influenced by factors like pollination type, plant type and environmental conditions. Variations can occur within the same species, with weather and climate impacting pollen production *(17–21).*

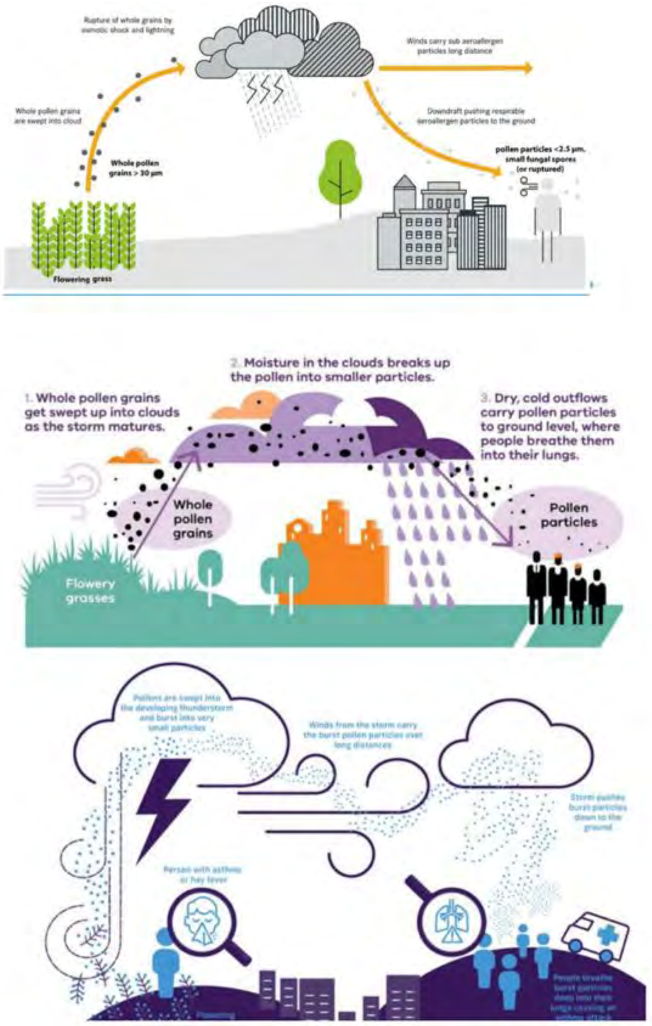
Effects on pollen dispersion: Pollen can spread through water, animals (insects, birds or bats), and wind, with wind being the most relevant for allergies. Pollen dispersal distances vary from a few meters to over 1000 kilometres, influenced by factors like flowering time, weather and landscape features *(22,23)*. Climate change alters atmospheric processes, which can intensify conditions that help spread larger airborne particles, such as strong winds, turbulence, heat-induced updrafts and higher boundary layer.

See SPS: *Green spaces – sectoral solutions for air pollution and health*

Box 1. Case study: thunderstorme-induced asthma

One classic example of an extreme weather condition is thunderstorm-induced asthma. While the exact mechanism of thunderstorm asthma is debated, it is hypothesized is that pollen particles are split into smaller particles during thunderstorm conditions enabling them to reach deeper into the airways causing acute asthma symptoms in those who normally have only mild allergic rhinitis (Fig. 1). Smaller particles can also be easily carried at greater distances thus affecting a larger population. First described nearly 40 years ago, this phenomenon is being reported almost yearly in Australia China, Europe, the Middle East and North America *(24,25).* Overcrowding in emergency rooms of epidemic proportions have been reported during thunderstorm asthma. Due to climate change, there are many greening projects to mitigate heat waves and for carbon sequestration; however, care is needed to select tree and grass species which do not increase allergenic pollen counts.

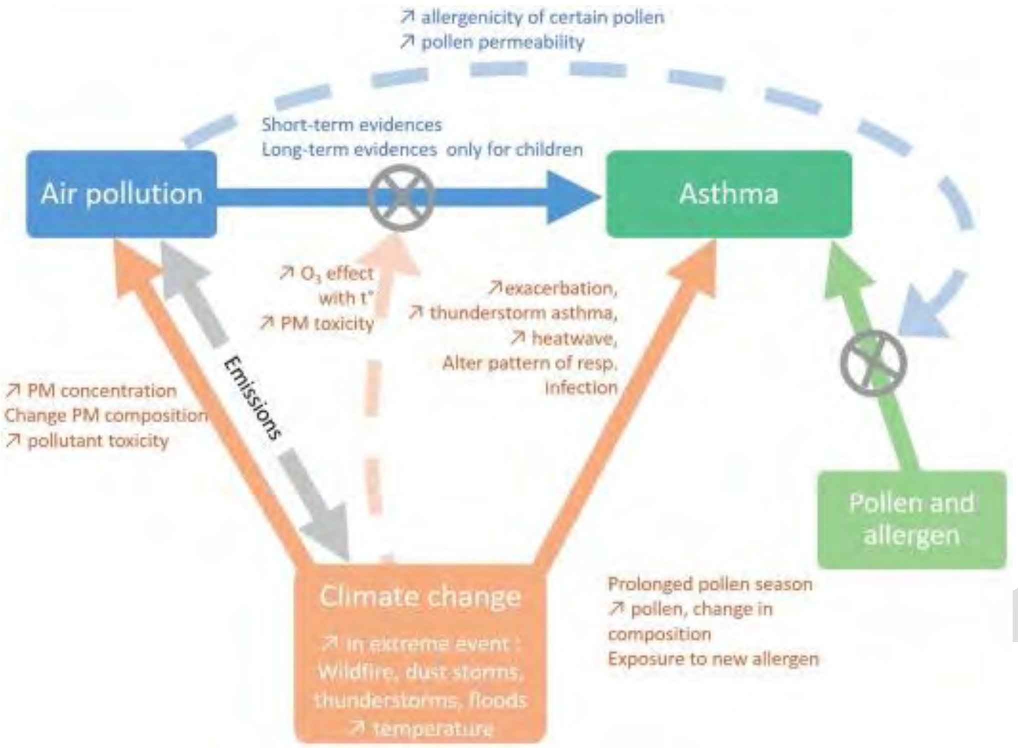
Fig. 1. Thunderstorm-induced asthma



Health effects of pollen exposure driven by air pollution and climate change

Increased pollen concentrations and longer pollen seasons, influenced by air pollution and climate change, lead to greater allergic sensitization and more asthma episodes *(11)* (Fig. 2). Studies show that air pollution increases the ability of pollen to increase inflammation *(19).* Allergens such as pollens can bind $PM_{2.5}$ and increase inflammatory reactions *(26,27).* Also, pollutants can change pollen structure, protein and lipid content, and timing of pollen release, all of which can influence allergenicity *(28).* Further, pollutants such as $PM_{2.5}$ and ground-level ozone also irritate the airways and make asthma worse *(29).*

Fig. 2. Effect of climate change and air pollution on pollen and allergic diseases



Land use changes and allergy-relevant pollen

Land use changes pose one of the major threats of climate change according to the latest IPCC report *(30)* – global warming affects habitat and biodiversity loss, habitat shifts and fragmentation and overall plant distribution by shifting species to higher elevations or latitudes, leading to variability in pollen seasons.

See SPS: *Land use planning – sectoral solutions for health*

Some allergy-relevant plants in Bavaria, Germany, such as birch, may lose their habitats *(31)*, while Mediterranean species such as olive trees and pellitory-of-the-wall could spread to higher latitudes, increasing sensitization rates. Emerging plant species (species sensitive to climate change and dramatically increasing their pollen production and/or allergenicity) and invasive plant species (weeds, ragweed, species tolerant to or favoured by soil and air pollution, urbanization and greenhouse gases) are expected to significantly contribute to the prevalence of allergies in the future, with the spread of such plants across the globe *(32–35).*

Vulnerable populations

Infants and children are uniquely sensitive to air pollution because their organs are developing, and they have higher air per body weight intake. Air pollution also disproportionately affects those who have limited access to health care and few resources to mitigate unhealthy air quality. Low-income communities, often situated in more polluted areas, also face a higher risk of severe allergic reactions and respiratory issues. Pregnant women, older adults and individuals with pre-existing respiratory conditions are immune compromised and more at risk of allergic disease.

See SPS: *Air pollution and vulnerable populations*

Success stories

Changes in transport behaviour and policy, even short term, have been shown to decrease allergies. This was observed for both the 1996 and 2008 Olympic games in Atlanta and Beijing, respectively. In both cities, major changes in transportation were implemented, for example, increased public transport and temporary vehicle restrictions. In Atlanta, these changes resulted in a reduction in ozone pollution as well as significantly lower rates of asthma events in children 1–16 years *(36)*. Similarly, in Beijing, during the 2008 Olympic Games, a prolonged reduction in air pollution and significantly lower rates of adult asthma events were observed *(37)*.

Another success story is the existence of a pollen database, created by the European Aeroallergen Network (EAN).[2] This is fundamental tool for pollen forecasting and essential for pollen information services in Europe. It is also important for international research projects and clinical studies. EAN currently includes information from more than 400 active and 300 historical pollen traps across Europe, including 39 countries, not all of which are on the European continent. The network has now been extended to the North American continent.

Way forward

Climate change is increasing air pollutants and may lead to higher levels of pollen, having negative consequences for human health, including the increased risk of allergies and asthma. Therefore, there is an urgent need to adapt and mitigate to these changes.

Monitoring allergen (pollens and biological particles) and air pollution exposures will be important to implement throughout the globe now and in the future to aid health systems prepare for increases in visits and admissions due to allergies and asthma and other immune-mediated and inflammatory diseases. Airborne pollen has been monitored for almost a century now, with quite consistent and comparable methods and acquired data. However, airborne pollen monitoring is an arduous task and there are challenges associated with sustaining pollen monitoring and pollen monitoring network management *(38).* In the last 10–15 years, there have been efforts to automate the task. These modern automated measurement methods are still experimental in terms of validation and comparability *(39–41)*.

Exposure to greenness and greyness also influence allergy in urban settings, in addition to air pollution. Monitoring these exposures in order to understand how best to design urban landscapes to minimize allergies is needed *(42).* Such systems and the associated biomonitoring networks have to show common grounds: comparability, reliability and free access to all individuals.

A better understanding of the environmental factors that mediate allergy and how to prevent the onset of allergenic reactions is urgently needed *(43).*

Environmental justice policies should be put in place in order to protect vulnerable populations, who, living in more polluted regions have higher risk of severe allergic reactions and lower resilience and capacity to adapt to climate change *(44–47).*

[2] https://ean.polleninfo.eu/info/en/about-us

Information of the health effects of pollen and early warning systems should be put in place to tackle weather- and climate-related risks and hazards of pollen-related diseases. Better risk knowledge, coupled with improved detection, monitoring, analysis, forecasting, warning dissemination, communication, preparedness and response capabilities, are needed.

Health care professionals should strive to incorporate environmental exposure counselling, environmental health precepts and education into their practice, for both themselves (especially younger practitioners) and their patients *(48–50)*. Educating patients to check for pollen and air quality; providing them with strategies for reducing exposure on high pollen and air pollution days, and information on how to adjust their allergy and asthma medications for optimal health; advocating for policies promoting clean air, water, soil and green spaces; and promoting sustainable practices should aid patients' short- and long-term health.

Innovative economic models of climate change interventions *(50)* not relying on individual methods in estimating health damages, incorporating a broader range of cause-specific mortality impacts, using improved climate parameters and accounting for socioeconomic trajectories and adaptation factors are also urgently needed.

Public education initiatives and campaigns for creating greater awareness on the effects of air pollution, global warming and climate change on allergic and respiratory diseases should be promoted to encourage preventive measures during peak seasons.

Policy-makers should integrate health considerations into climate action plans. This includes promoting policies that reduce emissions, enhance public transportation and support green infrastructure.

Continued research on the impacts of climate change on health is needed. Integration of One Health into public policy and climate action and recognizing the interconnectedness between human, animal and environmental health is the way forward.

Cross-sector collaboration fostering partnerships among health care, environment, urban planning and agricultural practices to address health policies is crucial. Global cooperation is essential to address these global challenges. Sharing data, best practices and funding initiatives can enhance efforts to combat air pollution and its effects on health and the environment.

Methodology for content development

WHO defined the scope of the document and collaborated with the Scientific Advisory Group on Air Pollution and Health (SAG), and other experts from various research institutes and universities, which cover a wide range of expertise, who prepared the initial draft – led by a key expert on the field of air pollution and health – based on an overview of climate change, air pollution, pollen and health, supplemented by expert advice. This consisted of exploring the most recent evidence and selecting key documents as a reference for the development of this SPS, prioritizing systematic reviews and meta-analysis.

The draft underwent peer review by specialists from the WHO Global Air Pollution and Health – Technical Advisory Group (GAPH-TAG), various research institutes, universities, public organizations and United Nations agencies. Feedback was addressed by the main contributors. Finally, WHO staff and consultants from the WHO Air Quality, Energy and Health Unit reviewed the report to ensure alignment with the WHO requirements for the collections of WHO Air Quality, Energy and Health Science and Policy Summaries. This series synthesizes current knowledge and evidence on air quality, energy access, climate change links and health, primarily to inform intergovernmental discussions.

Acknowledgements

The WHO gratefully acknowledges the many individuals and organizations, including those from its advisory groups (SAG and GAPH-TAG), who contributed to the development of this document.

This document was written by Kari Nadeau (Department of Environmental Health, Harvard T.H. Chan School of Public Health, Boston, United States; SAG member); Vanitha Sampath (Department of Environmental Sciences, Harvard T.H. Chan School of Public Health, Boston, United States); Ioana Agache (Transylvania University, Brasov, Romania); Cezmi Akdis (Swiss Institute of Allergy and Asthma Research, University of Zurich, Davos, Switzerland); Sharon Chinthrajah (Sean N. Parker Center for Allergy and Asthma Research at Stanford University, Stanford, United States); Ruby Pawankar (Department of Pediatrics, Nippon Medical School, Tokyo, Japan); Mohammed Shamji (National Heart and Lung Institute, Imperial College, London, United Kingdom of Great Britain and Northern Ireland); Maria Torres (Allergy Unit, IBIMA-Hospital Regional Universitario de Málaga-ARADyAL, UMA, Málaga, Spain); Claudia Traidl-Hoffman (Institute of Environmental Medicine, Helmholtz Munich, German Research Center for Environmental Health, Neuherberg, Germany); and Gary Wong (Chinese University of Hong Kong, Hong Kong SAR, China).

Peer reviewers included Joan Bartra (Pneumology and allergy Department, Hospital Clinic Barcelona, Spain); Sara Basart (WMO); Jordina Belmonte (Institute of Environmental Science and Technology (ICTA-UAB), Spain); Athanasios Damialis (Terrestrial Ecology and Climate Change, Department of Ecology, School of Biology, Faculty of Sciences, Aristotle University of Thessaloniki, Greece); Barbara Hoffmann (European Respiratory Society); Mary M Johnson (Harvard T.H. Chan School of Public Health, Boston, United States); Patrick Kinney (Boston University School of Public Health, United States; GAPH-TAG member); Irma Aurora Rosas Pérez (Instituto de Ciencias de la Atmósfera y Cambio Climático, México); Sayantani B Sindher (Stanford University School of Medicine, Standford, United States); Chrysanthi Skevaki (Institute of Laboratory Medicine and Pathobiochemistry, Molecular Diagnostics, Philipps University Marburg, University Hospital Gießen and Marburg, Germany); and Giovanni Viegi (National Research Council, Institutes of Clinical Physiology and Translational Pharmacology, Pisa, Italy).

The development of this document was led by Sophie Gumy, Pierpaolo Mudu, Kerolyn Shairsingh and Cristina Vert (WHO Department of Environment, Climate Change and Health), with input and review from Samantha Pegoraro and Karla Cervantes (WHO Department of Environment, Climate Change and Health).

Declarations of interest

All external experts submitted a declaration of interest to WHO disclosing potential conflicts of interest that might affect, or might reasonably be perceived to affect, their objectivity and independence in relation to the subject matter of the report. WHO reviewed each of the declarations and concluded that none could give rise to a potential or reasonably perceived conflict of interest related to the subjects covered by the report.

World Health Organization

References[3]

1. Pollen allergies. American College of Allergy, Asthma and Immunology; 2025 (https://acaai.org/allergies/allergic-conditions/pollen-allergies/).
2. Allergy symptoms. Arlington, VA: Asthma and Allergy Foundation of America; 2025 (https://aafa.org/allergies/allergy-symptoms/).
3. Wang H, Li XB, Chu XJ, Cao NW, Wu H, Huang RG et al. Ambient air pollutants increase the risk of immunoglobulin E-mediated allergic diseases: a systematic review and meta-analysis. Environ Sci Pollut Res Int. 2022;29(33):49534-52 (https://doi.org/10.1007/s11356-022-20447-z)
4. Fadadu RP, Grimes B, Jewell NP, Vargo J, Young AT, Abuabara K et al. Association of wildfire air pollution and health care use for atopic dermatitis and itch. JAMA Dermatol. 2021;157(6):658-66 (https://doi.org/10.1001/jamadermatol.2021.0179)
5. Fuertes E, Sunyer J, Gehring U, Porta D, Forastiere F, Cesaroni G et al. Associations between air pollution and pediatric eczema, rhinoconjunctivitis and asthma: a meta-analysis of European birth cohorts. Environ Int. 2020;136:105474 (https://doi.org/10.1016/j.envint.2020.105474)
6. Lin L, Li T, Sun M, Liang Q, Ma Y, Wang F et al. Effect of particulate matter exposure on the prevalence of allergic rhinitis in children: a systematic review and meta-analysis. Chemosphere. 2021;268:128841 (https://doi.org/10.1016/j.chemosphere.2020.128841)
7. Zou QY, Shen Y, Ke X, Hong SL, Kang HY. Exposure to air pollution and risk of prevalence of childhood allergic rhinitis: a meta-analysis. Int J Pediatr Otorhinolaryngol. 2018;112:82-90 (https://doi.org/ 10.1016/j.ijporl.2018.06.039)
8. Ai S, Liu L, Xue Y, Cheng X, Li M, Deng Q. Prenatal exposure to air pollutants associated with allergic diseases in children: which pollutant, when exposure, and what disease? a systematic review and meta-analysis. Clin Rev Allergy Immunol. 2024;66(2):149-63 (https://doi.org/10.1007/s12016-024-08987-3)
9. Lau HX, Lee JW, Yap QV, Chan YH, Samuel M, Loo EXL. Smoke exposure and childhood atopic eczema and food allergy: a systematic review and meta-analysis. Pediatr Allergy Immunol. 2023;34(8):e14010 (https://doi.org/10.1111/pai.14010)
10. Lopez DJ, Lodge CJ, Bui DS, Waidyatillake NT, Su JC, Knibbs LD et al. Air pollution is associated with persistent peanut allergy in the first 10 years. J Allergy Clin Immunol. 2024;154(6):1489-99.e9 (https://10.1016/j.jaci.2024.08.018)
11. Fann N, Brennan T, Dolwick P, Gamble J, Ilacqua V, Kolb L et al. Chapter 3: Air quality impacts. The impacts of climate change on human health in the United States: a scientific assessment. Washington, DC: US Global Change Research Program; 2016;69-98 (https://health2016.globalchange.gov/low/ClimateHealth2016_03_Air_Quality_small.pdf].
12. Agache I, Akdis C, Akdis M, Al-Hemoud A, Annesi-Maesano I, Balmes J et al. Immune-mediated disease caused by climate change-associated environmental hazards: mitigation and adaptation. Front Sci. 2024;2:1279192 (https://doi.org/10.3389/fsci.2024.1279192)
13. Paudel B, Chu T, Chen M, Sampath V, Prunicki M, Nadeau KC. Increased duration of pollen and mold exposure are linked to climate change. Sci Rep. 2021;11(1):12816 (https://doi.org/10.1038/s41598-021-92178-z)
14. Lee AS, Aguilera J, Efobi JA, Jung YS, Seastedt H, Shah MM et al. Climate change and public health: the effects of global warming on the risk of allergies and autoimmune diseases: EMBO Rep. 2023;24(4):e56821 (https://10.15252/embr.202356821)
15. Air quality impacts. Washington, DC: US Global Change Research Program; 2025 (https://health2016.globalchange.gov/air-quality-impacts].
16. Zhang Y, Steiner AL. Projected climate-driven changes in pollen emission season length and magnitude over the continental United States. Nat Commun. 2022;13(1):1234 (https://doi.org/10.1038/s41467-022-28764-0)

[3] Accessed 21 March 2025.

17. Ziska LH. Climate, Carbon dioxide, and plant-based aero-allergens: a deeper botanical perspective. Front Allergy. 2021;2:714724 (https://doi.org/10.3389/falgy.2021.714724)
18. Jung S, Estrella N, Pfaffl MW, Hartmann S, Ewald F, Menzel A. Impact of elevated air temperature and drought on pollen characteristics of major agricultural grass species. Plos One. 2021;16(3):e0248759 (https://doi.org/10.1371/journal.pone.0248759)
19. Rauer D, Gilles S, Wimmer M, Frank U, Mueller C, Musiol S et al. Ragweed plants grown under elevated CO(2) levels produce pollen which elicit stronger allergic lung inflammation. Allergy. 2021;76(6):1718-30 (https://doi.org/10.1111/all.14618)
20. Ghiani A, Ciappetta S, Gentili R, Asero R, Citterio S. Is ragweed pollen allergenicity governed by environmental conditions during plant growth and flowering? Sci Rep. 2016;6(1):30438 (https://doi.org/10.1038/srep30438)
21. Wayne P, Foster S, Connolly J, Bazzaz F, Epstein P. Production of allergenic pollen by ragweed (Ambrosia artemisiifolia L.) is increased in CO2-enriched atmospheres. Ann Allergy Asthma Immunol. 2002;88(3):279-82 (https://doi.org/10.1016/S1081-1206(10)62009-1)
22. Grewling Ł, Bogawski P, Kryza M, Magyar D, Šikoparija B, Skjøth CA et al. Concomitant occurrence of anthropogenic air pollutants, mineral dust and fungal spores during long-distance transport of ragweed pollen. Environ Pollut. 2019;254:112948 (https://doi.org/10.1016/j.envpol.2019.07.116)
23. Damialis A, Kaimakamis E, Konoglou M, Akritidis I, Traidl-Hoffmann C, Gioulekas D. Estimating the abundance of airborne pollen and fungal spores at variable elevations using an aircraft: how high can they fly? Sci Rep. 2017;7(1):44535 (https://doi.org/10.1038/srep44535)
24. Beggs PJ. Thunderstorm asthma and climate change. JAMA. 2024;331(10):878-9 (https://doi.org/10.1001/jama.2023.26649)
25. Fan C, Li X, Cai H, Tong X, Ai L, Li Y et al. Epidemic thunderstorm asthma in Hohhot, Northern China: a retrospective analysis of clinical characteristics in 155 patients. J Allergy Clin Immunol Pract. 2024;12(9):2514-6.e1 (https://doi.org/ 10.1016/j.jaip.2024.06.012)
26. Majd A, Chehregani A, Moin M, Gholami M, Kohno S, Nabe T, Shariatzade M. The effects of air pollution on structures, proteins and allergenicity of pollen grains. Aerobiologia. 2004;20:111-8 (https://doi.org/10.1023/B:AERO.0000032950.12169.38)
27. Sedghy F, Varasteh A-R, Sankian M, Moghadam M. Interaction between air pollutants and pollen grains: the role on the rising trend in allergy. Rep Biochem Mol Biol. 2018;6(2):219 (https://pubmed.ncbi.nlm.nih.gov/29766006/)
28. Singh AB, Kumar P. Climate change and allergic diseases: an overview. Front Allergy. 2022;3:964987 (https://doi.org/10.3389/falgy.2022.964987)
29. Air pollution and asthma. Arlington, VA: Asthma and Allergy Foundation of America; 2025 (https://aafa.org/asthma/asthma-triggers-causes/air-pollution-smog-asthma/).
30. Sixth assessment report. Working Group II. Intergovernmental Panel on Climate Change; 2023 (https://www.ipcc.ch/assessment-report/ar6/).
31. Rojo J, Oteros J, Picornell A, Maya-Manzano JM, Damialis A, Zink K, et al. Effects of future climate change on birch abundance and their pollen load. Glob Chang Biol. 2021;27(22):5934-49 (https://doi.org/10.1111/gcb.15824)
32. Bergmann KC, Brehler R, Endler C, Höflich C, Kespohl S, Plaza M, et al. Impact of climate change on allergic diseases in Germany. J Health Monit. 2023;8(Suppl 4):76-102 (https://doi.org/10.25646/11654)
33. Addison-Smith B, Milic A, Dwarakanath D, Simunovic M, Van Haeften S, Timbrell V, Davies JM. Medium-term increases in ambient grass pollen between 1994-1999 and 2016-2020 in a subtropical climate zone. Front Allergy. 2021;2:705313 (https://doi.org/10.3389/falgy.2021.705313)
34. Reid CE, Gamble JL. Aeroallergens, allergic disease, and climate change: impacts and adaptation. EcoHealth. 2009;6(3):458-70 (https://10.1007/s10393-009-0261-x)

35. Damialis A, Traidl-Hoffmann C, Treudler R. Climate change and pollen allergies. In: Marselle MR, Stadler J, Korn H, Irvine KN, Bonn A, editors. Biodiversity and health in the face of climate change. Cham: Springer International Publishing; 2019;47-66 (https://doi.org/10.1007/978-3-030-02318-8_3)
36. Friedman MS, Powell KE, Hutwagner L, Graham LM, Teague WG. Impact of changes in transportation and commuting behaviors during the 1996 Summer Olympic Games in Atlanta on air quality and childhood asthma. JAMA. 2001;285(7):897-905 8https://doi.org/10.1001/jama.285.7.897)
37. Li Y, Wang W, Wang J, Zhang X, Lin W, Yang Y. Impact of air pollution control measures and weather conditions on asthma during the 2008 Summer Olympic Games in Beijing. Int J Biometeorol. 2011;55(4):547-54 (https://doi.org/10.1007/s00484-010-0373-6)
38. Dwarakanath D, Milic A, Beggs PJ, Wraith D, Davies JM. A global survey addressing sustainability of pollen monitoring. World Allergy Organ J. 2024;17(12) (https://10.1016/j.waojou.2024.100997)
39. Plaza MP, Kolek F, Leier-Wirtz V, Brunner JO, Traidl-Hoffmann C, Damialis A. Detecting airborne pollen using an automatic, real-time monitoring system: evidence from two sites. Int J Environ Res Public Health. 2022;19(4) (https://10.3390/ijerph19042471)
40. Schiele J, Damialis A, Rabe F, Schmitt M, Glaser M, Haring F et al. Automated classification of airborne pollen using neural networks. Annu Int Conf IEEE Eng Med Biol Soc. 2019;2019:4474-8 (https://10.1109/EMBC.2019.8856910)
41. Bastl M, Bastl K, Dirr L, Berger M, Berger U. Methods and standards of pollen monitoring—significance of pollen measurements at different altitudes. Allergo J Int. 2023;32(6):162-6 (https://doi.org/10.1007/s40629-023-00268-3)
42. Cilluffo G, Ferrante G, Fasola S, Montalbano L, Malizia V, Piscini A et al. Associations of greenness, greyness and air pollution exposure with children's health: a cross-sectional study in Southern Italy. Environ Health. 2018;17(1):86 (https://doi.org/10.1186/s12940-018-0430-x)
43. Akdis CA, Akdis M, Boyd SD, Sampath V, Galli SJ, Nadeau KC. Allergy: mechanistic insights into new methods of prevention and therapy. Sci Transl Med. 2023;15(679):eadd2563 8https://doi.org/10.1126/scitranslmed.add2563)
44. Agency for Toxic Substances and Disease Registry (ATSDR). Atlanta; GA: Environmental Justice Index 2024 (https://www.atsdr.cdc.gov/place-health/php/eji/index.html).
45. Canaday FT, Georas SN, Croft DP. Examining the impact of air pollution, climate change, and social determinants of health on asthma and environmental justice. Curr Opin Pulm Med. 2024;30(3):276-80 (https://10.1097/MCP.0000000000001065)
46. Paciência I, Cavaleiro Rufo J, Moreira A. Environmental inequality: air pollution and asthma in children. Pediatr Allergy Immunol. 2022;33(6) (https:// 10.1111/pai.13818)
47. Smirnova N, Shaver AC, Mehta AJ, Philipsborn R, Scovronick N. Climate change, air quality, and pulmonary health disparities. Clin Chest Med. 2023;44(3):489-99 (https://doi.org/10.1016/j.ccm.2023.03.005)
48. Agache I, Laculiceanu A, Spanu D, Grigorescu D. The concept of One Health for allergic diseases and asthma. Allergy Asthma Immunol Res. 2023;15(3):290-302 (https://doi.org/10.4168/aair.2023.15.3.290)
49. Jutel M, Mosnaim GS, Bernstein JA, Del Giacco S, Khan DA, Nadeau KC et al. The One Health approach for allergic diseases and asthma. Allergy. 2023;78(7):1777-93 (https://doi.org/ 10.1111/all.15755)
50. Perera F, Nadeau K. Climate change, fossil-fuel pollution, and children's health. N Engl J Med. 2022;386(24):2303-14 (https://10.1056/NEJMra2117706)
51. Cromar KR, Anenberg SC, Balmes JR, Fawcett AA, Ghazipura M, Gohlke JM et al. Global health impacts for economic models of climate change: a systematic review and meta-analysis. Ann Am Thorac Soc. 2022;19(7):1203-12 (https:// 10.1513/AnnalsATS.202110-1193OC)

WHO Air Quality, Energy and Health Science and Policy Summaries

Agriculture – sectoral solutions for air pollution and health

Technical brief

Key messages

Air pollution from agriculture is responsible for a significant health and economic burden in many countries and regions.

- Though a less well-acknowledged source than other sectors (e.g. energy), agriculture is an important contributor to air pollution and climate change.
- As well as the impacts on human health, emissions also damage crops and decrease yields, harm ecosystems and decrease biodiversity.
- Urban areas face poor air quality and consequent health effects, but rural and agricultural areas also suffer high levels of air pollutants and chemicals, especially concentrations of secondary pollutants such as ozone. Their health effects are underreported.
- Thus, agriculture is a key sector in which measures to improve air quality, clean energy access and climate change mitigation are important.
- Both climate and health benefits arise from actions to decrease agricultural air pollution.
- Cutting air pollution from agriculture promotes the health of people and animals, saves money and reduces damage to ecosystems and biodiversity.
- Sustainable agriculture can provide healthy food while ensuring clean air and supporting natural ecosystems.

Clearly, there is a need for priority actions in both the short and long term to reduce air pollutants from agriculture, which includes ammonia, particulate matter (PM), nitrogen oxides and climate pollutants such as methane and nitrous oxide.

Priority actions for short-term impacts:

- Recognize the different connections between agriculture, air pollution and climate change by improving air quality monitoring in rural areas and establishing rural emissions inventories. Currently, there is a lack of measured data from rural areas on air pollutants and harmful chemicals.
- Implement no burn alternatives for crop residues, for example, by developing farming methods that include the incorporation of crop residues in soil management.
- Move to sustainable agriculture practices, in particular for the management of soil health and resources and the production of healthier food (reducing pesticide and herbicide use).
- Address emissions of ammonia, nitrous oxide and methane from livestock systems, especially nitrogen from manure and methane from ruminants. Move to sustainable management of manure and improve nutrient use efficiency in livestock production.
- Integrate actions to reduce ammonia emissions from agriculture into clean air plans and regulations.

- Implement sustainable management of synthetic fertilizers, which emit ammonia and nitrous oxide, and at the same time promote the use of organic fertilizers to recycle nutrients and prevent nutrient losses throughout the entire agricultural production chain.

Priority actions for long-term impacts:

- Support energy transitions that improve air quality and support climate change mitigation. The energy transition should consider the different food systems including inputs (fertilizer and feed), on-farm energy use, transport and food processing emissions.
- Protect ecosystem biodiversity.
- Promote and adopt healthier diets that have low environmental impact and are aligned with international and national dietary guidelines.

Overview

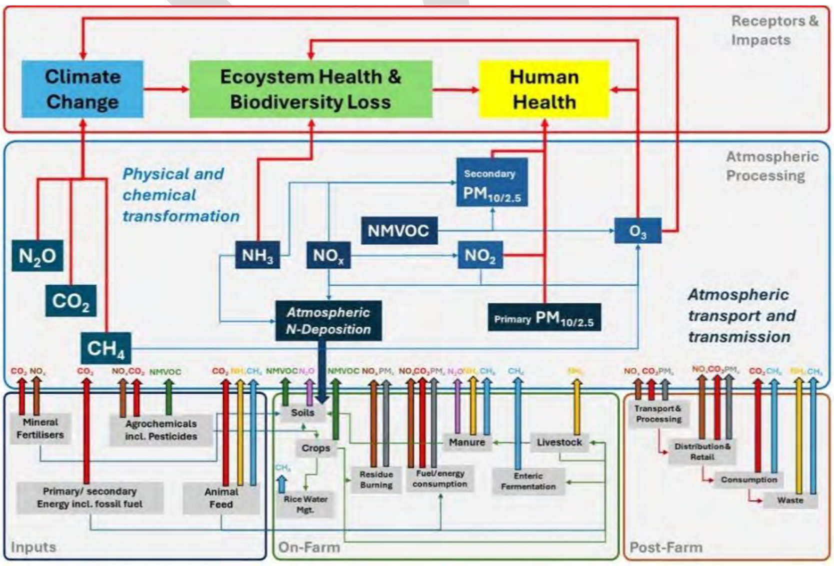
Agriculture-related air pollution and health impacts

The contribution of agriculture to air pollution and climate change is significant but not well acknowledged *(1)*. Agriculture contributes to air pollution, in particular, through:

- emissions of ammonia (a colourless irritant gas) from, for example, manure in confined animal feeding operations, and synthetic fertilizer use;
- direct emissions of fine particles and nitrogen oxides mainly from the combustion of agricultural waste or cropland burning; and
- emissions from motor vehicles, e.g. machinery and tractors *(2,3)*.

Ammonia is a precursor to fine particulate matter ($PM_{2.5}$) and represents a significant fraction of total $PM_{2.5}$ mass in many locations *(4,5).* Air pollution from agricultural activities is not just localized in the areas of planting and harvesting crops or livestock farming as PM and chemicals (fertilizers, herbicides and pesticides) can reach neighbouring lands and even distant and transboundary areas (see Fig. 1). Burning of crop residues is a prominent source of long-distance dispersion of air pollutants.

Fig. 1. Agricultural emissions and their effects



Notes: CH_4 methane; CO_2 carbon dioxide; NH_3 ammonia; NMVOC non-methane volatile organic compounds; NO_x nitrogen oxides; NO_2 nitrogen dioxide; N_2O nitrous oxide; O_3 ozone; PM particulate matter.

Crop residue burning has been increasing in various areas of the world such as Africa, Asia and the Americas, particularly in South Asia *(6,7)*. Data from the European Union show that, in 2021, agriculture (mostly livestock farming) was responsible for 94% of ammonia and 56% of anthropogenic methane emissions *(8,9)*. Methane is a short-lived climate pollutant (SLCP) (together with black carbon, ozone and hydrofluorocarbons), meaning that, in contrast to carbon dioxide, it has a relatively short atmospheric lifetime (days to few decades); SLCPs are responsible for up to 45% of current global warming *(10)*. Ammonia emissions in the European Union fell by only 8% between 2005 and 2020. This was the lowest percentage reduction of all pollutants *(11)*.

Crop or stubble burning is the practice of burning crop residues left after harvesting. It occurs with high frequency in some countries and regions, for example, in Asia between from September to November, and provokes serious health and social consequences. Although crop burning is prohibited in many countries, it is still carried out widely and often winds carry the air pollutants over long distances, negatively impacting those far from the source of the pollution. For example, large-scale open burning of post-harvest crop residue in nearby rural regions contributes to severe haze pollution in New Delhi during autumn and winter (~42% ± 17%) *(12)*. In Punjab (Pakistan) crop burning is responsible for 25% of air pollutant emissions *(13)*.

Regarding primary PM agriculture generates and secondary $PM_{2.5}$ from ammonia emissions, the effects of air pollution from agriculture on health are less well known than from other sectors. The bulk of exposure and health effects from agricultural activities comes from $PM_{2.5}$ (including ammonia-derived $PM_{2.5}$), which has the capacity to penetrate and affect all the main human organs *(14)*. However, it is difficult to identify specific components in PM that pose more risks than others *(15)*. If we consider ammonia, when assessed as a precursor to $PM_{2.5}$, overexposure in its gaseous form can cause acute health effects, making it a potential occupational hazard in many agricultural locations *(5,16)*. "However, exposure to lower concentrations over longer periods may still have a negative impact on human health. The most frequently reported health complaints from exposure to ammonia include eye, nose, and throat irritation, headache, nausea, diarrhea, hoarseness, sore throat, cough, chest tightness, nasal congestion, palpitations, shortness of breath, stress, drowsiness, and alterations in mood" *(5)*. Recent studies provide some figures on the health impacts of air pollution related to agricultural activities. One study of 59 countries, including a number in Europe, Canada, China, Russian Federation, Türkiye and the United States of America, indicated a 50% reduction in agricultural emissions could prevent > 200 000 deaths per year, accompanied with economic benefits of many US$ billions *(2)*. In particular, in the EU, mortality attributable to $PM_{2.5}$ could be reduced by 18% with an estimated annual economic benefit of US$ 89 billion *(2)*. In India, eliminating agricultural crop residue burning would avert 149 000 disability-adjusted life years lost per year, valued at US$ 1.529 billion over 5 years *(17)*.

Crop residue burning contributes to poor air quality and the consequent health burden, which includes acute respiratory infections and eye irritation, affects susceptible populations such as children and older people in particular *(17–19)*. The toll on health is high because air pollution due to agriculture generates multiple impacts on health. Using 2015 data for 857 European cities, it was estimated for $PM_{2.5}$ exposure that the main sectoral contributors to premature mortality were the residential and agricultural sectors *(20)*. "Agricultural production in the United States results in 17 900 annual air quality related deaths, 15 900 of which are from food production" *(21)*. In India, agricultural residue burning is estimated to be the cause of an annual average of 68 000 PM exposure-related premature deaths annually *(22)*. At the global level, agricultural air pollutant emissions in 2018 were estimated to be associated with 537 000 premature deaths attributable to fine $PM_{2.5}$ exposure and 184 000 premature deaths from methane-induced ground-level ozone *(23)*.

See SPS[1] *Health effects of air pollution – evidence and implications*

Agricultural impacts from agriculture-related air pollution

There is a bidirectional relationship between agriculture-related air pollution and agriculture, for example on crops (e.g. yellowing plants), livestock (animal health and welfare) and polluting urban horticultural land. Studies published on the effects of air pollution on animals have indicated that air pollution may cause respiratory disease in poultry, pigs, cattle and small ruminants *(24,25)*. Nitrogen dioxide, ozone, PM and sulfur dioxide levels affect vegetation and crop production.[2] Nitrogen dioxide and PM, and ozone and sulfur dioxide, appear to damage crops, with major consequences for yield *(23,26)*. A simulation of the possible gains from reducing emissions of nitrogen oxides and, consequently, the ambient concentrations of nitrogen dioxide, indicated that a 50% decrease in nitrogen dioxide emissions would improve crop yields by 28% for winter crops and 16% for summer crops in China; nearly 10% for both winter and summer crops in western Europe; and 8% for summer crops and 6% for winter crops in India *(26)*. In the United States, estimates of the total yield losses from nitrogen dioxide, PM, ozone and sulfur dioxide averaged roughly 5% for both maize and soybean between 1999 and 2019. Ozone damage depends on region and cultivar, ranging between 0% and 39%, with high yield losses for Asia. For wheat, the models indicate much higher losses for Asia than Europe or North America *(27,28)*. "Significant improvement in air quality since 1999 has halved the impact of poor air quality on major crops and contributed to yield increases that represent roughly 20% of overall yield gains over that period"; this corresponds to US$ 5 billion per year *(26)*.

Recent estimates show that the life-cycle of the global food system (pre-production, production, post-production, consumption and waste management) accounts for 58% of anthropogenic, global emissions of primary $PM_{2.5}$, 72% of ammonia, 13% of nitrogen oxides, 9% of sulfur dioxide and 19% of non-methane volatile organic compounds (NMVOC). These emissions result in at least 890 000 ambient $PM_{2.5}$-related deaths – equivalent to 23% of ambient $PM_{2.5}$-related deaths reported in the Global Burden of Disease Study 2015 *(29)*. "Air pollution disrupts not only food production, but also food access. In areas like the tropics and subtropics, not only will the productivity of food crops decline, but subsistence farmers and outdoor labourers will face reduced workdays, as breathability worsens and daily heat rises, limiting their incomes and increasing the price of food worldwide" *(30)*. "Worldwide 2.5 billion people depend on agriculture for their livelihoods. Many are smallholder farmers surviving on the margins of productivity from their agricultural products. For them, small changes in the climate and crop growth can have immediate and devastating consequences. Air pollution and climate change affect the global food system in such a way that those who suffer from hunger and malnutrition are also the most vulnerable to these added threats" *(31)*.

Success stories and progress to date

Several projects on reducing air and climate pollutants from agriculture are worth noting. Relevant activities include the United Nations/Global Environment Facility Global Nitrogen Management

[1] Science and Policy Summary

[2] See United Nations Economic Commission for Europe (UNECE) International Cooperative Programme on Effects of Air Pollution on Natural Vegetation and Crops (https://unece.org/vegetation).

project, the South Asian Nitrogen Hub and the UNECE Task Force on Reactive Nitrogen *(32)*.[3] Another example is the Clean Air Farming project, co-financed by the European Commission's LIFE-Programme. This has considered methods and their harmonization for the reduction of methane and ammonia; the necessary political framework conditions and incentives; and how food companies can set effective and verifiable criteria on ammonia and methane for suppliers and certified companies *(33)*. National projects are also important in showing effective strategies in minimizing the adverse health impacts and inequalities of air pollution from agricultural sources. For example, in the United Kingdom of Great Britain and Northern Ireland: AMPHoRA (Assessing Mitigation Pathways to Realise Public Health Benefits of Air Pollutant Emission Reductions from Agriculture)[4] *(34)* and AIM-HEALTH: Effectiveness of agricultural interventions to minimise the health impacts of air pollution.[5]

Box 1. The impact of emissions from sugarcane burning: reflections on integrated policies

In 2002 in São Paulo State, Brazil, law n. 11.24/2002 amended by law 47.700/ *(35)* specifically changed the regulation of sugarcane burning (of the leaf growth to facilitate cutting of the canes). The law set a gradual schedule for the elimination of sugarcane straw burning pre harvest. It required areas where mechanical harvesting is possible to cease burning by 2021 and for more difficult non-mechanized areas (with steeper inclines – slopes > 12%) to eliminate burning by 2031. At the time the law was adopted sugarcane was grown over 2.5 million ha – almost entirely subject to burning.

In 2003, flex fuel cars entered the Brazilian consumer market causing a dramatic expansion of sugarcane growing for ethanol production, to cover nearly 4 million ha in 2008 *(36),* and today the crop covers almost 5 million ha in São Paulo State. The private sector invested massively in mechanization making the impact of the legislation very effective. In 2007, the private sector (signatories represented 90% of the sugarcane production) signed a "green protocol" (*Protocolo agroambiental etanol verde*)[6] for a voluntary accelerated phase-out of burning, setting 2014 as the target year for the end of pre harvest burning for farmland with slopes ≤ 12% and 2017 for non-mechanizable areas. Satellite monitoring showed that the area harvested without straw burning was already about 50% in areas easily mechanized (most of the total) and even 30% in small areas (< 120 000 ha) with slopes > 12% *(36)*. Between 2006 and 2014, the burned sugarcane in São Paulo State decreased from 66% to just 10% of the whole harvested area *(37)*.

In mid-2022, after 15 years of the voluntary protocol, 99% of the area was unburned, avoiding the emission of more than 70 million tonnes of atmospheric pollutants, such as carbon monoxide, PM and hydrocarbons, according to the São Paulo State Environmental Company (CETESB).

Way forward

Key mitigation measures can reduce the various sources of air pollutants across agriculture and food systems. Each measure should be targeted at the main source of air pollution.

[3] Information on the Convention on Long-Range Transboundary Air Pollution (https://www.clrtap-tfrn.org/ and https://digitallibrary.un.org/record/447281/?ln=en&v=pdf).
[4] Information on AMPHoRA (https://www.ceh.ac.uk/our-science/projects/amphora).
[5] Information on AIM-HEALTH (https://fundingawards.nihr.ac.uk/award/NIHR129449).
[6] Information on Protocolo agroambiental (https://unica.com.br/iniciativas/protocolo-agroambiental/).

Burning is not the most effective way to clear land and prepare it for new planting. Burning makes a substantial contribution to air pollution with consequent high health and social costs. Additionally, it reduces water retention and soil fertility by 25–30%, and requires farmers to invest in expensive fertilizers and irrigation systems to compensate *(38)*. Education plays an important role in raising awareness of the opportunities resulting from changing the way harvest residues are treated *(13)*.

Relatively few studies provide estimates for the potential reduction of $PM_{2.5}$-related mortality in relation to on-farm interventions. However, a potential reduction in the United States by 50% is expected if a series of on-farm interventions are implemented. These interventions include improved livestock waste management and fertilizer application practices that reduce emissions of ammonia, and improved crop and animal production practices that reduce primary $PM_{2.5}$ emissions from tillage, field burning, livestock dust and machinery *(21)*. Improving nitrogen use efficiency in crop and livestock production and increasing crop-livestock integration can significantly decrease ammonia and nitrous oxide emissions and nutrient losses. Dietary shifts, such as vegetarian, vegan or flexitarian diets, toward more plant-based foods that maintain protein intake and other nutritional needs, or even substituting red meat for poultry, could reduce agricultural air pollution-related premature mortality *(39)* and reduce air and climate pollutants from the livestock sector. The estimates in reduction for mortality in the United States range between 68% and 83% *(21)*. "In sum, improved livestock and fertilization practices, and dietary shifts could greatly decrease the health impacts of agriculture caused by its contribution to reduced air quality" *(21)*. In Africa, 43 000 premature deaths are related to biomass burning, mainly driven by agriculture *(40)*.

Potential solutions and strategic measures to support a more sustainable and less polluting agriculture sector are available and effective *(41–43)*. Due past policy failure in this area, it is important to identify specific on-farm mitigation measures towards which farmers are positive in order to improve uptake rates *(44)*. Agricultural waste is generated by various processes: crop residues (harvest) waste, manure and other wastes from farms, poultry houses and slaughterhouses, fertilizer run-off from fields, pesticides that enter into water, air or soils, and salt and silt drained from fields *(45)*. "The solution to crop residue burning lies in the effective implementation of sustainable management practices with Government interventions and policies. […] The agricultural waste sector can benefit immensely from some of the examples from other waste sectors such as municipal solid waste and wastewater management where collection, segregation, recycling and disposal are institutionalized to secure an operational system" *(42)*.

According to Burden of Disease estimates, agriculture/food systems are linked to at least four of the top 10 health risks: air pollution, dietary health risks, high body mass index and malnutrition. There is a great opportunity to identify strategies in agrifood systems which simultaneously target multiple risks. An international agenda to develop suggestions and interventions is required.

International organizations including the World Health Organization (WHO) and Food and Agriculture Organization (FAO)

- **Develop an international agenda on the health impacts of air pollution related to agriculture:**
  - FAO is collaborating with the Climate and Clean Air Coalition on two new assessments: nitrous oxide (all sectors, though agriculture accounts for > 75%) due at COP29; and methane from agrifood systems (due at COP30) *(46)*.

- WHO is assessing the impacts of air pollution due to specific sectors on health.

- **Foster the One Health vision:**
  - Adopt an integrated, unifying approach to balance and optimize the health of people, animals and the environment *(47)*, implementing biodiversity protection policies *(48).*
- **Circulate new methodologies to report short-lived climate forcers (usually also SLCPs):**
  - The Intergovernmental Panel on Climate Change is leading activities concerning ammonia, black carbon, carbon monoxide, hydrogen, nitrogen oxides, non-methane volatile organic compounds, organic carbon and sulfur dioxide. Volume 4 is dedicated to agriculture, forestry and other land uses.
- **Ensure policy-makers benefit from international processes and initiatives:**
  - The International Nitrogen Management System (INMS) provides global scientific support for international nitrogen policy development.[7]
  - The South Asian Nitrogen Hub was instrumental in getting nitrogen waste into the United Nations Environment Assembly (UNEA) 5.2 resolution.[8]
  - The UNECE Framework Code for Good Agricultural Practice to reduce Ammonia has mapped out several measures and their effectiveness.

Member States

- **Acknowledge the health and economic benefits from reducing agricultural air pollution.**
- **Establish/expand air quality monitoring networks:**
  - High-resolution information on rural air quality is needed, especially in hot spots such as the Indo-Gangetic Plain.
  - Create centralized platforms for information on low-cost interventions to reduce agricultural emissions.
- **Support implementation of sustainable agricultural practices (both in crop and livestock systems):**
  - Reduce direct emissions of particles from agricultural machinery and associated motor vehicles.
  - Limit the dispersion of harmful chemicals that affect the health and well-being of rural populations.
  - Stop burning of crops, which impacts local and regional populations.
  - Implement sustainable management of synthetic fertilizers, while promoting the use of organic fertilizers to recycle nutrients and prevent nutrient losses.
- **Develop a series of case studies for increasing awareness and disseminating information on local solutions.**
- **Increase intersectoral cooperation especially between agriculture, environment and health ministries.**

Research community

- **Increase research on the impacts of air pollution from agriculture and policies and interventions to limit them:**

[7] Information on INMS (https://www.inms.international/inms-process-and-supporting-projects).
[8] In March 2022, the UNEA adopted a second resolution on sustainable nitrogen management (resolution 5/2), encouraging Member States to accelerate actions to significantly reduce nitrogen waste globally by 2030 through improved sustainable management and to share information on national action plans. Information on the resolution (https://www.unep.org/nitrogen-management-WG#:~:text=In%20March%202022%2C%20the%20resumed,nitrogen%20management%20and%20to%20share).

- Gather data from rural cohort studies.
- Generate knowledge on the significant impact of air pollution on animals.

Medical community

- **Increase public health sector focus:**
  - Consider the health effects on various populations, including in the workplace.
  - Increase rural health surveillance capacities for air quality and climate-related health effects.

Methodology for content development

WHO defined the scope of the document and prepared the initial draft based on an overview of agriculture-related air pollution and health impacts, supplemented by expert advice. This consisted of exploring the most recent evidence and selecting key documents as a reference for the development of the SPS, prioritizing systematic reviews and metanalysis.

Significant contributions were provided by experts on the field, from various research institutes, universities, and UN agencies, including its Global Air Pollution and Health – Technical Advisory Group (GAPH-TAG) members.

The draft underwent peer review by a group of experts, including a member from the WHO Scientific Advisory Group on Air Pollution and Health (SAG), and a member of a WHO Collaborating Center, which cover a wide range of expertise. Additionally, an early version of the document was presented for peer-review at the Technical Advisory Group and Scientific Advisory Group on Air Pollution and Health meeting.

Feedback was addressed by the main contributors. Finally, WHO staff from the WHO Air Quality, Energy and Health Unit reviewed the report to ensure alignment with the WHO requirements for the collections of WHO Air Quality, Energy and Health Science and Policy Summaries. This series synthesizes current knowledge and evidence on air quality, energy access, climate change links and health, primarily to inform intergovernmental discussions.

Acknowledgements

The WHO gratefully acknowledges the many individuals and organizations, including those from GAPH-TAG and SAG, and its Collaborating Centres, who contributed to the development of this document.

This document was written by Pierpaolo Mudu (WHO Department of Environment, Climate Change and Health), with support from Martial Bernoux, Flavia Casu, Aimable Uwizeye (FAO, Rome, Italy); Gregor Kiesewetter (International Institute for Applied Systems Analysis, Austria. GAPH-TAG member); Chris Malley (Stockholm Environment Institute, Sweden. GAPH-TAG member); Stefan Reis (Deutsches Zentrum für Luft- und Raumfahrt, Germany); Eri Saikawa (Emory University, United States) and Lidwien Smit (Utrecht University, the Kingdom of the Netherlands).

Technical inputs and review were provided by Kalpana Balakrishnan (Sri Ramachandra Institute of Higher Education and Research, Chennai, India. Member of WHO Collaborating Center) and Annette Peters (Helmholtz Munich, Germany. SAG member).

Additionally, an early version of this document was presented for peer-review at the Technical Advisory Group and Scientific Advisory Group on Air Pollution and Health meeting in Beijing, China, in October 2024.

Declarations of interest

All external experts submitted a declaration of interest to WHO disclosing potential conflicts of interest that might affect, or might reasonably be perceived to affect, their objectivity and independence in relation to the subject matter of the report. WHO reviewed each of the declarations and concluded that none could give rise to a potential or reasonably perceived conflict of interest related to the subjects covered by the report.

References[9]

1. Feng T, Sun Y, Shi Y, Ma J, Feng C, Chen Z. Air pollution control policies and impacts: a review. Renew Sust Energ Rev. 2024;191:114071. DOI: 10.1016/j.rser.2023.114071.
2. Giannadaki D, Giannakis E, Pozzer A, Lelieveld J. Estimating health and economic benefits of reductions in air pollution from agriculture. Sci Total Environ. 2018;622:1304-1316. DOI: 10.1016/j.scitotenv.2017.12.064.
3. Bist RB, Subedi S, Chai L. Yang X. Ammonia emissions, impacts, and mitigation strategies for poultry production: a critical review. J Environ Manage. 2023;328:116919. DOI: 10.1016/j.jenvman.2022.116919.
4. Gu B, Zhang L, Van Dingenen R, Vieno M, Van Grinsven HJ, Zhang X et al. Abating ammonia is more cost-effective than nitrogen oxides for mitigating PM2. 5 air pollution. Science. 2021;374(6568):758-762. DOI: 10.1126/science.abf8623.
5. Wyer KE, Kelleghan DB, Blanes-Vidal V, Schauberger G, Curran TP. Ammonia emissions from agriculture and their contribution to fine particulate matter: a review of implications for human health. J Environ Manage. 2022;323:116285. DOI: 10.1016/j.jenvman.2022.116285.
6. Lin M, Begho T. Crop residue burning in South Asia: a review of the scale, effect, and solutions with a focus on reducing reactive nitrogen losses. J Environ Manage. 2022;314:115104. DOI: 10.1016/j.jenvman.2022.115104.
7. Deshpande MV, Kumar N, Pillai D, Krishna VV, Jain M. Greenhouse gas emissions from agricultural residue burning have increased by 75% since 2011 across India. Sci Total Environ. 2023;904:166944. DOI: 10.1016/j.scitotenv.2023.166944.
8. European Union emission inventory report 1990-2021. EEA Report 04/2023. Copenhagen: European Environment Agency; 2023 (https://www.eea.europa.eu/en/analysis/publications/european-union-emissions-inventory-report-1990-2021).
9. EEA Greenhouse gases — data viewer. Copenhagen: European Environment Agency; 2024 (https://www.eea.europa.eu/data-and-maps/data/data-viewers/greenhouse-gases-viewer).
10. Short-lived climate pollutants and food security. Climate & Clean Air Coalition; 2021 (https://www.ccacoalition.org/content/short-lived-climate-pollutants-and-food-security).
11. Air quality in Europe 2022. Sources and emissions of air pollutants in Europe. Copenhagen: European Environment Agency; 2022 (https://www.eea.europa.eu/publications/air-quality-in-europe-2022/sources-and-emissions-of-air).
12. Bikkina S, Andersson A, Kirillova EN, Holmstrand H, Tiwari S, Srivastava AK et al. Air quality in megacity Delhi affected by countryside biomass burning. Nat Sustain. 2019;2(3):200-205. DOI: 10.1038/s41893-019-0219-0.

[9] Accessed 10 February 2025.

13. Remote sensing for space-time mapping of smog in Punjab and identification of the underlying causes using geographic information system (R-SMOG). Islamabad: Food and Agriculture Organization; 2020 (https://doi.org/10.4060/ca6989en).
14. WHO global air quality guidelines. Particulate matter (PM2.5 and PM10), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide. Geneva: World Health Organization; 2021 (https://iris.who.int/handle/10665/345329). Licence: CC BY-NC-SA 3.0 IGO.
15. Brunekreef B, Harrison RM, Künzli N, Querol X, Sutton MA, Heederik DJ et al. Reducing the health effect of particles from agriculture. Lancet Respir Med. 2015;3(11):831-832. DOI: 10.1016/S2213-2600(15)00413-0.
16. Naseem S, King AJ. Ammonia production in poultry houses can affect health of humans, birds, and the environment – techniques for its reduction during poultry production. Environ Sci Pollut Res Int. 2018;(25):15269-15293. DOI: 10.1007/s11356-018-2018-y.
17. Chakrabarti S, Khan MT, Kishore A, Roy D, Scott SP. Risk of acute respiratory infection from crop burning in India: estimating disease burden and economic welfare from satellite and national health survey data for 250 000 persons. Int J Epidemiol. 2019;48(4):1113-1124. DOI: 10.1093/ije/dyz022.
18. Cançado JE, Saldiva PH, Pereira LA, Lara LB, Artaxo P, Martinelli LA et al. The impact of sugar cane-burning emissions on the respiratory system of children and the elderly. Environ Health Perspect. 2006;114(5):725-729. DOI: 10.1289/ehp.8485.
19. Karanasiou A, Alastuey A, Amato F, Renzi M, Stafoggia M, Tobias A et al. Short-term health effects from outdoor exposure to biomass burning emissions: a review. Sci Total Environ. 2021;781:146739. DOI: 10.1016/j.scitotenv.2021.146739.
20. Khomenko S, Pisoni E, Thunis P, Bessagnet B, Cirach M, Iungman T et al. Spatial and sector-specific contributions of emissions to ambient air pollution and mortality in European cities: a health impact assessment. Lancet Public Health. 2013;8(7):e546-e558. DOI: 10.1016/S2468-2667(23)00106-8.
21. Domingo NG, Balasubramanian S, Thakrar SK, Clark MA, Adams PJ, Marshall JD et al. Air quality-related health damages of food. Proc Natl Acad Sci U S A. 2021;118(20):e2013637118. DOI: 10.1073/pnas.2013637118.
22. Lan R, Eastham SD, Liu T, Norford LK, Barrett SR. Air quality impacts of crop residue burning in India and mitigation alternatives. Nat Commun. 2022;13(1):6537. DOI: 10.1038/s41467-022-34093-z.
23. Malley CS, Hicks WK, Kulyenstierna JC, Michalopoulou E, Molotoks A, Slater J et al. Integrated assessment of global climate, air pollution, and dietary, malnutrition and obesity health impacts of food production and consumption between 2014 and 2018. Environ Res Commun. 2021;3(7):075001. DOI: 10.1088/2515-7620/ac0af9.
24. Rahal A, Ahmad AH, Prakash A, Mandil R, Kumar AT. Environmental attributes to respiratory diseases of small ruminants. Vet Med Int. 2014;(1):853627. DOI: 10.1155/2014/853627.
25. Ni JQ, Erasmus MA, Croney CC, Li C, Li Y. A critical review of advancement in scientific research on food animal welfare-related air pollution. J Hazard Mater. 2021;408:124468. DOI: 10.1016/j.jhazmat.2020.124468.
26. Lobell DB, Di Tommaso S, Burney JA. Globally ubiquitous negative effects of nitrogen dioxide on crop growth. Sci Adv. 2022;8(22):eabm9909. DOI: 10.1126/sciadv.abm9909.
27. Schauberger B, Rolinski S, Schaphoff S, Müller C. Global historical soybean and wheat yield loss estimates from ozone pollution considering water and temperature as modifying effects. Agric For Meteorol. 2019;265:1-15. DOI: 10.1016/j.agrformet.2018.11.004.
28. Sillmann J, Aunan K, Emberson L, Büker P, Van Oort B, O'Neill C. Combined impacts of climate and air pollution on human health and agricultural productivity. Environ Res Lett. 2021;16(9):093004 (https://doi.org/10.1088/1748-9326/ac1df8).
29. Balasubramanian S, Domingo NG, Hunt ND, Gittlin M, Colgan KK, Marshall JD et al. The food we eat, the air we breathe: a review of the fine particulate matter-induced air quality health

impacts of the global food system. Environ Res Lett. 2021;16(10):103004. DOI: 10.1088/1748-9326/ac065f.
30. Agricultural outlook: how limiting air pollution will protect farms. 18 June 2019. Leuven: EIT Food; 2019 (https://www.eitfood.eu/blog/agricultural-outlook-how-limiting-air-pollution-will-protect-farms).
31. Short-lived climate pollutants. Climate & Clean Air Coalition; 2024 (https://www.ccacoalition.org/content/short-lived-climate-pollutants).
32. Sutton MA, Howard CM, Mason KE, Brownlie WJ, Cordovil CMdS. Nitrogen opportunities for agriculture, food & environment. UNECE guidance document on integrated sustainable nitrogen management. Edinburgh: UK Centre for Ecology & Hydrology; 2022 (https://nora.nerc.ac.uk/id/eprint/534033).
33. Final report. LIFE project number LIFE17 GIE/DE/000610. Brussels: Clean Air Farming; 2022 (https://www.clean-air-farming.eu/downloads-und-links?tx_downloads_download%5Baction%5D=show&tx_downloads_download%5Bcontroller%5D=Download&tx_downloads_download%5Bitem%5D=139&cHash=7df73207ee765afa1a848aa38cd835e8).
34. Pastorino S, Milojevic A, Green R, Beck R, Carnell E, Colombo PE et al. Health impact of policies to reduce agriculture-related air pollutants in the UK: the relative contribution of change in $PM_{2.5}$ exposure and diets to morbidity and mortality. Environ Res. 2024;262:119923. DOI: 10.1016/j.envres.2024.119923.
35. Assambleia Legislativa Do Estado de São Paulo. Decreto N.47.700, de 11 de março de 2003 (https://www.al.sp.gov.br/repositorio/legislacao/decreto/2003/decreto-47700-11.03.2003.html).
36. Rudorff BFT, Aguiar DA, Silva WF, Sugawara LM, Adami M, Moreira MA. Studies on the rapid expansion of sugarcane for ethanol production in São Paulo State (Brazil) using Landsat data. Remote Sens. 2010;2(4):1057-1076. DOI: 10.3390/rs2041057.
37. Baccarin JG, de Oliveira JA, Mardegan GE. The environmental, social and economic effects of recent technological changes in sugarcane on the State of São Paulo, Brazil. J Agrar Change. 2020;20(4):598-617. DOI: 10.1111/joac.12384.
38. Toxic blaze: the true cost of crop burning. Nairobi: United Nations Environment Programme; 2021 (https://www.unep.org/news-and-stories/story/toxic-blaze-true-cost-crop-burning).
39. Himics M, Giannakis E, Kushta J, Hristov J, Sahoo A, Perez-Dominguez I. Co-benefits of a flexitarian diet for air quality and human health in Europe. Ecol Econ. 2022;191:107232. DOI: 10.1016/j.ecolecon.2021.107232.
40. Bauer SE, Im U, Mezuman K, Gao CY. Desert dust, industrialization, and agricultural fires: health impacts of outdoor air pollution in Africa. J Geophys Res Atmos. 2019;124(7):4104-4120. DOI: 10.1029/2018JD029336.
41. Bhattacharyya P, Bisen J, Bhaduri D, Priyadarsini S, Munda S, Chakraborti M et al. Turn the wheel from waste to wealth: economic and environmental gain of sustainable rice straw management practices over field burning in reference to India. Sci Total Environ. 2021;775:145896. DOI: 10.1016/J.SCITOTENV.2021.145896.
42. Bhuvaneshwari S, Hettiarachchi H, Meegoda JN. Crop residue burning in India: policy challenges and potential solutions. Int J Environ Res Public Health. 2019;16(5):832. DOI: 10.3390/ijerph16050832.
43. Review of interventions to improve outdoor air quality and public health. London: Public Health England; 2019 (https://assets.publishing.service.gov.uk/media/5fbf93258fa8f559dbb1add9/Review_of_interventions_to_improve_air_quality_March-2019-2018572.pdf).
44. Collins AL, Zhang YS, Winter M, Inman A, Jones JI, Johnes PJ, et al. Tackling agricultural diffuse pollution: what might uptake of farmer-preferred measures deliver for emissions to water and air? Sci Total Environ. 2016;547:269-281. DOI: 10.1016/j.scitotenv.2015.12.130.

45. Nagendran R. Agricultural waste and pollution. In: Letcher TM, Vallero DA, editors. Waste. Amsterdam: Elsevier; 2011:341-355. DOI: 10.1016/B978-0-12-381475-3.10024-5.
46. IPCC scoping meeting for a methodology report on short-lived climate forcers (SLCFs). Report of the IPCC Scoping Meeting 26–28 February 2024, Brisbane, Australia. IGES, Japan; 2024 (https://www.ipcc.ch/site/assets/uploads/2024/04/IPCC_SLCF_ScopingMeetingReport.pdf).
47. One Health joint plan of action (2022–2026): working together for the health of humans, animals, plants and the environment. World Health Organization, Food and Agriculture Organization of the United Nations, World Organisation for Animal Health and United Nations Environment Programme. Geneva: World Health Organization; 2022 (https://iris.who.int/handle/10665/363518). Licence: CC BY-NC-SA 3.0 IGO.
48. Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Bonn: IPBES Secretariat; 2019 (https://files.ipbes.net/ipbes-web-prod-public-files/inline/files/ipbes_global_assessment_report_summary_for_policymakers.pdf).

WHO Air Quality, Energy and Health Science and Policy Summaries

Open waste burning – sectoral solutions for air pollution and health

Technical brief

Key messages

Reducing open waste burning is essential for achieving clean air, clean energy access, climate change mitigation and health and well-being. Globally, over 2 billion tonnes of waste are produced annually. Household waste usually comprises a variety of materials including glass, plastics, metals, cardboard, paper, polystyrene, and organic matter such as food and garden waste. Infrequently, demolition waste, household chemicals or tyres may be included. Open waste burning may occur at major landfills, small or remote dumpsites, individual households or in streets. Emissions from open waste burning include various air pollutants, some of which may have more harmful climate and health impacts. Short- and long-term exposure to these pollutants result in adverse health effects such as coughing, dermatological symptoms, respiratory diseases and other health outcomes.

Some household waste is collected and managed appropriately while uncollected waste is often burned, especially in low- and middle-income countries (LMICs), but also in rural areas regardless of country income. Waste burned at the household level is usually due to a non-existent or poor municipal solid waste collection and waste management system. This is often the case in informal settlements and rural areas where the return on investment in collection facilities is poor. To compound this issue there may be a lack of awareness of the associated adverse health impacts as well as embedded cultural practices. Other reasons behind burning refuse, particularly in LMICs, may be to support livelihoods such as retrieval of metals from electrical items or to generate heat for food preparation or warmth, especially in regions with poor access to clean energy solutions.

Short- to medium-term priority actions for resolving the impacts of waste burning include:

- Applying reduce, reuse and recycle principles:
  - Encourage household separation and effective recovery and recycling of separated materials.
  - Generate accessible recycling opportunities.
  - Send waste for recovery rather than disposal, e.g. solvents.
  - Compost biodegradable wastes.
- Addressing the role of waste pickers and waste separators.
- Adopting consistent, effective waste removal and management and dispose of waste at authorized landfill sites.

Priority actions for long-term impacts are more difficult to address, but include:

- Applying a systemic transformation to waste management using an integrated solid waste management system especially in urban areas where populations are growing rapidly and exposure is therefore highest. This starts with implementing waste minimization strategies and improving data on waste composition at local and national levels to create a waste management information system to inform policy changes and support improved landfill management for existing sites.
- Implementing strong regulations and surveillance to prevent dumping and burning of waste.

- Investing in community-based good practices and behavioural changes for waste handling methods, particularly for households and waste pickers, could support adopting and promoting a circular economy approach, which directs refuse away from landfill sites. This could include creating decentralized, locally led, waste separation initiatives with economic or societal incentives for segregation of waste (see the waste exchanged for food programme in Brazil). However, these activities should be done in a safe way.
- Getting buy-in from larger companies, which could result in implementing packaging alternatives, including going plastic-free.

Overview

Open waste burning and its health impacts

Over 2 billion tonnes of waste are generated globally each year *(1).* In 2012, the estimated amount of waste generated in lower income countries was 0.6 kg/capita/day; in high-income countries it was 2.1 kg/capita/day *(2).* Due to the heterogeneous nature of household waste, the emissions from burning it differ in composition *(3).* This makes it difficult to accurately quantify pollutants emitted during waste burning. The management of domestic waste differs greatly depending on region and, most importantly, country income level.

Box 1. SDG 11: Sustainable Cities and Communities Indicator 11.6.1

Not all countries have data on municipal solid waste generation per capita. For those lacking data, a household survey method can be used to determine the daily waste generation. Bin liners are distributed with the survey and a household's 7 days of waste is collected in the bin liner and weighed. Such a survey should evaluate the waste generation habits of households from differing income levels. The survey should be repeated seasonally (or, at a minimum, twice a year).

Although 77% of global waste is collected, 33% is waste still openly dumped. In LMICs only 40% of generated waste is collected, 93% of which is dumped or openly burned *(1).* Moreover, without active surveillance it is not clear how often and how many households burn their waste. There are serious concerns regarding the volume of waste which is either unmanaged (no formal waste management service) or mismanaged (dumped or burned), particularly in LMICs. Evidence from Africa and Asia suggests thousands of premature deaths are linked to biomass burning, mainly driven by agriculture. In Lagos, Nigeria, more than 50% of pollution emissions come from open burning, including the burning of waste, emphasizing how critical it is to consider waste burning when doing source apportionment studies *(4).*

See SPS[1] *Agriculture – sectoral solutions for air pollution and health*

Air pollutants and their health effects

Open waste burning, a common waste management practice, is a significant contributor to air pollution worldwide**.** This practice releases air contaminants which include particulate matter ($PM_{2.5}$ and PM_{10}), black carbon, carbon monoxide, nitrogen dioxide, sulfur dioxide, carbon dioxide (CO_2) as well as toxic compounds, such as heavy metals (e.g. lead), polychlorinated and polybrominated dioxins and furans, and polycyclic aromatic hydrocarbons *(5).* It has been estimated that the climate impact of black carbon emitted from open burning of waste is equivalent to 2–10% of global CO_2eq emissions *(6).* These pollutants may result in acute health effects including eye and nose irritation, difficulty

[1] Science and Policy Summary

breathing, coughing and headaches, as well as respiratory infections. Long-term exposure to these pollutants has been linked to increased risk of adverse birth or neonatal outcomes, such as low birth weight, and increased risk of mortality and mental health conditions associated with living near landfills or incinerators *(7).* There is also mixed evidence on other health outcomes, for example, cardiovascular diseases and gastroenteritis *(7).* A 2016 study estimated that Approximately 270 000 deaths (95% CI: 213 000–328 000) each year are attributed to $PM_{2.5}$ from waste burning *(8).*

Solid waste incinerators are known contributors to air pollution given their toxic emissions via chimney stacks *(9).* Incinerators are also used to burn medical waste, and it is important to use controlled facilities with filters and scrubbers fitted to smokestacks to reduce harmful emissions and for hospitals to follow national regulations *(10).* In resource-constrained countries, proper segregation of hazardous health care waste coupled with training in waste handling can reduce disposal costs, toxic emissions and accidental injury/infection *(11).* Moving towards environmentally sustainable health care facilities would include phasing out of incineration of medical waste and implementation of non-burn technologies. While systematic reviews show significant risks from waste incineration as a form of waste management *(9)*; here we focus on open waste burning, where smoke and emissions are released directly into the air, and not via chimney stacks.

Regulations for open waste burning

Waste burning may not always be considered an illegal activity. Furthermore, even when it is considered illegal at the municipal level, it may not be prohibited at the national level. It is important to note that not all countries have laws or policies prohibiting the open combustion of refuse in private or public spaces, and even when such policies exist, they are often not enforced. A 2021 a United Nations Environment Programme report found that 94 countries (43 more than in 2016) regulate waste burning, but only 38 of these countries have strict regulations in place *(12).* However, open waste burning produces toxic air pollutants even if it is legal; and the legality of waste burning may not be a primary consideration in communities that do not have access to waste management services. Open dumps/landfills can catch fire and be extremely difficult to extinguish. They are also known to attract pests which spread disease.

Currently, there are fundamental barriers to sustainable waste management, including insufficient regulations and enforcement for waste management, inconsistent (and frequently non-existent) formal waste removal, lack of access to finance and knowledge or replicable circular economic models, and an informal economy based on the burning and destruction of waste products (e.g. extraction of metals, production of wood charcoal and ash). Population growth and the consequent increased volumes of waste compound the problems caused by inadequate waste management and recycling infrastructure. Enablers to promote immediate improvements in waste management include increasing awareness of the health impacts associated with open waste burning and systematic and consistent formalized waste removal. Raising awareness alone cannot be effective if feasible alternative solutions for cooking, heating and lighting are not available. In addition, legal enforcements such as penalties for open waste burning should be implemented if waste burning is illegal.

Box 2. Successful factors in reducing waste from Rwanda

In 2008, Rwanda banned single-use plastic bags and bottles and this led to cleaner cities (e.g. Kigali). What were some of the contributing success factors?

- Government commitment and implementation of littering fines.
- Privatized home-based waste collection of separated waste.
- *Umuganda* (communities come together) programme, where all adults participate in community service once a month.
- Showcasing of Rwanda for its environmental leadership *(13).*

Considerations for social and environmental equity

In LMICs, poor planning laws and rapid urban migration lead to informal settlements with no waste collection or clean fuel access. Developing and implementing integrated waste management systems with the inclusion of informal waste collectors will empower communities to hold themselves and service providers accountable for waste removal. Similarly, providing communities with information on the health impacts of open waste burning will promote agency and healthier lifestyle choices. These changes need to occur in conjunction with education about and infrastructure for alternative waste management practices, such as the use of biodigesters for generating biogas as a sustainable energy source as well as offering alternatives for clean household cooking, heating and lighting.

In countries where resources are limited, the "polluter pays" principle, i.e. the need for polluters to contribute to the full cost of waste management, from collection to disposal, as well as of environmental externalities and their associated costs, can aid a model of production and consumption that involves sharing, leasing, reusing, repairing, refurbishing and recycling existing materials and products similar to a circular economy *(14).*

Success stories of effective waste management approaches

Multipronged approach to increase waste collection and management in Tonga
Before 2018 in Tonga, due to irregular waste collection, many households did not pay the required monthly fee and resorted to unsustainable methods such as burning or openly dumping their waste. To address this, several approaches were adopted to encourage households to resume payment for municipal waste collection and raise fee recovery rates. Key measures included:

- **Redesigned fee collection system:** Incorporation of waste removal fees into residents' utility bills allowed for greater surveillance of payment compliance, which, in turn, enabled improved enforcement as full payment was required to avoid disconnection. The collected revenues were channelled toward operational costs and improving service delivery, which encouraged customers to continue payments.
- **Multimedia communication campaign:** Focusing on schools, communities and businesses, educational workshops provided information on the importance of sustainable waste collection, disposal and treatment.
- **Enforcement:** Waste burning was discouraged by conducting active surveillance, with police and environmental officers issuing warnings and in-person visits to offenders.
- **Stakeholder engagement:** Engaging respected cultural, religious and government leaders to gain community support *(15).*

Waste exchanged for food programme in Brazil
In Curitiba, Brazil, traditional waste collection was inaccessible to lower income communities, causing improper waste disposal and health issues. The 1991 Green Exchange Program (Câmbio Verde) allowed citizens to trade recyclable waste for fresh produce, benefiting farmers and ensuring food security. Through the programme, 4 kg of recyclables or 4 L of used oil can be exchanged for 1 kg of fruit and vegetables. Recyclables are processed at recovery facilities, and waste pickers are integrated into the system with better conditions and training. A communication campaign using mascots and educational materials promoted waste separation. The initiatives diverted roughly 70% of recyclables from landfill. The programme costs were lower than for private waste collection, and food security and income for waste pickers increased. The programme has been expanded to other municipalities in Brazil *(16).*

Way forward

Managing open waste burning is important for both environmental and public health protection and requires comprehensive policies from governments worldwide. In centralized waste burning facilities, where waste aggregated from a community is burned together, governments may wish to prioritize emissions standards and continuous monitoring to minimize risk from air pollutant exposure. Centralized waste inspections, where particularly hazardous waste products are removed from the stream to be processed separately, can further reduce harmful emissions. Additionally, increasing education and outreach to waste aggregators – in the formal and informal sectors – can be useful to reduce the flow of hazardous waste components that are delivered to burn sites.

Decentralized waste burning is also routinely encountered, where individuals or small groups burn waste informally. Governments should focus on education and awareness campaigns to promote alternative waste management practices like recycling and composting, and on making facilities convenient and economical. Providing subsidies or incentives for communities to adopt safer disposal methods can discourage open burning. Restricting or reducing the availability of materials commonly burned in decentralized sites, such as single-use plastic bags, may also be effective in reducing waste burning activities and the toxicity of emissions. Providing waste receptacles or bins together with waste removal will also reduce the use of plastic bags for waste disposal and/or dumping.

In both success stories, fostering partnerships with local communities, businesses and nongovernmental organizations is vital to implementing effective waste management policies, though reducing the waste stream should be prioritized. Governments may also consider the development of sustainable waste-to-energy technologies, which employ emissions control strategies to convert waste into useful energy. By doing so, governments can mitigate the harmful effects of open waste burning while promoting sustainable waste management practices across different scales of operation.

Manage the different factors leading to the burning of waste

Waste is burned for a variety of reasons (to generate heat, cook, retrieve metals and as a method of disposal). To address the issue of open waste burning adequately, it is essential to identify the factors causing it (such as no waste collection or the need to burn waste for heating or cooking). In some places while open waste burning has been banned, there is limited enforcement due to a lack of action on underlying structural issues.

Community engagement – critical to successful waste management programmes

The success stories from Brazil and Tonga highlight that policy must be anchored in and supported by community engagement and methods to encourage adherence. The success of transforming how waste is managed is reliant on the active engagement of the community.

Health professionals' role in mitigating open waste burning

Public health officials can support informed decision-making about the health implications of waste management projects by promoting the use of both standalone health impact assessments and integrated health assessments within environmental impact assessments *(17).* Health care and procurement staff should work together to minimize over-purchasing and prioritize waste prevention. They should also maximize the reuse and recycling of resources and divert waste from landfill or incineration where possible *(18).*

Raising awareness for sustained behavioural change

The long-term success and adherence to changes in policy can only be achieved by instituting behavioural change. Educational campaigns for adults and children will differ in tone but must communicate the same message, such as separation at source. Ensuring buy-in from the community by engaging local cultural, traditional, religious and political leaders is essential to successfully attain a culture of sustainability.

Moving forward

Any actions taken should be holistic in nature as the drivers of waste burning are so varied. Many informal settlements lack access to waste management services primarily as they do not have the income to pay for weekly waste collection and there is no state provision as the settlements are "unofficial". As a result, waste is openly discarded, littered or burned. To address such a challenge, exchange systems, as adopted in Brazil, are highly effective, collecting recyclable materials in exchange for food items. This barter system is particularly appropriate in LMICs where many residents have limited resources.

General principles to guide action on reducing waste generation include *(18,19)*:

- Endorse/support the circular economy approach.
- Endorse/support bans on single-use plastics and consumables.
- Implement consistent waste removal, including supporting safe implementation of the informal waste collection stream and banning international sale or movement of waste.
- Calculate the net economic benefits of replacing open burning with sustainable management.
- Understand public perceptions around waste burning, especially in LMICs, by engaging with communities to understand needs and perceptions around waste and waste management.
- Maintain stricter inventory control to mitigate potential expiration of consumable items by implementing a FEFO process (first expired, first out).

Methodology for country development

WHO defined the scope of the document and collaborated with a member of the WHO Global Air Pollution and Health – Technical Advisory Group (GAPH-TAG), which cover a wide range of expertise, and prepared the initial draft based on an overview of open waste burning and its health effects, supplemented by expert advice. This consisted of exploring the most recent evidence and selecting key documents as a reference for the development of the SPS, prioritizing systematic reviews and metanalysis.

The draft underwent peer review by GAPH-TAG members and specialists from various research institutes, universities, public organizations and UN agencies. Additionally, an early version of the document was presented for peer-review at the Technical Advisory Group and Scientific Advisory Group on Air Pollution and Health meeting. And feedback was addressed by the main contributors. Success stories were sourced from LMICs where the impact of waste burning is greatest.

Finally, WHO staff and consultants from the WHO Air Quality, Energy and Health Unit reviewed the report to ensure alignment with the WHO requirements for the collections of WHO Air Quality, Energy and Health Science and Policy Summaries. This series synthesizes current knowledge and evidence on air quality, energy access, climate change links and health, primarily to inform intergovernmental discussions.

Acknowledgements

The World Health Organization (WHO) gratefully acknowledges the many individuals and organizations, including those from its Advisory Groups (the Scientific Advisory Group on Air Pollution and Health, SAG; and the Global Air Pollution and Health – Technical Advisory Group, GAPH-TAG) and its Collaborating Centres who contributed to the development of this document.

This document was written by members of SAG and GAPH-TAG: Hanna Boogard, Pallavi Pant (Health Effects Institute, Boston, United States); Caradee Y Wright (South African Medical Research Council, South Africa); and Richard E Peltier (University of Massachusetts Amherst, United States). Also, by Thandi Kapwata, Danielle A Miller, Natasha Naidoo, Candice Webster (South African Medical Research Council, South Africa).

Peer reviewers included Jennifer Richmond-Bryant (North Carolina State University, United States. Member of GAPH-TAG); Jo Barnes (UWE Bristol, United Kingdom); Ranjit Dhiman (UNICEF); Charlie Fenn (Engineering X, London, United Kingdom); Francesco Forastiere (Imperial College London, United Kingdom); Raja Ram Pote Shrestha (WHO); and Heba Safi (WHO Regional Office for the Eastern Mediterranean).

An early version of this SPS was presented for peer-review at the Technical Advisory Group and Scientific Advisory Group on Air Pollution and Health meeting in Beijing, China, in October 2024.

The development of this document was led by Pierpaolo Mudu, and Kerolyn Shairsingh (WHO Department of Environment, Climate Change and Health) with inputs and review from Cristina Vert and Sophie Gumy (WHO Department of Environment, Climate Change and Health).

Declarations of interest

All external experts submitted a declaration of interest to WHO disclosing potential conflicts of interest that might affect, or might reasonably be perceived to affect, their objectivity and independence in relation to the subject matter of the report. WHO reviewed each of the declarations and concluded that none could give rise to a potential or reasonably perceived conflict of interest related to the subjects covered by the report.

References[2]

1. Kaza S, Yao LC, Bhada-Tata P; Van Woerden F. What a waste 2.0: a global snapshot of solid waste management to 2050. Washington, DC: World Bank; 2018 (https://hdl.handle.net/10986/30317). Licence: CC BY 3.0 IGO.
2. Hoornweg D. Bhada-Tata P. What a waste: a global review of solid waste management. Washington, DC: World Bank; 2012 (https://hdl.handle.net/10986/17388). Licence: CC BY 3.0 IGO.
3. Mebratu D, Mbandi A. Open burning of waste in Africa: challenges and opportunities. Engineering X; 2022 (https://engineeringx.raeng.org.uk/media/u4mnsto5/open-burning-final-report_1.pdf).
4. Supporting a breath of fresh air for Lagos. Washington, DC: World Bank; 2022 (https://blogs.worldbank.org/en/nasikiliza/supporting-breath-fresh-air-lagos).
5. Wiedinmyer C, Yokelson RJ, Gullett BK. Global emissions of trace gases, particulate matter, and hazardous air pollutants from open burning of domestic waste. Environ Sci Technol. 2014. 48(16):9523-9530 (https://doi.org/10.1021/es502250z).
6. Common vision – collective impact approach. International Waste Platform; 2024 (https://internationalwasteplatform.org/open-burning-awareness/).

[2] Accessed 2 December 2024.

7. Vinti G, Bauza V, Clasen T, Medlicott K, Tudor T, Zurbrügg C et al. Municipal solid waste management and adverse health outcomes: a systematic review. Int J Environ Res Public Health. 2021;18(8):4331 (https://doi.org/10.3390/ijerph18084331).
8. Kodros JK, Wiedinmyer C, Ford B, Cucinotta R, Gan R, Magzamen S et al. Global burden of mortalities due to chronic exposure to ambient $PM_{2.5}$ from open combustion of domestic waste. Environ Res Lett. 2016;11(12):124022 (https://iopscience.iop.org/article/10.1088/1748-9326/11/12/124022).
9. Tait PW, Brew J, Che A, Costanzo A, Danyluk A, Davis M et al. The health impacts of waste incineration: a systematic review. Aust NZ J Public Health. 2020;44(1):40-48 (https://doi.org/10.1111/1753-6405.12939).
10. Safe management of wastes from health-care activities. Geneva: World Health Organization; 2014 (https://www.who.int/publications/i/item/9789241548564).
11. Khan BA, Cheng L, Khan AA, Ahmed H. Healthcare waste management in Asian developing countries: a mini review. Waste Manag Res. 2019;37(9):863-875 (https://doi.org/10.1177/0734242X19857470).
12. Actions on air quality: a global summary of policies and programmes to reduce air pollution. Nairobi: United Nations Environment Programme; 2021 (https://www.unep.org/resources/report/actions-air-quality-global-summary-policies-and-programmes-reduce-air-pollution).
13. Umuganda: Rwanda's audacity of hope to end plastic pollution. Nairobi: United Nations Environment Programme; 2023 (https://www.undp.org/blog/umuganda-rwandas-audacity-hope-end-plastic-pollution).
14. Chapter 4. Solid waste. In: Compendium of WHO and other UN guidance in health and environment, 2024 update. Geneva: World Health Organization; 2024 (https://iris.who.int/handle/10665/378095). Licence: CC BY-NC-SA 3.0 IGO.
15. Solid waste management in the Pacific – Tonga country snapshot. Manila: Asian Development Bank; 2014 (https://www.adb.org/sites/default/files/publication/42660/solid-waste-management-tonga.pdf).
16. The Green Exchange Program, Curitiba: urban food policy snapshot. Hunter College New York City Food Policy Center; 2016 (https://www.nycfoodpolicy.org/green-exchange-program-curitiba-urban-food-policy-snapshot/).
17. Assessing the health impacts of waste management in the context of the circular economy. Copenhagen: WHO Regional Office for Europe; 2023 (https://iris.who.int/handle/10665/366667). Licence: CC BY-NC-SA 3.0 IGO.
18. Less waste, more health: a health professional's guide to reducing waste. London: Royal College of Physicians; 2018.
19. Global treaty to end plastics pollution. WWF; 2024 (https://www.worldwildlife.org/pages/global-plastics-treaty).

World Health Organization

WHO Air Quality, Energy and Health Science and Policy Summaries

Transport – sectoral solutions for air pollution and health

Technical brief

Key messages

Globally, transport ranks as an important source of air pollution and generates the fourth largest share of greenhouse gas (GHG) emissions. Further, while the growth of global GHG emissions in other sectors such as energy supply and industry are slowing down, those from transport remain unchanged.

Transport-related air pollution is a complex mixture of gases and particles resulting from motor vehicle emissions, both from exhaust and non-exhaust sources such as road dust or brake and tyre wear. Strong evidence links transport related air pollution (TRAP) to early death due to cardiovascular diseases, asthma in children and adults and other adverse health outcomes.

Although high-income countries (HICs) have generally reduced TRAP levels through stringent air quality regulations and technological advances, many low- and middle-income countries (LMICs) face rising TRAP levels due to rapid urbanization, population growth and the need for more regulatory frameworks. Evidence shows that both HICs and LMICs experience variability in outcomes, with some LMICs making significant progress and certain HICs still confronting localized TRAP challenges. Effective local action to reduce TRAP should adhere to key principles: adopting a holistic approach to transport and mobility, prioritizing interventions that minimize emissions at their source, and seeking opportunities for co-benefits that enhance overall health and well-being.

Some interventions involving behavioural changes such as shifting commuting modes toward public and active transport improve air quality and have health and climate co-benefits through increased physical activity by walking and cycling, increased road safety, enhanced local greening or residential conditions. Other non-technological measures include traffic restrictions, speed limit reductions, road pricing, pricing of fuels and congestion charging. Technical measures, such as improvements in fuel and vehicular emission-control technologies, remain important.

Overview

Transport-related air pollution and its health effects

Transport-related air pollution remains a significant risk for poor health across the globe, particularly in urban areas and for those who live, work or play near busy roadways *(1).* High exposures to TRAP occur not only in vehicles, but also in transit (e.g. walking, cycling), especially on major roads during rush hours. While this brief focuses on air quality and health from road transport, it is important to note that many other transport modes, including shipping, aviation, rail and non-road vehicles (e.g. agricultural equipment) can adversely impact health and air quality (see Box 1). In some instances, data are reported by national authorities or academia and may not represent World Health Organization's (WHO) official statistics.

See SPS[1] *Agriculture – sectoral solutions for air pollution and health*

[1] Science and Policy Summary

The transport sector accounts for about one fifth of global emissions of fine particulate matter (PM) *(2).* It also generates roughly 15% of total GHG emissions and about 23% of global energy-related carbon dioxide (CO_2) emissions *(3,4).* Motor vehicles, such as heavy and light-duty trucks, buses, passenger cars and motorcycles produce a complex mixture of tailpipe (i.e. engine exhaust) and non-tailpipe pollutants (e.g. brake wear) emissions. Vehicle emissions can be both primary (i.e. produced by the vehicle) and secondary (i.e. formed from chemical reactions with other pollutants such as ozone). TRAP emitted by motor vehicles exhaust include nitrogen oxides (NO_x), carbon monoxide (CO), black carbon/elemental carbon and organic carbon (BC/EC and OC), polycyclic aromatic hydrocarbons (PAHs), ultrafine particles, $PM_{2.5}$ and PM_{10} *(5).* While the quantity of non-tailpipe PM emissions from the wear of brakes and tyres may be three times less than tailpipe emissions, the toxicity of the pollutants (e.g. heavy metals) is concerning *(6,7).* In many cities, transport is the main source of nitrogen dioxide (NO_2) and a contributor to $PM_{2.5}$ and PM_{10}.

Box 1. The impact of maritime shipping and port logistics on air quality and health

Maritime transport moves 80% of traded goods across the world and it has been an increasing source of air pollutants as well as GHG emissions, with port regions being more polluted than non-port regions (8). Traffic congestion is also common in areas close to harbours. A recent study estimated that 265 000 premature deaths attributable to global shipping-sourced emissions were estimated for 2020 (~0.5% of global mortality) (9).

Additionally, in the last decade there has been a huge transformation in the supply chain and logistics without much consideration on the economic impacts (10). For example, e-commerce has generated a constant increase in demand for quick and cheap deliveries of goods, that has been accelerated during the COVID-19 pandemic.

In response, emission control areas (ECAs) are being developed to mitigate the pollution impact by establishing stricter controls to minimize airborne emissions from ships. ECAs for sulfur oxide (SO_x) exist the Baltic Sea and the North Sea, while both SO_x and NOx are covered in the North American east and west coasts and the United States' areas of the Caribbean Sea (11).

People's exposure to TRAP varies with mobility patterns, meteorology (e.g. wind speed and direction, atmospheric stability) and proximity to roadways and other pollution sources, such as industry, power generation, biomass burning and agriculture. It is important to recognize that TRAP exposure occurs not only outdoors, but also indoors as outdoor air pollution can enter indoor environments. Furthermore, marginalized communities, often located close to busy roadways, are disproportionately exposed to air pollution and experience health disparities *(12).*

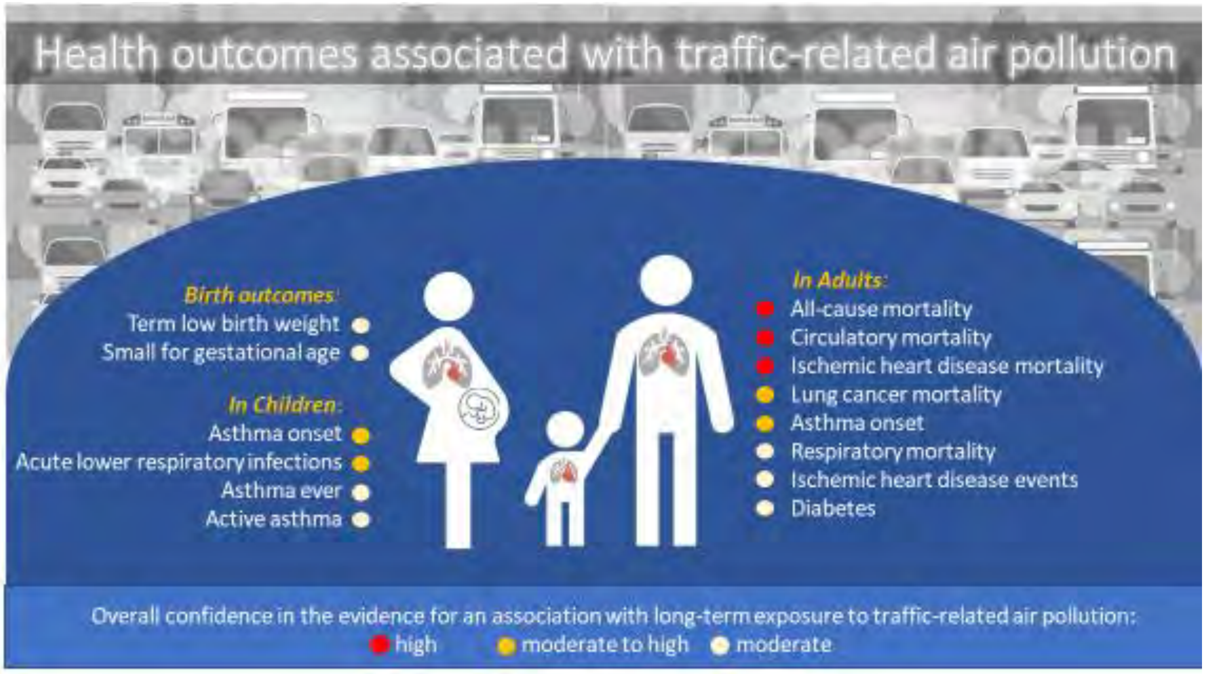
A study estimated that in 2015, across the world there were 385 000 (95% CI: 274 000–493 000) deaths due to transport-related $PM_{2.5}$ and ozone (O_3) annually *(13).* A systematic review of long-term exposure to TRAP and selective adverse health outcomes found a high level of confidence that strong connections exist between TRAP and early death due to cardiovascular diseases (Fig. 1). A strong link was also found between TRAP and lung cancer mortality, asthma onset in children and adults, and acute lower respiratory infections in children. Other reviews arrived at similar conclusions for specific TRAP such as diesel and gasoline exhaust *(14–16).*

Ella Roberta Adoo Kissi Debrah is the first person in the world to have air pollution listed as a cause of death on her death certificate. Having grown up in London, age 7, she was diagnosed with asthma and 2 years later she suffered a fatal asthma attack. The findings from the coroner's inquest concluded:

"Air pollution was a significant contributory factor to both the induction and exacerbations of her asthma. During the course of her illness between 2010 and 2013 she was exposed to levels of NO_2 and PM in excess of WHO Guidelines. The principal source of her exposure was traffic emissions. During this period there was a recognized failure to reduce the level of NO_2 to within the limits set by EU and domestic law which possibly contributed to her death. Ella's mother was not given information about the health risks of air pollution and its potential to exacerbate asthma. If she had been given this information, she would have taken steps which might have prevented Ella's death." [About Ella | The Ella Roberta Foundation]

See SPS *The role of health systems on air pollution communication*

Fig. 1. Health outcomes associated with TRAP



Source: Health Effects Institute; 2022 *(5).*

Fig. 1 shows the overall confidence levels in the evidence for an association between long-term exposure to TRAP and selected health outcomes. Health outcomes for which the overall confidence in the evidence was low to moderate, low, or very low are discussed in *Systematic review and meta-analysis of selected health effects of long-term exposure to traffic-related air pollution (5).*

In addition to the burden of disease imposed by TRAP, transport injuries increase this burden with approximately 1.2 million people dying each year due to road traffic accidents. Poor air quality during extreme events (e.g. dust storms) can reduce visibility and literature is emerging on the extent of its contribution to road injuries. Road traffic injuries are the leading cause of death for children and young adults aged 5–29 years *(17,18).*

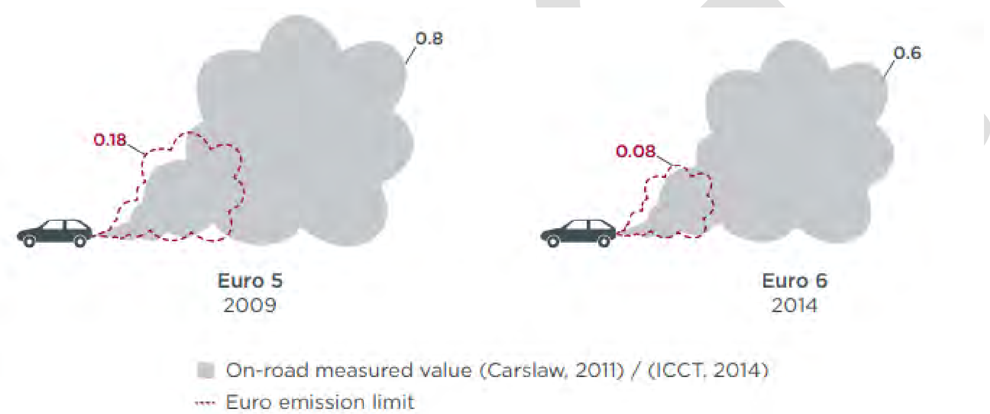
See SPS *Understanding the health impacts of sand and dust storms;* and *The impacts of wildfires on health*

Progress to date

While tailpipe emissions and concentrations of many transport-related pollutants have generally decreased in several HICs over the past decades *(19,20),* it is important to recognize that trends can vary significantly within and between these countries. Assessing the contribution of the transport sector to ambient air pollution requires the combination of model and/or measurement methods such as source apportionment and emissions inventories *(21).*

Success in curtailing emissions result from air quality regulations and improvements in fuel and vehicular emission-control technologies such as the Euro 7 standards and the first non-exhaust emissions regulations *(22).* While the adoption of more stringent regulations should be celebrated, it must be emphasized that monitoring and implementation must go hand in hand to prevent discrepancies that have been reported between regulated emission standards and real-world emissions (see Fig. 2), underscoring the importance of improved compliance programmes including on-road testing programmes. To address this, several HIC countries (e.g. within the European Union) have introduced real-driving testing during on-road trips as part of the engine approval procedure, which is expected to improve compliance and reduce the scope for manufacturers to evade accountability for emissions *(23,24).*

Fig. 2. NO_X emission limits for Euro 5 and Euro 6 diesel cars versus on-road emissions of NO_x



Source: Franco V et al.; 2014 *(23).*

When looking at LMICs, different and concerning trends are observed with increases in TRAP emissions due to inadequate transport policies, population growth, urbanization and economic activity during the past decade *(25).* In addition, TRAP emissions are exacerbated by lax regulations on vehicle importations, the high average age of the fleet, poor fuel quality, poorly maintained roads, lack of vehicle emission regulations and inadequate implementation of vehicle inspection and maintenance programmes, particularly in parts of Asia, Africa, Latin America and Eastern and Central Europe. There is a current, largely unregulated, practice where millions of used (older, more polluting) vehicles are exported every year from HICs to LMICs *(25).* The exporting of lower emission standard vehicles and dirty fuels or diesel to LMIC markets is a problem that requires regional cooperation and multisectoral agreement. This issue is compounded by the fact that millions around the world, especially in Asia, Africa and the Middle East, do not have access to public transport in either urban or rural areas, which makes transitioning away from private vehicle ownership more difficult.

Emerging technologies, such as electric vehicles, coupled with changes in behaviour and consumption patterns can change transport and mobility trends resulting in the transformation of the movement of people and goods around the world. Transforming mobility options should also focus on transition from private electric vehicle ownership to electrifying mass transit systems. It is important for transport solutions to be holistic, addressing exhaust and non-exhaust emissions and the wider range of environmental stressors associated with traffic such as noise, urban heat and reduced physical activity (see Box 2) *(26,27).* The benefits of adoption of new technologies such as electric vehicles – while promising alleviation of some components of TRAP – have been relatively slow so far due to the high cost and environmental impact of batteries, infrastructural barriers, challenges in electrifying freight, increases in non-exhaust emissions and the slow rate of fleet turnover. Moreover, the full benefits of electrification will be realized only by concomitant decarbonization of the electric grid *(28).*

Box 2. Transport, Health and Environment Pan-European Programme (THE PEP)

THE PEP is a tripartite, cross-sectoral, pan-European policy framework that brings together the transport, health, and environment sectors on an equal footing. Established in 2002 by the Member States of the UNECE and the WHO European Region, it is the first and only international programme designed to integrate environmental and health aspects into transport, mobility, and urban planning policies. It operates through national focal points representing the health, environment, and transport sectors, nominated by 56 Member States. Under THE PEP, the first-ever Pan-European Master Plan for Cycling Promotion and the Master Plan on Walking were adopted.

Examples of success

Multistakeholder collaboration and improved transport emissions in Canada

In most countries, different ministries are responsible for monitoring air pollution and regulating vehicle and engine standards. To compound this issue, the regulatory body responsible for transport policies is rarely the same body that controls fuel standards. For example, in an effort to reduce sulfur content in fuel, the Canadian Government set up a multistakeholder process which brought together provincial/territorial governments, vehicle and engine manufacturers, fuel producers and importers, fuel users, and environment and health nongovernmental organizations. The inclusion of all relevant stakeholders ensured broad acceptance of the final conclusions: that the level of sulfur in diesel fuel should be lowered through regulation by the federal government *(29).*

Implementation and enforcement of existing transport policies helped Indonesia clean the air

In 2021, Jakarta District Court ruled that national and local governments had failed to uphold citizens' rights to clean air – responsible for causing 10 000 deaths, more than 5000 hospitalizations for cardio-respiratory diseases and an economic burden of US$ 2.9 billion *(30)*. As 57% of $PM_{2.5}$ emissions are generated by the 25 million vehicles in the city, in 2023, the city estimated that the greatest benefits could be achieved through regular emission testing to ensure compliance with at least Euro 2 emission standards *(31).*

A multipronged framework helped China to expand and decarbonize public transport while reducing emissions from new and in-use vehicles

In Beijing, the integrated Vehicle-Fuel-Road framework includes:

- new vehicle controls, e.g. China 5;
- in-use vehicle controls, e.g. enhanced inspection/maintenance;
- traffic measures, e.g. quota for new private vehicles;
- economic measures, e.g. scrappage of older vehicles;
- better fuel quality, e.g. China 6 fuel standard; and
- alternative fuel vehicles, e.g. promote electric.

With this holistic approach to transport, Beijing experienced a three-fold increase in vehicles over the last 20 years, but its air quality continues to improve *(32).*

Way forward

An integrated urban planning and mobility strategy is one of the most effective ways of increasing public transport use and active mobility modes, while progressively reducing emissions and exposure to TRAP.

Mobilize political commitment for abatement measures to attain air quality objectives

Implementation of emission reductions from vehicles, promotion of emission control technologies and large-scale shifts to public and active transport are needed at local, national, regional and global levels. Measures should include:

- Promote intersectoral collaboration at the national level by engaging the health and environmental sectors in transport and mobility policymaking
- International cooperation to minimize the import and export of polluting fuels and older vehicles.
- Addressing emissions from older vehicles through retrofitting and replacement programmes and policies to discourage the use of highly polluting vehicles (e.g. low emission zones, measures to restrict exportation of old vehicles).
- Encourage a shift of large populations to public and active transport by creating favourable conditions and enhancing road safety measures.
- Promoting electric vehicles while controlling for road dust.
- Optimizing the movement of goods and freight logistics to reduce delivery vehicle densities and emissions in residential areas.

Develop innovative country- and city-specific measures to limit transport emissions through integrated urban planning

Cities should finance measures to encourage a modal shift from private vehicles towards public and active transport.

- Urban re-planning to increase the distance between traffic and residents (e.g. “superblocks” initiative).
- Establish low-traffic or car-free neighbourhoods – reducing car dependency can be achieved by developing bike lanes and pedestrian paths.
- Strengthen and electrify the public transport network.
- Reduce the cost of public transport or eliminate it altogether for certain sectors of the population.
- Implement economic incentives for the use/purchase of active or shared mobility solutions (e.g. bikes, e-bikes, e-scooters, dockless bike systems).

Incorporate transport-related emissions such as black/elemental carbon into national determined contributions (NDCs)

Black carbon is a short-lived climate pollutant, and its reduction can have multiple benefits. Countries like Chile, Colombia and Mexico are currently leveraging this benefit in their NDC commitments.

More intervention studies that investigate exposure reductions and improvements in health

While effective air quality management from a broad range of policies has resulted in significant reductions in levels of air pollution in many countries, there are limited empirical studies that report the effects of interventions on transport-related emissions, TRAP exposures and the resulting health effects *(33–36).* Most of the intervention studies documented reductions in air pollution but did not investigate exposure reductions and improvements in health as policy tracking is very often neglected. Considering the strength of evidence between traffic emissions and their health effects, interventions that reduce emissions from road transport are likely to improve health, but the magnitude of such improvements may be context and method specific and remains understudied.

The selection of policies is a challenging process and needs to be underpinned by the scientific evidence base and a solid policy option generation and selection method that overcomes known weaknesses in policy selection *(37).* Selection should be preceded by the generation of policy options and packages which combine various options that can enable implementation and overcome barriers.

While some interventions in Table 1 may be useful in one location to reduce exposure to TRAP, others may not be applicable. To address TRAP and its health impacts, policy-makers should implement targeted interventions based on their local contexts.

Table 1. Commonly used interventions to reduce exposure to TRAP (in no particular order)

Interventions that may be relevant across the globe	
Reduce car dependency and traffic density	Implement driving restrictions including: road (toll) pricing; implement or reduce speed limits, particularly in urban areas and near schools and other sensitive land-uses; increase fuel prices; promote remote-working policies.
Emission standards for road vehicles	Strengthen all vehicle emissions standards; special focus on regulation of light- and heavy-duty diesel vehicles including real-world testing; reduce vehicle size/weight.
Vehicle inspection and maintenance	Enforce and or implement better mandatory checks and repairs for vehicles.
Electric vehicles	Promote the use of hybrid and electric vehicles and public transit and decarbonize the electric grid. This includes development of a dense electric vehicle charging infrastructure.
Improve public transport	Encourage a shift from private passenger vehicles to affordable and safe public transport in both urban and rural areas; improve mass transport via rail; electrify the public transport network.
Increase active travel	Encourage a shift from private passenger vehicles to active transport. Ensure safe cycling and walking infrastructure, preferably some distance away from major roads. Provide active travel routes through green spaces.
Increase people's distance from traffic	Interventions that separate people from traffic or introduce barriers that can reduce people's exposure to pollutants.
Enhance green areas	Increase well-designed, publicly accessible green spaces. Implement nature-based solutions such as greening of streetscapes and roads, green buildings and green infrastructure that use specific types of greenery that may decrease air pollution concentrations.
Raise public awareness	Raise public awareness about the health impacts of TRAP and how to mitigate the risks.
Interventions that may be more relevant in LMICs	
Improve fuel quality	Improve the fuel quality, particularly reduce the sulfur content, and use of diesel.
Road dust control	Supress road dust; pave major roads or moisten surfaces.
Discourage importing of old vehicles	Promote fiscal government programmes that increase the affordability of clean, low-emission technologies while disincentivizing polluting technologies, by measures such as economic incentives for the purchase of active and shared mobility solutions (e.g. bikes, e-bikes, e-scooters).

Interventions that may be more relevant in HICs	
Discourage use of highly polluting vehicles	Congestion charging zones; low emission zones; diesel bans; truck restrictions in urban areas; scrappage schemes for old vehicles; economic incentives for smaller, lighter vehicles; freight consolidation centres.
Restrict exportation of old vehicles	Place restrictions on the export of used (older, more polluting) vehicles to reduce/avoid transfer of emissions burden to LMICs.
New building restrictions for sensitive land use	Avoid or limit the development of new schools, hospitals, housing and other sensitive land use in close proximity to major roads.

Methodology for content development

WHO defined the scope of the document and collaborated with a member of the WHO Global Air Pollution and Health – Technical Advisory Group (GAPH-TAG), who prepared the initial draft based on an overview of transport-related air pollution and its health effects, supplemented by expert advice. Contributions and comments were provided by members of the Scientific Advisory Group (SAG) and GAPH-TAG, who cover a wide range of expertise.

The draft underwent peer review by specialists from various research institutes, universities, public organizations and UN agencies. Additionally, an early version of the document was presented for peer-review at the Technical Advisory Group and Scientific Advisory Group on Air Pollution and Health meeting. And feedback was addressed by the main contributors. Finally, WHO staff and consultants from the WHO Air Quality, Energy and Health Unit reviewed the report to ensure alignment with the WHO requirements for the collections of WHO Air Quality, Energy and Health Science and Policy Summaries. This series synthesizes current knowledge and evidence on air quality, energy access, climate change links and health, primarily to inform intergovernmental discussions.

Acknowledgements

The WHO gratefully acknowledges the many individuals and organizations, including those from its Advisory Groups (the Scientific Advisory Group on Air Pollution and Health, SAG; and the Global Air Pollution and Health – Technical Advisory Group, GAPH-TAG) and its Collaborating Centres who contributed to the development of this document.

This document was written by Hanna Boogaard (Health Effects Institute, Boston, United States. Member of the GAPH-TAG).

Contributions and comments were provided by members of the SAG and GAPH-TAG: Dayana Agudelo-Castañeda (Universidad del Norte, Colombia); Ali Al-Hemoud (Kuwait Institute for Scientific Research, Kuwait); Zorana Andersen (University of Copenhagen, Denmark); Susan Annenberg (George Washington University, Washington, DC, United States); Aaron Cohen, Pallavi Pant (Health Effects Institute, Boston, United States); Philip Hopke (University of Rochester, New York, United States); Patrick Kinney (Boston University, Boston, United States), Rob Maas (RIVM, Netherlands); Christian Nagl (Environment Agency Austria); Xavier Querol (Spanish National Research Council, Institute of Environmental Assessment and Water, Barcelona, Spain); Jennifer Richmond-Bryant (North Carolina State University, United States); Oriol Teixido (Ricardo PLC, Abu Dhabi, United Arab Emirates);

Marialuisa Volta (University of Brescia, Italy); and Caradee Wright (South African Medical Research Council, Cape Town, South Africa).

An early version of this SPS was presented for peer-review at the Technical Advisory Group and Scientific Advisory Group on Air Pollution and Health meeting in Beijing, China, in October 2024.

Peer-revision was conducted by Sean Beevers, Francesco Forastiere (Imperial College London, United Kingdom); Haneen Khreis (Texas A&M University System, United States and University of Cambridge, United Kingdom); Meelan Thondoo (University of Cambridge, United Kingdom), and Mar Viana (Spanish National Research Council, Institute of Environmental Assessment and Water, Barcelona, Spain).

The development of this document was led by Pierpaolo Mudu, and Kerolyn Shairsingh (WHO Department of Environment, Climate Change and Health), with inputs and review from Sophie Gumy and Cristina Vert (WHO Department of Environment, Climate Change and Health).

Declarations of interest

All external experts submitted a declaration of interest to WHO disclosing potential conflicts of interest that might affect, or might reasonably be perceived to affect, their objectivity and independence in relation to the subject matter of the report. WHO reviewed each of the declarations and concluded that none could give rise to a potential or reasonably perceived conflict of interest related to the subjects covered by the report.

References[2]

1. Krzyzanowski M, Kuna-Dibbert B, Schneider. Health effects of transport-related air pollution. Copenhagen: WHO Regional Office for Europe; 2005 (https://iris.who.int/handle/10665/328088).
2. Hopke P, Dai Q, Li L, Feng Y. Global review of recent source apportionments for airborne particulate matter. Sci Total Environ. 2020;740 (https://doi.org/10.1016/j.scitotenv.2020.140091).
3. Intergovernmental Panel on Climate Change. Climate change 2022: mitigation of climate change. Summary for policymakers. Cambridge University Press, Cambridge and New York (https://www.cambridge.org/core/books/climate-change-2022-mitigation-of-climate-change/summary-for-policymakers/ABC31CEA863CB6AD8FEB6911A872B321#).
4. Tracking transport 2020. International Energy Agency, Paris; 2020 (https://www.iea.org/energy-system/transport).
5. Systematic review and meta-analysis of selected health effects of long-term exposure to traffic-related air pollution. Special Report 23. Health Effects Institute: Boston, MA; 2022 (https://www.healtheffects.org/publication/systematic-review-and-meta-analysis-selected-health-effects-long-term-exposure-traffic).
6. Singh V, Biswal A, Kesarkar AP, Mor S, Ravindra K. High resolution vehicular PM_{10} emissions over megacity Delhi: relative contributions of exhaust and non-exhaust sources. Sci Total Environ. 2020;699:134273 (doi: 10.1016/j.scitotenv.2019.134273).
7. Daellenbach KR, Uzu G, Jiang J, Cassagnes LE, Leni Z, Vlachou A et al. Sources of particulate-matter air pollution and its oxidative potential in Europe. Nature. 2020; 87:414–419 (https://doi.org/10.1038/s41586-020-2902-8).

[2] Accessed 2 December 2024.

8. Ducruet C, Martin BP, Sene MA, Prete ML, Sun L, Itoh H et al. Ports and their influence on local air pollution and public health: a global analysis. Sci Total Environ. 2024;915:170099 (doi: 10.1016/j.scitotenv.2024.170099).
9. Mueller N, Westerby M, Nieuwenhuijsen M. Health impact assessments of shipping and port-sourced air pollution on a global scale: a scoping literature review. Environ Res. 2023:216(pt 1):114460 (https://doi.org/10.1016/j.envres.2022.114460).
10. Mostert MA, Caris A, Limbourg SA. Road and intermodal transport performance: the impact of operational costs and air pollution external costs. RTBM. 2017(1);23:75-85.
11. Global environment outlook 6: Part B: policies, goals, objectives and environmental governance: an assessment of their effectiveness. Chapter 12: air policies. Nairobi: United Nations Environment Programme; 2019 (https://www.unep.org/resources/assessment/part-b-policies-goals-objectives-and-environmental-governance-assessment-their).
12. Hajat A, Hsia C, O'Neill MS. Socioeconomic disparities and air pollution exposure: a global review. Curr Environ Health Rep. 2015;2:440-450 (doi: 10.1007/s40572-015-0069-5).
13. Anenberg S, Miller J, Henze D. Minjares R, Achakulwisut S. The global burden of transport tailpipe emissions on air pollution-related mortality in 2010 and 2015. Environ Res Lett. 2019;14:094012 (doi: 10.1088/1748-9326/ab35fc).
14. Diesel and gasoline engine exhausts and some nitroarenes: IARC monographs on the evaluation of carcinogenic risks to humans. Vol. 105. Lyon: International Agency for Research on Cancer; 2013 (https://publications.iarc.fr/Book-And-Report-Series/Iarc-Monographs-On-The-Identification-Of-Carcinogenic-Hazards-To-Humans/Diesel-And-Gasoline-Engine-Exhausts-And-Some-Nitroarenes-2013).
15. Human health risk assessment for diesel exhaust. Ottawa: Health Canada; 2016 (https://www.canada.ca/en/health-canada/services/publications/healthy-living/human-health-risk-assessment-diesel-exhaust-summary.html).
16. Integrated science assessment for oxides of nitrogen – health criteria. EPA/600/R-15/068. Research Triangle Park, NC: U.S. Environmental Protection Agency; 2016 (https://cfpub.epa.gov/ncea/isa/recordisplay.cfm?deid=310879).
17. Global status report on road safety 2023. Geneva: World Health Organization; 2023 (https://iris.who.int/handle/10665/375016). Licence: CC BY-NC-SA 3.0 IGO.
18. Stockholm Declaration. Third Global Ministerial Conference on Road Safety: Achieving Global Goals 2030 Stockholm, 19–20 February 2020 (https://www.roadsafetysweden.com/contentassets/b37f0951c837443eb9661668d5be439e/stockholm-declaration-english.pdf).
19. Walking and cycling: latest evidence to support policy-making and practice. Copenhagen: WHO Regional Office for Europe; 2022 (https://iris.who.int/handle/10665/354589). Licence: CC BY-NC-SA 3.0 IGO.
20. Health in the green economy: health co-benefits of climate change mitigation – transport sector. Geneva: World Health Organization; 2012 (https://iris.who.int/handle/10665/70913).
21. Overview of methods to assess population exposure to ambient air pollution. Geneva: World Health Organization; 2023 (https://iris.who.int/handle/10665/373014). Licence: CC BY-NC-SA 3.0 IGO.

22. Commission proposes new Euro 7 standards to reduce pollutant emissions from vehicles and improve air quality. Brussels: European Commission; 2022 (https://ec.europa.eu/commission/presscorner/detail/en/ip_22_6495).
23. Franco V, Sánchez FP, German J, Mock P. Real-world exhaust emissions from modern diesel cars. A meta-analysis of PEMS emissions data from EU (Euro 6) and US (Tier 2 Bin 5/ULEV II) diesel passenger cars. Part 1: Aggregated results. International Council on Clean Transport; 2014 (https://theicct.org/sites/default/files/publications/ICCT_PEMS-study_diesel-cars_20141010.pdf).
24. Zardini A, Bonnel P. Real driving emissions regulation – European methodology to fine tune the EU real driving emissions data evaluation method. European Commission: Joint Research Centre. Publications Office of the European Union; 2020 (https://data.europa.eu/doi/10.2760/176284).
25. Used vehicles and the environment: a global overview of used light duty vehicles – flow, scale and regulation. Nairobi: United Nations Environment Programme; 2020 (https://wedocs.unep.org/20.500.11822/34175).
26. Urban transport and health – sustainable transport: a source-book for policy makers in developing cities. BMZ and Geneva: World Health Organization; 2011 (https://www.who.int/publications/i/item/9789241502443).
27. Glazener A, Sanchez K, Ramani T, Zietsman J, Nieuwenhuijsen MJ, Mindell JS et al. Fourteen pathways between urban transport and health: a conceptual model and literature review. J Transp Health. 2021;21:101070 (https://doi.org/10.1016/j.jth.2021.101070).
28. Requia WJ, Moataz M, Higgins CD, Arain A, Ferguson M. How clean are electric vehicles? Evidence-based review of the effects of electric mobility on air pollutants, greenhouse gas emissions and human health. Atmos Environ. 2018;185:64-77 (doi: 10.1016/j.atmosenv.2018.04.040).
29. Partnership for Clean Fuels and Vehicles: regulatory toolkit. Nairobi: United Nations Environment Programme; 2024 (https://www.unep.org/partnership-clean-fuels-and-vehicles-regulatory-toolkit).
30. Syuhada G, Akbar A, Hardiawan D, Pun V, Darmawan A, Heryati SHA, Siregar AYM, Kusuma RR, Driejana R, Ingole V, et al. Impacts of Air Pollution on Health and Cost of Illness in Jakarta, Indonesia. *International Journal of Environmental Research and Public Health*. 2023; 20(4):2916. https://doi.org/10.3390/ijerph20042916
31. Real-world solutions for clean air and health: six city examples to inspire action on urban air pollution. Clean Air Fund Vital Strategies; 2023 (https://www.cleanairforhealth.org/).
32. A review of 20 years' air pollution control in Beijing. Nairobi: United Nations Environment Programme; 2019 ().
33. Chamberlain RC, Fecht D, Davies B, Laverty AA. Health effects of low emission and congestion charging zones: a systematic review. Lancet Public Health. 2023;8:e559-e574 (doi: 10.1016/S2468-2667(23)00120-2).
34. Burns J, Boogaard H, Polus S, Pfadenhauer LM, Rohwer AC, van Erp AM et al. Interventions to reduce ambient air pollution and their effects on health: an abridged Cochrane systematic review. Environ Int. 2020;135:105400 (DOI: 10.1016/j.envint.2019.105400).
35. Review of interventions to improve outdoor air quality and public health. London: Public Health England; 2019 (https://www.gov.uk/government/publications/improving-outdoor-air-quality-and-health-review-of-interventions).

36. Khreis H, Sanchez KA, Foster M, Burns J, Nieuwenhuijsen MJ, Jaikumar R et al. Urban policy interventions to reduce traffic-related emissions and air pollution: a systematic evidence map. Environ Int. 2023;172:107805 (https://doi.org/10.1016/j.envint.2023.107805).
37. May AD, Khreis H, Mullen C. Option generation for policy measures and packages: an assessment of the KonSULT knowledgebase. Case Stud Transp Policy. 2018;6(3):311-318 (doi: 10.1016/j.cstp.2018.03.002).

WHO Air Quality, Energy and Health Science and Policy Summaries

Green spaces – sectoral solutions for air pollution and health

Technical brief

Key messages

Exposure to green spaces is widely associated with health benefits, including mental (e.g. reduced risk of depression and anxiety), physical (e.g. improved cardiovascular health), healthy behaviours (e.g. physical activity) and social health (e.g. reduced loneliness). These health benefits can result in major health sector cost savings. Additionally, health co-benefits of green spaces may arise from interventions aimed at improving air quality, which could partially explain the relationship between green spaces and health.

Air pollution is a major environmental risk to health and urgent action is needed to reduce it. Lowering emissions at their source is the most effective strategy for reducing air pollution, but well-designed and biodiverse green spaces within communities may offer an additional policy option to improve air quality, helping to passively mitigate the impacts of harmful air pollutants and create healthier environments. However, the evidence remains limited and the effects of green spaces on reducing air pollution are variable and context-dependent and may even be small or marginal depending on factors such as the type of green space, size, location, biodiversity and weather conditions.

Vegetation impacts air quality both directly and indirectly and can have both positive and negative impacts on pollutant concentrations and characteristics depending on the design and setting. For example, air pollutants can be deposited on the surface of plants, and vegetation can decrease pollutant concentration, and act as a barrier to dispersion. Also, green spaces can reduce soil erosion, improve urban drainage and help prevent desertification and dust exposure. Nevertheless, unintended consequences may also occur. For example, increased concentration of pollutants due to the trapping effect (such as in street canyons – streets flanked by buildings on both sides creating a canyon-like environment), emission of biogenic volatile organic compounds (BVOCs) that contribute to the formation of ground-level ozone, and pollen production can have a negative impact on air quality when green spaces are not properly designed and managed.

Priority actions for short-term health benefits include:

- the use of properly designed and maintained vegetation in highly polluted areas to reduce exposure to air pollution and decrease the associated disease burden. However, this should be considered as part of a broader strategy including other interventions (e.g. reducing emissions, improving transport infrastructure to promote active mobility, and integrating green spaces with built infrastructure such as green walls and permeable surfaces) to provide more immediate and long-term health benefits.

Priority actions for long-term health benefits include:

- assessment, guidance and outreach on the role of green spaces in air pollution reduction from different vegetation types and green space design in varying contexts and climates.

- plans for afforestation in arid lands that generate dust, considering the climatic conditions of the area and the most efficient and resistant vegetation in each case.

Stakeholders from multiple sectors, including the health sector and academia, can play an important role in planning, designing, monitoring and evaluating green spaces to enhance their co-benefits.

Key definitions

- **Green spaces:** Surfaces partially or completely covered by vegetation (e.g. grass, trees, shrubs, etc.). These include—but are not limited to—parks, gardens, street trees, forests and fields, which can be present in urban, suburban or rural areas (1,2).
- **Green infrastructure:** Network of natural and semi-natural systems, such as green roofs or urban forests, that provide environmental, social and economic benefits by using nature-based solutions. It helps create healthier, more resilient urban environments (3).

Overview

Current status

Green spaces and health: The health benefits of green spaces (Fig. 1) have long been recognized, with a comprehensive and growing compilation of rigorous studies supporting such association (2,4–6). The scientific evidence suggests that exposure to green spaces is associated with improved physical and mental health. The mental health benefits are the most documented in the scientific literature (4,5,7–10). Social health benefits and healthy behaviours are now also increasingly recognized, such as reduced feelings of loneliness by creating space for social interaction (4,11).

The evidence detailing the pathways by which green spaces contribute to health is still evolving, and several theories exist (e.g. improved social cohesion, improved relaxation and restoration, increased physical activity). The reduction of air pollution is another potential pathway that has been proposed to explain the health benefits associated with urban green spaces (4,5), although an informed design approach must be taken to maximize the cumulative positive effects and meet users' needs.

Fig. 1. Health benefits of green spaces

Green spaces and air pollution reduction: Air pollution, a mixture of particles and harmful gases, is a leading environmental risk to health. It negatively impacts physical and mental health. The World Health Organization (WHO) estimated that air pollution caused about 6.7 million global deaths in 2019 (12).

See SPS[1] *Health effects of air pollution – evidence and implications*

Reducing exposure to and health impacts of air pollution should be a high public health priority. The most important and effective strategy is to lower emissions at their sources. In this sense, policies for reducing motorized traffic or lowering industrial and energy production emissions are considered for anthropogenic sources. Additionally, the role of green spaces in reducing exposure to air pollution has been suggested by different studies published worldwide. However, the evidence is still limited and the effects of green spaces for reducing air pollution are variable and context-dependent and may even be small or marginal depending on the design (4,9,13–15).

The main mechanisms (see Fig. 2) that explain the role of green spaces in air pollution reduction include:

- **Deposition**, the mechanism most frequently discussed among the scientific community, is the residence (or deposition) of particulate matter on the surface of a plant, where it can be adsorbed and broken down. It can be permanent or temporary and reduces the overall pollution load (9,13).
- **Modification** refers to physical, chemical or biological changes in gaseous pollutants' (e.g. volatile organic compounds) properties that occur on, within and around plants through their absorption. The modification of pre-conditions for air pollution may also have indirect impacts (e.g. green spaces can lower air temperature, reducing the potential for ground-level ozone formation) (9,13).
- **Dispersion** is the process by which vegetation helps to divert and dilute pollutants (either particulate matter or gases) by changing their trajectory and velocity through its physical structure, thus acting as a potential barrier for the pollutants (9,13,16). This is particularly relevant at the local scale since well-designed green spaces can reduce particle loads in specific areas that may be near the source or close to vulnerable populations (e.g. near schools or hospitals). However, this also means that pollution levels can increase under certain vegetation characteristics, either at the location of the vegetation or in other localities (17).
- **Reduced desertification** can occur due to green spaces promoting soil and dust retention, helping to reduce land degradation, erosion and desertification across various scales, thereby contributing to air pollution reduction. This is particularly relevant in areas affected by sand from agricultural fields, mining sites, lands degraded by human activities or natural deserts (e.g. see the Great Green Wall Initiative (18)), which can exacerbate air quality issues. Desertification is interconnected with air pollution and one can exacerbate the other and vice versa.

See SPS *Understanding the health impacts of sand and dust storms*

Additionally, replacing built environment infrastructure (e.g. paved roads or car parks) with green spaces can improve air quality in the intervened areas because of the increased presence of vegetation and the reduction of significant sources of pollution. This is particularly relevant in urban areas where

[1] Science and Policy Summary

air pollution levels are often high, and the availability and quality of green spaces are typically limited. In urban areas it can be challenging to have green spaces of at least 0.5 hectares accessible within a reasonable distance (e.g. 300 m of residences) to maximize their health benefits (4).

Fig. 2. Mechanisms by which green spaces reduce air pollution

Box 1. Indoor vegetation and air quality

Introducing a range of indoor plants may also improve air quality by lowering pollutant levels (e.g. carbon dioxide, formaldehyde, benzene, toluene, nitrogen dioxide), while also increasing humidity and reducing temperature (19,20). Indoor plants may provide these benefits at lower cost, with less energy demand, and with pleasing aesthetic features, compared with technological solutions such as air purifiers and air conditioning.

Barriers, drivers and enablers

Barriers in implementing green space to improve air quality

- The effectiveness of green spaces in improving air quality is not completely understood and varies based on physical, geographical and environmental factors such as the type of green space, its size, design, location, biodiversity and weather conditions (9,14).
- Due to the complexities of appropriate vegetation design and site conditions, it is difficult to offer global recommendations (9,14). Under certain circumstances (e.g. heat and drought), areas with green spaces can also show high concentrations of certain pollutants such as ozone. Certain vegetation species can release significant amounts of reactive gases (BVOCs), which can react and form small-sized secondary particles that can affect the chemistry of other pollutants and contribute to the formation of ground-level ozone or the increase of particulate matter (9,21).

  See *SPS The synergies of heat stress and air pollution and its health impact*
- Also, green spaces might promote pollen production and the potential synergistic interaction between pollen and air pollution (9).

  See SPS *Climate change, air pollution, pollen and health*
- Finally, climate change challenges green infrastructure due to increasing water shortages, extended periods of heat, extreme rainfall events and strained city budgets which threaten maintenance activities. And the green infrastructure suitable for today's climate may not be suitable in the future, complicating current planning decisions.

The design, type and characteristics of green spaces are crucial to avoid unintended consequences (22), such as the creation of areas where air flow is restricted or pollutants accumulate. This makes it essential to consider local factors during planning, while also ensuring city-wide accessibility and equitable distribution of benefits

Drivers and enablers in the use of green spaces to improve air quality and health

- As cities grow – and become denser in some circumstances – city dwellers' demand for accessible green spaces is increasing *(2).*
- There is increasing public awareness and concern about the negative health effects of air pollution exposure. This creates a stronger impetus for policy-makers and urban planners to implement informed strategies to reduce air pollution, including green space interventions when applicable, acknowledging the value and prioritization of these spaces as critical public health infrastructure *(2).*
- When utilized to improve air quality, green space delivers important co-benefits, including recreational opportunities, physical activity, nature contact, settings for social connections, reduced noise levels, and resilience to climate-related threats such as extreme heat, drought, extreme rainfall and flooding (2,5,23). Recreational use of green spaces is especially relevant for children, whose ability to play is a right recognized by the United Nations, and is considered to be critical for their development, health and general well-being. In line with Sustainable Development Goal 11 Target 11.7, all countries should ensure that their populations (including children) have access to parks, open and green spaces and playgrounds. These spaces are essential for children's health and well-being, supporting their physical activity outdoors and socializing with other children (24). Physical activity is also very relevant for the entire population, as it plays a significant role in the prevention and treatment of noncommunicable diseases (NCDs) and addresses a leading risk factor for global mortality (4). Notably, about 90% of air pollution-related deaths are attributable to NCDs.

  See SPS *Health effects of air pollution – evidence and implications*

These enabling factors create opportunities to harness the potential of green spaces to create healthier communities and enhance public health and, as an additional co-benefit, improve air quality. However, realizing this potential will require targeted policies, investments and community engagement to overcome the existing barriers and ensure that green space benefits are maximized and equitably distributed. Integrating green space strategies into larger air quality and public health initiatives can help build momentum and support. And integrating air quality considerations into broader green infrastructure projects will be important to maximize benefits and avoid unintended consequences.

Interlinkages with other topics

Green spaces offer synergistic benefits for air quality, reduction of perceived traffic noise and ambient temperature, climate change mitigation, stormwater management and public health benefits (5). There is a clear overlap between classic air pollutants and climate pollutants. Green spaces can help store carbon dioxide and also capture black carbon and increase methane removal in the soil.

Additionally, green spaces increase biodiversity, mitigate the impacts of natural disasters and reduce the impacts of heat stress. Vegetation helps lower temperatures in urban areas, mitigating the heat island effect and decreasing energy demand, for example, by reducing reliance on air conditioning (2,23). The vegetation planted for climate change mitigation can have a positive impact on air quality, if it has the appropriate characteristics. Without careful consideration, greening projects may either represent a lost opportunity to improve air quality or even lead to a deterioration in air quality. Air pollution interventions should consider climate implications, and green space strategies should be designed to maximize co-benefits for both air quality and climate resilience. An integrated, cross-sectoral approach is crucial for leveraging the full potential of urban nature to create healthier, more sustainable cities.

Green spaces can also contribute to improving environmental, socioeconomic and health conditions. It is crucial to consider health equity in greening efforts as lower income and marginalized communities often have limited access to green spaces. Green space initiatives may also have the potential to positively impact air quality, which is often a concern in disadvantaged communities. Efforts should prioritize ensuring that these vulnerable populations benefit from green space interventions equitably, without contributing to displacement through green gentrification due to rising property values (8,25).

Box 2. Blue spaces improve health and air quality

Although the evidence is less established because of markedly fewer studies to date, there is a growing recognition that, in addition to green spaces, blue spaces – "water bodies, such as coastal margins of cities, natural or canalized rivers, ponds within city parks or even fountains" *(2)* – can positively impact health. Recent research supports the hypothesis that air pollution on land surfaces is higher in those areas without a water body, but the extent of pollutant uptake by bodies of water, and the ecological effects on affected waterways, are not well understood (26). Air quality around blue spaces may improve due to the settling of airborne pollutants, the sequestration of carbon and the release of oxygen. Additionally, the cooling effect of blue spaces can decrease the formation of certain pollutants like ground-level ozone. Overall, urban blue spaces, such as lakes, can help reduce air pollution concentrations, and a combination of lakes and greenery can improve urban air quality (27,28).

Way forward

Different stakeholders – including WHO, academia, health and social care professionals – have identified key actions to accelerate progress in reducing air pollution and improving public health through green spaces.

WHO global and regional policy frameworks
Several WHO policy frameworks cover the issues of nature and more sustainable, liveable cities (5,27) and make a number of suggestions for Member States when integrating green spaces into urban and territorial plans to tackle air pollution

- **Planning and design considerations:**
  - consult evidence-based, up-to-date reliable data to select suitable green space interventions that promote deposition, modification, dispersion or reduced desertification depending on

specific air pollution reduction goals (e.g. reduction of total pollution loads, avoidance of peak concentrations), given that the effects of green spaces on air pollution are not yet fully understood.
  - consider different types and scales of green spaces (e.g. park, tree, roadside vegetation) and select plant species in urban areas that effectively reduce air pollution while managing pollen and volatile organic compounds. This selection should consider the overall biodiversity of the place, local demographics, changing climatic conditions, inequalities, ecosystems, area characteristics, water use and other maintenance needs (29).
  - ensure suitable configurations of green spaces, considering the vegetation type, height, thickness and design, to avoid unintentionally impeding urban air flow and wind streams (9,14).
  - when reducing greenhouse gas concentrations is a priority, manage the replacement of trees or woodland effectively, considering that the capacity of carbon storage changes as the vegetation growths.
  - prioritize areas with vulnerable populations (e.g. hospitals, schools) and marginalized communities, often including racialized communities, who may experience worse air quality and have less access to green spaces due to socioeconomic barriers *(6,23,24).*

- **Stakeholder engagement:**
  - strengthen collaborations between the health sector and all green space-related actors (e.g. landscape architects, arboriculturists, gardeners), including citizens (25).
  - clearly communicate the health benefits and co-benefits of green spaces to all sectors and stakeholders (25).
  - consider the needs of the population (even those that do not have access or do not use green spaces) in the planning, design and evaluation of green spaces. Active involvement of the local community and end users is essential (3,25).

- **Setting expectations:**
  - recognize that green infrastructure may require long-term maintenance and funding commitments (25).
  - acknowledge that some of the environmental and health effects of green spaces may not be immediate and may take time to manifest, whereas some other benefits can be short or medium term (e.g. loneliness reduction) (11,25).

- **Monitoring and evaluation:**
  - conduct environmental assessments to evaluate the impact of green space interventions on air quality.
  - use health impact assessments to assess air pollution exposure and the health benefits resulting from reduced air pollution through green spaces (25). WHO (e.g. GreenUr, AirQ+, HEAT) and non-WHO tools (e.g. i-tree [https://www.itreetools.org/]) can be used.
  - leverage the outcomes of these evaluations to show the health benefits of green space interventions in improving air quality and to drive further action and policy decisions.

Scientific research considerations (13)

- **Understanding pollution context** by assessing air pollution and mapping pollution types and sources, considering the characteristics of the area (e.g. spatial and temporal patterns considering local climate, ventilation, time of the day).
- **Estimating exposure risk** by considering the number of people affected, population vulnerability, and the prevalence of pollution-related diseases using urban microclimate modelling and simulation of environmental exposure. Well-designed studies are suggested for the production of the best available evidence of impact.
- **Designing and managing green spaces** by selecting the desired mechanism for reducing air pollution through green spaces, their location, design and plant variety.

More research is needed to better characterize the role of green spaces in improving air quality and, consequently, improving public health, and to clearly understand the mechanisms often under complex and variable conditions. Further evidence-based findings and practice sharing are essential for designing effective policies for the strategic deployment of green infrastructure.

Health and social care sector

Although the medical community has not issued specific suggestions on using green spaces to improve air quality, some initiatives indirectly support this goal.

- **Nature prescriptions,** including nature-based/green social prescriptions, are programmes usually offered by health care providers who encourage patients to spend time in nature. This innovative socioenvironmental approach encourages engagement with nature and often emphasizes group-based activities. Evidence indicates that these programmes can increase daily step counts and reduce high blood pressure, depression and anxiety (30). Additionally, nature prescriptions might indirectly benefit patients through the expected improved air quality provided by green spaces, amplifying the positive effects of doing activities in nature.
- **Health system and health care facilities** may also benefit from green spaces and the resulting lower levels of air pollution, particularly if health care facilities are located away from pollution hotspots and vegetation and green spaces are integrated both inside and around these settings. The health economic returns on investment on greening can be substantial, and nature prescriptions can be a way to maximize both the health benefits and the health care cost savings for society.
- **Medical and health curricula** should include environmental health issues, including the public health benefits of green spaces, especially for relaxation and stress alleviation, and other potential co-benefits such as air pollution reduction.

World Health Organization

Methodology for content development

WHO defined the scope of the document and prepared the initial draft based on an overview of the health co-benefits of green spaces and their role in reducing air pollution exposure. Evidence was gathered through a structured search in PubMed and additional sources, including WHO reports and relevant grey literature. The search strategy included keywords related to green spaces, air pollution, and health outcomes, prioritizing systematic reviews and meta-analyses published in recent years. Expert advice further guided the selection and interpretation of evidence to develop the document. Significant contributions were provided by experts on the field, from various research institutes, universities, public organizations and UN agencies.

The draft underwent peer review by a group of experts, including members of the WHO Global Air Pollution and Health – Technical Advisory Group (GAPH-TAG), and members of WHO Collaborating Centers, which cover a wide range of expertise. Additionally, an early version of the document was presented for peer-review at a scientific conference in Europe and at the Technical Advisory Group and Scientific Advisory Group on Air Pollution and Health meeting. A final version of the document was revised by another group of experts from various research institutes and universities.

Feedback was addressed by the main contributors. Finally, WHO staff and consultants from the WHO Air Quality, Energy and Health Unit reviewed the report to ensure alignment with the WHO requirements for the collections of WHO Air Quality, Energy and Health Science and Policy Summaries. This series synthesizes current knowledge and evidence on air quality, energy access, climate change links and health, primarily to inform intergovernmental discussions.

Acknowledgements

The WHO gratefully acknowledges the many individuals and organizations, including those from its Advisory Groups (the Scientific Advisory Group on Air Pollution and Health, SAG; and the Global Air Pollution and Health – Technical Advisory Group, GAPH-TAG) and its Collaborating Centres, who contributed to the development of this document.

This document was led and written by Cristina Vert and Pierpaolo Mudu (WHO Department of Environment, Climate Change and Health), with the support of Kofi Amegah (University of Cape Coast, Ghana); Thomas Astell-Burt (University of Sydney, Australia); Xiaoqi Feng (University of New South Wales, Australia); Howard Frumkin (University of Washington and the Trust for Public Land, United States); Nadja Kabisch (Leibniz University Hannover, Germany); Mark Nieuwenhuijsen (ISGlobal, Barcelona Institute for Global Health, Spain); David Rojas-Rueda (Colorado State Univeristy, United States); and Matthias Braubach (European Centre for Environment and Health, WHO Regional Office for Europe).

Peer reviewers included Dayana Milena Agudelo (Universidad del Norte, Colombia. Member of the GAPH-TAG); Andrey Egorov (formerly with the US Environmental Protection Agency, United States), Richard Baldauf (US Environmental Protection Agency, United States); John Gallagher (Trinity College Dublin, Ireland); Prashant Kumar (University of Surrey, United Kingdom); and Marion Porcherie (University of Rennes, EHESP, CNRS, ARENES – UMR 6051, France. Member of a WHO Collaborating Center).

WHO would like to extend special thanks to Samuel Agyei-Mensah (University of Ghana, Ghana); Erica Di Ruggiero (Dalla Lana School of Public Health, University of Toronto, Canada. Member of a WHO

Collaborating Center); Olga Lucia Sarmiento Dueñas (Department of Public Health, School of Medicine, Universidad de los Andes, Colombia); and Steve Hung-Lam Yim (Centre for Climate Change and Environmental Health, Nanyang Technological University, Singapore. Member of the GAPH-TAG) for their thorough review and valuable feedback on the final version of the document. Input and review were also provided by Sophie Gumy, Kerolyn Shairsingh, Karla Cervantes, and Samantha Pegoraro (WHO Department of Environment, Climate Change and Health).

An early version of this document was presented at the Future Green City World Congress (Kingdom of the Netherlands, September 2024). It was also presented for peer-review at the Technical Advisory Group and Scientific Advisory Group on Air Pollution and Health meeting in Beijing, China in October 2024.

Declarations of interest

All external experts submitted a declaration of interest to WHO disclosing potential conflicts of interest that might affect, or might reasonably be perceived to affect, their objectivity and independence in relation to the subject matter of the report. WHO reviewed each of the declarations and concluded that none could give rise to a potential or reasonably perceived conflict of interest related to the subjects covered by the report.

References[2]

1. WHO Regional Office for Europe. Urban Green Spaces and Health. A review of evidence [Internet]. Copenhaguen; 2016. Available from: http://www.euro.who.int/__data/assets/pdf_file/0005/321971/Urban-green-spaces-and-health-review-evidence.pdf?ua=1
2. WHO Regional Office for Europe. Assessing the value of urban green and blue spaces for health and well-being [Internet]. 2023. Available from: https://www.who.int/europe/publications/i/item/WHO-EURO-2023-7508-47275-69347
3. Nieuwenhuijsen MJ. Green Infrastructure and Health. Annu Rev Public Health. 2020;42:317–28.
4. WHO Regional Office for Europe. Urban green spaces and health. A review of evidence [Internet]. Copenhagen; 2016. Available from: https://iris.who.int/handle/10665/345751
5. WHO Regional Office for Europe. Green and blue spaces and mental health: new evidence and perspectives for action [Internet]. Copenhagen; 2021. Available from: http://apps.who.int/bookorders.
6. Bratman GN, Anderson CB, Berman MG, Cochran B, de Vries S, Flanders J, et al. Nature and mental health: An ecosystem service perspective. Sci Adv [Internet]. 2019;5(7). Available from: https://www.ncbi.nlm.nih.gov/pubmed/?term=(Bratman%5BAuthor+-+First%5D)+AND+(%222019%2F01%2F01%22%5BDate+-+Publication%5D+%3A+%223000%22%5BDate+-+Publication%5D)
7. Xie Y, Fan S, Luo Y, Li J, Zhang Y, Hu L, et al. Credibility of the evidence on green space and human health: an overview of meta-analyses using evidence grading approaches. Lancet.

[2] Accessed 10 December 2024.

2024;106:1–14.

8. Hunter RF, Nieuwenhuijsen M, Fabian C, Murphy N, O'Hara K, Rappe E, et al. Advancing urban green and blue space contributions to public health. Lancet Public Heal [Internet]. 2023;8(9):e735–42. Available from: http://dx.doi.org/10.1016/S2468-2667(23)00156-1

9. Kumar P, Druckman A, Gallagher J, Gatersleben B, Allison S, Eisenman TS, et al. The nexus between air pollution, green infrastructure and human health. Environ Int [Internet]. 2019;133(June):105181. Available from: https://doi.org/10.1016/j.envint.2019.105181

10. Qiu Y, Zuo S, Yu Z, Zhan Y, Ren Y. Discovering the effects of integrated green space air regulation on human health: A bibliometric and meta-analysis. Ecol Indic [Internet]. 2021;132:108292. Available from: https://doi.org/10.1016/j.ecolind.2021.108292

11. Astell-Burt T, Hartig T, Putra IGNE, Walsan R, Dendup T, Feng X. Green space and loneliness: A systematic review with theoretical and methodological guidance for future research. Sci Total Environ [Internet]. 2022;847(July):157521. Available from: https://doi.org/10.1016/j.scitotenv.2022.157521

12. World Health Organization. Sustainable Development Goal indicator 3.9.1: mortality attributed to air pollution. Geneva; 2024.

13. Diener A, Mudu P. How can vegetation protect us from air pollution? A critical review on green spaces' mitigation abilities for air-borne particles from a public health perspective - with implications for urban planning. Sci Total Environ [Internet]. 2021;796:148605. Available from: https://doi.org/10.1016/j.scitotenv.2021.148605

14. Venter Z, Hassani A, Stange E, Schneider P, Castell N. Reassessing the role of urban green space in air pollution control. Proc Natl Acad Sci [Internet]. 2024;121. Available from: http://www.pnas.org/lookup/suppl/doi:10.1073/pnas.2216830120/-/DCSupplemental.https://doi.org/10.1073/pnas.2216830120

15. Gong C, Xian C, Wu T, Liu J, Ouyang Z. Role of urban vegetation in air phytoremediation: differences between scientific research and environmental management perspectives. npj Urban Sustain. 2023;3(1):1–15.

16. Baldauf R. Recommendations for constructing roadside vegetation barriers to improve near-road air quality. Vols. 600/R-16/0, U.S. Environmental Protection Agency. 2016.

17. Deshmukh P, Isakov V, Venkatram A, Yang B, Zhang KM, Logan R, et al. The effects of roadside vegetation characteristics on local, near- road air quality. Air Qual Atmos Heal. 2019;12:259–70.

18. United Nations. Great Green Wall Initiative [Internet]. [cited 2024 Jun 13]. Available from: https://www.unccd.int/our-work/ggwi

19. Han KT, Ruan LW. Effects of indoor plants on air quality: a systematic review. Vol. 27, Environmental Science and Pollution Research. Environmental Science and Pollution Research; 2020. 16019–16051 p.

20. Gubb C, Blanusa T, Griffiths A, Pfrang C. Potted plants can remove the pollutant nitrogen dioxide indoors. Air Qual Atmos Heal [Internet]. 2022;15(3):479–90. Available from: https://doi.org/10.1007/s11869-022-01171-6

21. Fitzky AC, Sandén H, Karl T, Fares S, Calfapietra C, Grote R, et al. The Interplay Between Ozone and Urban Vegetation—BVOC Emissions, Ozone Deposition, and Tree Ecophysiology.

Front For Glob Chang. 2019;2:1–17.

22. Abhijith K V., Kumar P, Gallagher J, McNabola A, Baldauf R, Pilla F, et al. Air pollution abatement performances of green infrastructure in open road and built-up street canyon environments – A review. Atmos Environ [Internet]. 2017;162:71–86. Available from: http://dx.doi.org/10.1016/j.atmosenv.2017.05.014

23. Kumar P, Debele SE, Khalili S, Halios CH, Sahani J, Aghamohammadi N, et al. Urban heat mitigation by green and blue infrastructure: Drivers, effectiveness, and future needs. Innovation [Internet]. 2024;5(2):100588. Available from: https://doi.org/10.1016/j.xinn.2024.100588

24. Adjei-Boadi D, Agyei-Mensah S, Adamkiewicz G, Rodriguez JI, Gemmell E, Ezzati M, et al. Neighbourhood, built environment and children’s outdoor play spaces in urban Ghana: Review of policies and challenges. Landsc Urban Plan [Internet]. 2022;218:104288. Available from: https://doi.org/10.1016/j.landurbplan.2021.104288

25. World Health Organization (WHO). Urban Green Space Interventions and Health. A review of impacts and effectiveness. Vol. 3, World Health Organisation. 2017.

26. Zhu D, Zhou X. Effect of urban water bodies on distribution characteristics of particulate matters and NO2. Sustain Cities Soc [Internet]. 2019;50:101679. Available from: https://doi.org/10.1016/j.scs.2019.101679

27. WHO Regional Office for Europe. Nature, biodiversity and health: an overview of interconnections [Internet]. Copenhagen; 2021. Available from: https://www.euro.who.int/en/health-topics/environment-and-health/urban-health/publications/2021/nature,-biodiversity-and-health-an-overview-of-interconnections-2021

28. Zhao L, Li T, Przybysz A, Guan Y, Ji P, Ren B, et al. Effect of urban lake wetlands and neighboring urban greenery on air PM10 and PM2.5 mitigation. Build Environ. 2021;206.

29. World Health Organization. Vector-borne diseases [Internet]. 2017 [cited 2020 Jan 27]. Available from: https://www.who.int/news-room/fact-sheets/detail/vector-borne-diseases

30. Nguyen PY, Astell-Burt T, Rahimi-Ardabili H, Feng X. Effect of nature prescriptions on cardiometabolic and mental health, and physical activity: a systematic review. Lancet Planet Heal [Internet]. 2023;7(4):e313–28. Available from: http://dx.doi.org/10.1016/S2542-5196(23)00025-6

WHO Air Quality, Energy and Health Science and Policy Summaries

Air quality legislation and implications for health

Technical brief

Key messages

- There is a large body of evidence on the adverse health effects of air pollution, which is the basis for developing the WHO air quality guidelines.
- The WHO Air Quality Guidelines are a set of non-binding evidence-based recommendations of limit values for specific air pollutants developed to support countries in establishing air quality legislation, including air quality standards, to protect public health.
- Information on air quality standards (AQS) for selected pollutants – a given level of air pollutant which is adopted and enforced by a regulatory authority – is currently publicly available for 128 countries. There is great heterogeneity in both their availability and the levels chosen as standard across countries and regions.
- Air quality standards are part of a package of legislative measures to reduce the health risks of air pollution. Other measures include source control, land use planning, and transportation measures.
- Effective air quality laws and regulations which include AQS are two of the key policy actions to significantly improve air quality and protect health.
- Legislation which embeds AQS can enable national air quality management to be operationalized through the establishment of robust institutional and governance structures.
- In addition to AQS, legislation should also integrate reliable and representative measurement of air quality as part of an effective monitoring system, in addition to accountability and enforcement mechanisms.

Box 1. Key concepts

Air quality guidelines: A series of WHO publications that provide evidence-informed, non-binding recommendations for protecting public health from the adverse effects of air pollutants by eliminating or reducing exposure to hazardous air pollutants and by guiding national and local authorities in their risk management decisions. The latest volume was published in 2021. (4)

Air quality standard: A given level of an air pollutant (for example, a concentration or deposition level) that is adopted by a regulatory authority as enforceable. Unlike an air quality guideline level, a number of elements in addition to the effect-based level and averaging time must be specified in the formulation of an air quality standard. (4)

Legislation: includes all laws and regulations established by any formal state-sponsored legislative process, in accordance with the constitutional structure and norms of the relevant country. (14)

Overview

From health studies to the WHO air quality guidelines

The World Health Organization (WHO) has been compiling and reviewing evidence on the health effects of air pollution since the 1950's (1, 2). As of today, a wide range of diseases are well documented, as short-term effects (with exposures of hours and days) and long-term effects (months and years), for almost all organ systems (including respiratory, cardiovascular, nervous, and metabolic systems, as well as the outcome of pregnancy), and for all ages.

See the SPS on *Health effects of air pollution – evidence and implications*.

Air pollution is a complex mixture for which several components have long been covered by standards. These pollutants (particulate matter (PM), O_3, NO_2, CO and SO_2) have been studied extensively and the resulting evidence is sufficiently robust to support standards for each pollutant. Additionally, regulation of these pollutants addresses the major contributors to ambient air pollution.

Based on the scientific knowledge, the first edition of the WHO air quality guidelines (AQG) was published in 1987 (3), providing recommendations on air quality guideline levels for selected air pollutants. The AQG levels address ambient air pollution and cover the many microenvironments where people spend time. Rapidly growing evidence of the health effects of air pollutants – PM, O_3, NO_2, CO and SO_2 – provided the basis for the latest global update of the WHO AQG in 2021, based on the health outcomes that are critical for decision-making and for both long- and short-term periods of exposure (See table 1) (4). Guidelines on a wider set of pollutants are provided in previous volumes of WHO air quality guidelines (5, 6).

Table 1. Summary of recommended 2021 Air Quality Guidelines (AQG) levels and interim targets (IT).

Pollutant	Averaging time	IT1	IT2	IT3	IT4	AQG level
$PM_{2.5}$, μg/m^3	Annual	35	25	15	*10*	5
$PM_{2.5}$, μg/m^3	24-hour [a]	75	50	37.5	*25*	15
PM_{10}, μg/m^3	Annual	70	50	30	*20*	15
PM_{10}, μg/m^3	24-hour [a]	150	100	75	*50*	45
O_3, μg/m^3	Peak season[b]	100	70	–	–	60
O_3, μg/m^3	8-hour	160	120	–	–	100
NO_2, μg/m^3	Annual	*40*	30	20	–	10
NO_2, μg/m^3	24-hour [a]	120	50	–	–	25
NO_2, μg/m^3	1-hour	–	–	–	–	200
SO_2, μg/m^3	24-hour [a]	125	50	–	–	40

SO_2, µg/m³	10-minute	–	–	–	–	500
CO, mg/m³	24-hour [a]	7	–	–	–	4
CO, mg/m³	8-hour	–	–	–	–	10
CO, mg/m³	1-hour	–	–	–	–	35
CO, mg/m³	15-minute	–	–	–	–	100

a. 99th percentile (i.e. 3–4 exceedance days per year).
b. Average of daily maximum 8-hour mean O3 concentration in the six consecutive months with the highest six-month running-average O3 concentration.

The **air quality guideline level** is a specific format of a guideline recommendation consisting of a numerical value, expressed as a concentration of a certain pollutant in the air and linked to an averaging time (i.e. the duration of the exposure with a given mean air pollutant concentration associated with certain health effects). In setting the AQGs, WHO did find evidence that adverse health effects do not occur or are minimal below this concentration level. However, complete exclusion of harmful effects at concentrations below the given value is uncertain and cannot be guaranteed.

Since the 2005 version, the WHO AQG also provides **interim targets** for selected pollutants, which are air pollutant concentrations associated with a specific decrease of health risk on the path to achieving the AQG levels. Interim targets serve to stimulate policy makers to take incremental steps in the progressive reduction of air pollution towards the air quality guideline levels, particularly for those countries well above the AQG. Designed especially for areas with high pollution, these targets set pollutant levels above AQG standard but provide achievable milestones for developing effective reduction policies. Therefore, the interim targets should be regarded as steps towards the ultimate achievement of AQG levels in the future, rather than the end goal for those countries using the targets for regulation and decision-making (7).

From WHO air quality guidelines to air quality standards

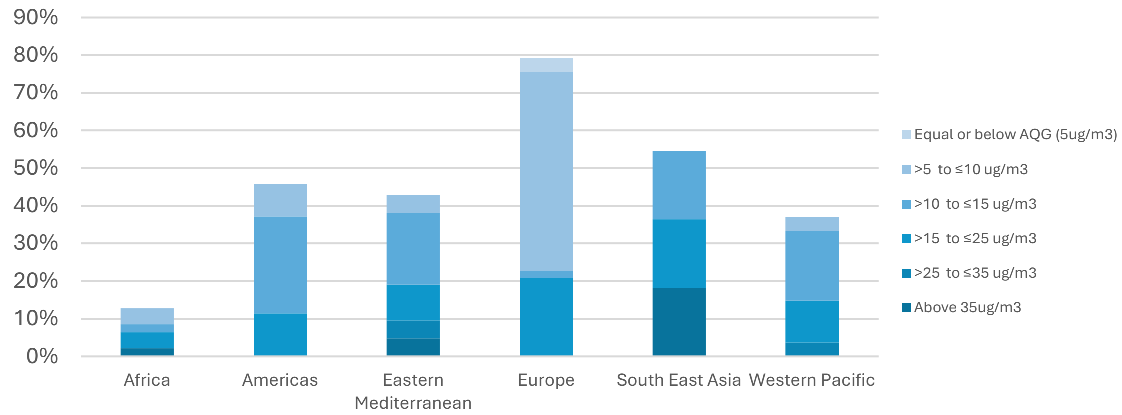
Air quality standards aim to reduce levels of air pollutants and decrease the health burden associated with air pollution. Whilst not legally-binding, like all WHO guidelines, the AQGs are an evidence

-informed tool for decision-makers to guide the development and updating of national air quality standards (AQS), legislation, policies and programmatic planning.

A first comprehensive review and compilation of air quality standards for 194 countries in 2017 provided some insights on how the WHO AQGs are utilized. Findings showed that air quality standards vary greatly among regions and countries, and these discrepancies amplify the differences in air quality and related health effects around the world. Only a handful of countries had AQS in line with WHO guideline values. In general, air quality standards for $PM_{2.5}$, PM_{10} and SO_2 rarely complied with WHO guideline values (8). A more recent review in the WHO Eastern Mediterranean Region showed that almost all (19 out of 22) countries have air quality standards, but the standards' concentrations are up to 10 times the recommended 2021 WHO guidelines values, for $PM_{2.5}$ for example (9).

An update of this compilation of air quality standards has recently been published as a database, available in the format of a WHO interactive tool (10). Information is available on air quality standards for selected pollutants and averaging times for 194 WHO Member States, of which 128 countries, including the European Union countries, have established air quality standards. The alignments of the air quality standard for PM2.5 (annual) with the WHO AQG is presented in Figure 1. For all WHO regions except Africa, more than 30% of countries within the regions have a standard for PM2.5, with Europe peaking at 78%. A more detailed analysis will be available shortly (11).

Figure 1. Percentage of countries with air quality standard for $PM_{2.5}$ (annual), by WHO region and AQG levels.



Note: For the EU 27 countries, the new value of 10 µg/m3 is considered.
Source: WHO Air Quality Standards database: interactive tool (update 2025). Version 2.2. Geneva, World Health Organization, 2025.

Legislation and Ambient Air Quality Standards

Air quality laws and regulations are key policy actions to significantly improve air quality. Indeed, efforts to attain the WHO AQG and to significantly reduce the danger posed by air pollution to human health cannot succeed without a legal and institutional foundation that establishes a robust system of air quality governance, as identified by UNEP (12).

To better understand the global landscape of national air quality management, UNEP conducted a *Global Assessment of Air Pollution Legislation* (GAAPL) in 194 countries and the European Union (13), using the WHO AQG as a starting point[1] for evaluation of national ambient

[1] This study was conducted and finalized before the release of the updated 2021 WHO Air Quality Guidelines. The review of country legislation therefore used the 2005 WHO Air Quality Guidelines as a benchmark.

air quality standards (AQS). The GAAPL report examined the legal measures for determining whether AQS are being met and what legal tools exist when there are failures to meet them.

The GAAPL report emphasized that robust air quality governance is critical to attaining air quality standards and public health goals. This can be achieved through developing legislation for air quality control which integrates accountability, enforceability, transparency, and public participation (see Figure 2).

Figure 2. Air quality governance system founded in legislation. Source: (13).

Why legislation? The report makes the case that legislative processes are well adapted to the collective, cross-sectoral, evolving problem of air pollution. As knowledge evolves, legislative processes allow for the review and update of regulatory arrangements, including standards. It also enables legitimate political deliberation in balancing socioeconomic priorities to set and deliver air quality standards. Further, legislation provides enforceability of ambient air quality standards, and administrative processes for delivering them.

To function effectively, AQS need to be operationalized. This requires the establishment of robust institutional and governance structures to support AQS. It also requires reliable information about air quality, in addition to accountability and enforcement mechanisms.

Legislative regimes can construct administrative processes and structures for implementing AQS, such as monitoring regimes, accountability of public actors and formal sanctions.

Based on the findings of GAAPL report, UNEP developed a *Guide on Ambient Air Quality Legislation* (14) designed to assist national lawmakers in developing or improving ambient air quality laws prioritizing public health outcomes. It translates key findings of the GAAPL into concrete guidance and considerations for lawmakers.

Specific national legal expertise will be needed to adapt and apply the Guide within national legal contexts. Additionally, countries' unique governance structure, political contexts, and environmental conditions (such as air pollution emission sources and who is affected), will be relevant influences on these legislative processes. For that reason, the Guide does not propose a model for the development of air quality laws. It does, however, provide the key elements of effective air quality governance that should be considered in developing air quality legislation, which countries can use to tailor legislation, according to their national needs and priorities.

AQS are the key drivers for improving air quality. For this reason, tracking a country's action on developing and embedding AQS in legislation can be useful in understanding how countries are moving towards improved air quality.

The World Health Assembly, as well as the United Nations Environment Assembly (UNEA), have on various occasions, called on Member States to develop policies to reduce air pollution across sectors, while providing support to ongoing efforts to reduce in-country and transboundary air pollution (15-17). Both UNEP and WHO are urging Member States to set ambitious ambient air quality standards, taking into account the WHO AQG (18, 19).

Way forward

One of the avenues for achieving this is through supporting countries in building relevant capacity in environmental law (including air quality law) and contributing to the environmental dimension of the 2030 Agenda for Sustainable Development through the intergovernmental Programme for the Development and Periodic Review of Environmental Law (Montevideo Programme) (20)[2]. Member States of the Montevideo Programme agreed to the development of "*legal responses to address the air pollution crisis*" as a priority area under the Programme (21).

WHO and UNEP are continuously working to support countries to develop or update air quality standards aligned with WHO AQG, as well as develop and implement ambient air quality legislation, air quality management and track national progress towards cleaner air.

Acknowledgment

This document was developed by Renée Gift (UNEP Law Division), Karla Cervantes, Sophie Gumy and Kerolyn Shairsingh with inputs and review from Meltem Kutlar Joss (Swiss Tropical and Public Health Institute), Pierpaolo Mudu, Samantha Pegoraro and Cristina Vert (WHO Department of Environment, Climate Change and Health), Michal Krzyzanowski (Imperial College London) and Jonathan Samet (Colorado School of Public Health).

[2] See paragraph 97(d) of the medium-term strategy 2022-2025

References

[1] Barker K et al. Air Pollution. Geneva: World Health Organization; 1961 (WHO Monograph Series, No. 46; http://apps .who.int/iris/handle/10665/41722).

[2] Evolution of WHO air quality guidelines: past, present and future, Copenhagen: WHO Regional Office for Europe; 2017.

[3] Air quality guidelines for Europe. Copenhagen: WHO Regional Office for Europe; 1987. (https://extranet.who.int/iris/restricted/handle/10665/107364).

[4] WHO global air quality guidelines. Particulate matter (PM2.5 and PM10), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide. Geneva: World Health Organization; 2021 (https://apps.who.int/iris/handle/10665/345329). Licence: CC BY-NC-SA 3.0 IGO.

[5] Air quality guidelines for Europe, second edition. Copenhagen: WHO Regional Office for Europe; 2000. (http://www.euro.who.int/en/publications/abstracts/air-quality-guidelines-foreurope).

[6] WHO guidelines for indoor air quality: selected pollutants. Copenhagen: WHO Regional Office for Europe; 2010. (http://www.euro.who.int/en/health-topics/environment-and-health/air-quality/policy/who-guidelines-for-indoor-airquality/ chemical-indoor-air-pollutants-selected-pollutants-2010/who-guidelines-for-indoorair- quality-selected-pollutants).

[7] WHO Air Pollution and Health Training Toolkit for Health Workers. 2025. [Online]. (https://www.who.int/tools/air-pollution-and-health-training-toolkit-for-health-workers).

[8] M. Kutlar Joss et al. Time to harmonize national ambient air quality standards. Int J Public Health. 2017; 62:453-46.

[9] S. Faridi et al. Ambient Air Quality Standards and Policies in Eastern Mediterranean. Int J Pubic Health.2023;68:605352.

[10] WHO Air quality standards database. 2025. [Online]. (https://www.who.int/tools/air-quality-standards).

[11] WHO and Swiss TPHI, manuscript in preparation.

[12] Actions on Air Quality. Nairobi: United Nations Environment Programme; 2021.

[13] Global Assessment of Air Pollution Legislation. Nairobi: United Nations Environment Programme; 2021.

[14] Guide on Ambient Air Quality Legislation. Nairobi: United Nations Environment Programme; 2023.

[15] Health and the environment: addressing the health impacts of air pollution. WHA 68.8. Geneva: World Health Organization; 2015.

[16] UNEA Resolution 1/7 Strenghtening the role of the United Nantios Environment Programme on promoting air quality. Nairobi: United Nations Environment Programme, Nairobi; 2016.

[17] UNEA Decision 5/2 - Medium term strategy for the period 2022-2025 and programme of work and budget for the biennium 2022–2023. Nairobi: United Nations Environment Programme; 2022.

[18] Updated Road Map for an enhanced global response to the health impacts of air pollution. EB156/24. Geneva: World Health Organization; 2025.

[19] UNEA Resolution 3/4, Environment and health. Nairobi: United Nations Environment Programme; 2017.

[20] The Montevideo Environmental Law Programme: a decade of action on environmental law [Online]. (https://www.unep.org/explore-topics/environmental-rights-and-governance/what-we-do/promoting-environmental-rule-law-1).

[21] Report of the first global meeting of national focal points for the Fifth Programme for the Development and Periodic Review of Environmental Law (Montevideo Programme V). Nairobi: United Nations Environment Programme, Nairobi; 2021.

WHO Air Quality, Energy and Health Science and Policy Summaries

Transboundary cooperation for our shared air - protecting public health

Technical brief

Key messages

- To date, a wide range of global bodies, regional agreements and transboundary cooperation initiatives have been set up to generate cooperation between countries on air quality management. These initiatives can be leveraged to combat the dual climate and health risks caused by air pollution.
- As outlined in United Nations Environment Assembly resolution (UNEA 6/10), there is potential for significant progress to be made to reduce global air pollution, by broadening the scope of existing geographical collaboration to mobilize finances, expertise and resources, and expand capacity building across the world.
- Although there is more to be done, resources are already available to enable key stakeholders to enhance air quality management capacities at a local, national and regional level for climate and health co-benefits. These include the Air Quality Management Exchange Platform (AQMx) for technical tools, models, data and knowledge to build capacity among air quality managers; and the United Nations Environment Programme (UNEP) Global Air Quality Cooperation Network, which aims to empower participants to reduce air pollution through international partnerships and knowledge-sharing.
- The Joint Task Force on Health Aspects of Air Pollution under the United Nations Economic Commission for Europe Convention on Long-Range Transboundary Air Pollution (UNECE Air Convention or CLRTAP) has been instrumental as a platform for discussions and sharing knowledge among key stakeholders, fostering the development and use of major risk quantification tools. These tools include AirQ+, CLIMAQ-H, and the World Health Organization (WHO) global air quality guidelines, which have been key to informing decision-making and monitoring progress.
- The WHO updated road map on air pollution and health (EB156/24) calls for a stronger engagement from the health workforce in multisectoral action.

Overview

Introduction

Air pollution is one of the greatest environmental risks to health, associated with 7 million deaths per year globally, as estimated by WHO, of which around 90% deaths occur in low- and middle-income countries *(1)*. A 2022 World Bank report estimated the cost of the health damage caused by air pollution as US$ 8.1 trillion a year (equivalent to 6.1% of global GDP) *(2)*. Air pollutants can travel across national borders – to neighbouring countries and beyond – and impact air quality, ecosystems and population health far from the source. In addition, air pollution is inextricably linked to climate change through emission sources and atmospheric chemistry (e.g. scattering/absorbing of light by aerosol effects and tropospheric ozone formation). Evidently, this challenge cannot be addressed through local action alone. Therefore, regional cooperation is essential to sustainably combat this dual risk to both health and the climate.

Whilst global bodies of the United Nations system have a critical role to play in international coordination on air pollution as mandated by their constituencies *(3–5),* a powerful tool is regional cooperation. Both the recent WHO *Updated road map for an enhanced global response to address the health impacts of air pollution* (EB156/24) *(6)* and UNEA resolution 6/10: *Promoting regional cooperation on air pollution globally*, adopted in 2024, have begun building momentum for more regional agreements across the globe *(7).* This latter document provides an overview of the global, regional and complementary work to reduce air pollution either as an explicit objective or as a function of other objectives. These include multilateral environmental agreements, legislative frameworks, monitoring networks, intergovernmental organizations and continent-wide action plans. It also highlights the potential for the health sector to promote and support transboundary agreements, with the example of the Task Force on Health under the UNECE Air Convention.

Mapping of existing transboundary cooperation on air pollution

Global bodies which have air quality in their mandate

UN Environment Programme (UNEP): UNEP plays a pivotal role in addressing this pressing need to enhance global air quality by mobilizing industry and private sector partnerships to redirect investments in high-impact sectors. It also provides advisory support to countries and cities in detecting and reducing harmful pollutants through policy and regulatory actions. To enhance the evidence base for informed decision-making, UNEP is promoting air quality monitoring, health impact assessments, sector-specific interventions and economic analyses. It also works to strengthen global and regional movements focusing on air quality advocacy and networks *(8).*

Climate and Clean Air Coalition (CCAC): Convened within UNEP, CCAC is a voluntary partnership of over 160 governments, intergovernmental organizations and nongovernmental organizations founded in 2012. Collectively and individually, partners who join CCAC are working to reduce powerful but short-lived climate pollutants (SLCPs) – methane, black carbon, hydrofluorocarbons and tropospheric ozone – which drive both climate change and air pollution. The CCAC aims to connect ambitious agenda-setting with targeted mitigation action within countries and sectors. CCAC supports action and capacity building to reduce SLCPs in more than 70 countries through the funding of projects and the individual actions of its partners *(9).*

World Health Organization (WHO): WHO also addresses key risks to health from household and ambient air pollution by promoting interventions and initiatives for healthy sectoral policies (including energy, transport, waste burning, housing, urban development and electrification of health care facilities). This contributes to achieving health co-benefits from climate change mitigation policies. WHO also provide technical support to its Member States in the development of normative guidance, tools and provision of authoritative advice on health issues related to air pollution and its sources. It monitors and reports on global trends and changes in health outcomes associated with actions taken to address air pollution at the national, regional and global levels as well as developing and implementing a strategy for raising awareness on the risk of air pollution to human health and available solutions that can be implemented to mitigate the risks of exposure to air pollution. Through digital outreach and partnerships, WHO has helped enrich the value proposition of addressing air pollution for health and environment ministries, city governments and other stakeholders from sectors with significant emissions *(10).*

World Meteorological Organization (WMO): WMO plays a pivotal role in addressing air quality by providing scientific and technical expertise to monitor, model and assess air pollution and its transboundary impacts. Through its Global Atmosphere Watch (GAW) programme, WMO facilitates the standardization and harmonization of air quality monitoring data, creating a robust evidence base for informed decision-making. This includes forecasting sand and dust storms, urban smog and wildfire smoke pollution; this can be tailored to the needs of society from global to urban scales. It provides the scientific and technical foundation to support air pollution and health assessments. In its global role, WMO advances science-policy interactions by translating complex atmospheric science into actionable insights for policy-makers, and promotes capacity-building initiatives to strengthen national and regional expertise in air quality management. In addition, WMO supports atmospheric modelling, including under the UNECE Air Convention Task Force on Measurements and Modelling (TFMM), to better understand the long-range transport of pollutants and their impacts on air quality *(5,11).*

Regional bodies and agreements to tackle air pollution

UNECE Convention on Long-Range Transboundary Air Pollution (UNECE Air Pollution or CLRTAP): Initiated due to the public outcry against the detrimental impacts of acid rain in Europe, the UNECE Convention on Long-Range Transboundary Air Pollution was signed in 1979 and entered into force in 1983. As the first regional environmental convention to deal with air pollution on a broad regional basis, this convention has been instrumental in the reduction of key harmful pollutants (e.g. sulfur dioxide, ammonia, particulate matter, tropospheric ozone precursors, heavy metals and persistent organic pollutants) in both Europe and North America. The convention supports countries in the region with capacity-building activities for assessment and action on air pollution issues. Whilst originating from an environmental convention, CLRTAP has integrated health through the Joint Task Force on the Health Aspects of Air Pollution, which is now a well-established intersectoral platform, putting human health at the centre of its work and has emerged as a valuable model for discussing and promoting these issues at the regional level. Knowledge from the convention is also shared through a dedicated task force, the Forum for International Cooperation on Air Pollution (FICAP), which works collaboratively with global stakeholders such as UNEP, CCAC, WHO and WMO *(12).*

Arctic Council – 2017 Fairbanks Declaration: The Arctic Council addresses air pollution and climate change impacts in the Arctic through initiatives such as its Framework for Action on Black Carbon and Methane adopted in the Council's 2017 Fairbanks Ministerial Declaration, where Arctic states committed to a collective goal for reducing their black carbon emissions. Supported by its Arctic Monitoring Assessment Programme (AMAP) Working Group and Expert Group on Black Carbon and Methane (EGBCM), the Atlantic Council conducts scientific assessments, monitors pollutants and develops policy recommendations on air pollution and climate change issues. AMAP assessment results feed into international processes including work under the Intergovernmental Panel on Climate Change (IPCC), UNECE Air Convention, UNEP and WHO. The Arctic Council promotes collaboration among Member States, Indigenous Peoples' organizations and observers to tackle transboundary pollution and implement mitigation strategies, including cleaner energy and sustainable transport solutions. By combining scientific research with practical policies, the Arctic Council contributes to protecting the Arctic environment and supporting global air quality and climate goals *(13).*

UN Economic and Social Commission for Asia and the Pacific (UNESCAP) Regional Action Programme on Air Pollution: Spearheaded by UNESCAP, the Regional Action Programme on Air Pollution encompasses the Asia-Pacific region, which is the first region-wide action plan negotiated and adopted by regional countries in 2022. As this region is grappling with rapid urbanization and industrialization, the programme's aim is to facilitate science-based and policy-oriented cooperation among countries, enabling them to collectively improve air quality monitoring and management, and the adverse impacts of air pollution. The programme enhances this collaboration through promoting the exchange of best practices and outreach, providing a regional open platform for partnership and coordination, and identifying technical and financial resources for multilateral action *(14).*

Association of Southeast Asian Nations (ASEAN) Haze Agreement: Following severe land and forest fires in 1997–1998, ASEAN Member States AM) signed the ASEAN Agreement on Transboundary Haze Pollution (AATHP) in 2002. This agreement aims to prevent, monitor and mitigate land and forest fires to control transboundary haze pollution through concerted national, regional and international efforts. The Roadmap on ASEAN Cooperation towards Transboundary Haze Pollution Control with Means of Implementation serves as a strategic framework to mobilize resources, strengthen legal and policy frameworks at all levels, enhance cross-sectoral cooperation and coordination, and increase public awareness and engagement. This framework strives to implement collaborative action to control transboundary haze pollution in ASEAN in aid of realizing the vision of Transboundary Haze-Free ASEAN by 2030 *(15).*

Acid Deposition Monitoring Network in East Asia (EANET): EANET was established in 2001. This initiative, born out of intergovernmental cooperation, aims to create a common understanding of acid deposition problems in East Asia, and support decision-making to combat acid deposition. Over the years, EANET's scope has expanded to address wider air pollution issues, leading to the establishment of the EANET Project Fund. It is the only network in East Asia monitoring both acid deposition and air pollution, therefore producing high-quality open data, providing knowledge-sharing, capacity building and public awareness to government officials, researchers and the public. Through shared research and understanding, participating countries contribute to informed decision-making and cooperation in the region *(16).*

Malé Declaration: The Malé Declaration on Control and Prevention of Air Pollution and Its Likely Transboundary Effects for South Asia emerged in 1998 as the first regional agreement on air pollution in South Asia. This pioneering declaration has prompted collaborative efforts among countries including Bangladesh, Bhutan, India, the Maldives, Nepal, Pakistan and Sri Lanka to develop emission inventories, monitor air pollutants and assess the impacts on various sectors. The declaration's revival in recent years underscores the region's commitment to addressing air pollution as a communal, regional problem. South Asian countries reinforced their desire for the Malé Declaration to be revived at the last South Asia Cooperative Environment Programme (SACEP) Governing Council in June 2024 *(17).*

International Centre for Integrated Mountain Development (ICIMOD): ICIMOD is an intergovernmental knowledge and learning centre working on behalf of the people of the Hindu Kush Himalaya. The centre partners with its eight regional member countries (Afghanistan, Bangladesh, Bhutan, China, India, Myanmar, Nepal and Pakistan) to address the rapidly changing regional context of extreme weather events, biodiversity loss and air pollution. ICIMOD's Clean Air unit is working through partners to monitor, assess and communicate the scale of the problem, increase the ambition of reduction targets and speed up the adoption of solutions. ICIMOD's interventions include promoting the adoption of cleaner fuels and energy efficient technologies, researching the impacts of short-lived climate forcers (SLCFs), and increasing the volume, quality and accessibility of data on air quality. ICIMOD has been active in the Malé Declaration since its inception in 1998. It also co-organizes, with the World Bank, the Science Policy and Finance Dialogue (SPFD) on Air Quality Management in the Indo-Gangetic Plain and Himalayan Foothills

(IGP-HF) – a regional forum focused on the critical impact of poor air quality on health, environment, economy and social well-being in the IGP-HF region. Key recommendations from the forum show a need for advancing air quality management, including operationalizing the Kathmandu Road Map (a framework on action for clean air signed between Bangladesh, India, Nepal and Pakistan) *(18,19).*

South Asia Co-operative Environment Programme (SACEP): SACEP is an intergovernmental organization, established in 1982 by the governments of South Asia (Afghanistan, Bangladesh, Bhutan, India, Maldives, Nepal, Pakistan and Sri Lanka) to promote and support protection, management and enhancement of the environment in the region. Since its creation, SACEP has implemented projects and programmes in the areas of environment education, environment legislation, biodiversity, air pollution and the protection and management of the coastal environment *(20).*

West Asia Air Quality Network (WAAQN): West Asian countries met in 2023 and recommended the establishment of a regional air quality network for to foster a coordinated approach for air quality management in West Asia. The network objectives are to: enhance coordination and cohesion among West Asian countries on air quality management issues; and discuss the proposed establishment of a regional network for West Asian countries to collaborate on air quality management solutions. In a follow-up meeting in 2024, countries in West Asia have developed a regional framework and workplan to promote clean air across the region, through a review of the regional assessment of air quality management. Under the WAAQN, the framework establishes a mechanism for regional cooperation on air pollution, while the workplan outlines concrete activities for 2025 and 2026 *(21).*

Intergovernmental Network on Atmospheric Pollution for Latin America and the Caribbean (LAC): LAC was established in 2008 in the framework of the LAC Forum of Ministers of Environment. The network is comprised of the heads of air quality units in LAC countries and other key stakeholders. The activities of the network are guided by the Regional Air Quality Action Plan 2022–2025, which demonstrates a concerted commitment to addressing air quality challenges in the region, reflecting the urgency of confronting air pollution and underscoring that regional cooperation is crucial to effective solutions. Through the implementation of the action plan, LAC countries have enhanced their capacity to formulate and implement different actions to mitigate and improve air quality. This has included air quality monitoring, solid waste management, cleaner production and energy efficiency in industry and sustainable transport *(22).*

Integrated Assessment of Air Pollution and Climate Change for Sustainable Development in Africa and proposed **Africa Clean Air Programme (ACAP):** In 2022, a partnership consisting of the African Union Commission, UNEP and CCAC published the *Integrated assessment of air pollution and climate change for sustainable development in Africa.* The assessment provides a robust scientific basis for clean air action in Africa and recommends 37 measures across five sectors – transport, residential energy, energy generation and industry, agriculture, and waste – for a continent-wide clean air programme. At the 18th Session of the African Ministerial Conference on Environment (AMCEN) in 2022, AMCEN Decision 18/4 "urged African countries to support further development and implementation of the 37 recommended measures as a continent-wide Africa Clean Air Programme (ACAP), coordinated by strong country-led initiatives, cascaded to the regional economic communities and higher levels of policy". It underscored the need for integrated approaches through strong partnerships, involving national governments, city authorities, regional economic communities, intergovernmental agencies, scientists, donors, businesses and non-state actors. Subsequently, in 2023, the African Union Specialized Technical Committee (STC) on Agriculture, Rural Development, Water and Environment (ARDWE), reinforced the African Union Commission's mandate to lead on the establishment of ACAP and foster collaboration between relevant partners in the region. The establishment of ACAP was also acknowledged by UNEA resolution 6/10: *Promoting regional cooperation on air pollution to improve air quality globally (23).*

Regional economic communities in Africa: The environment and energy ministers of all the 15 countries of the Economic Community of West African States (ECOWAS), met in 2020 and adopted a comprehensive set of regulations for introducing cleaner fuels and vehicles in the region. The high-level ministerial meeting was organized by the ECOWAS Commission with the support of UNEP and other partners. The regulations adopted by the ministers were the culmination of several years' work by UNEP towards improving the standards of fuels and vehicles in the region, building on the 2009 Abidjan Agreement – West and Central Africa Regional Framework Agreement on Air pollution. There have been similar processes supported by UNEP for introducing cleaner fuels and vehicles across Africa, which have built on regional cooperative agreements, for example, the Southern African Development Community (SADC) Regional Policy Framework on Air Pollution (Lusaka Agreement, 2008) and the Eastern Africa Regional Framework Agreement on Air Pollution (Nairobi Agreement, 2008). As these regional framework agreements recommend actions in various key sectors producing air pollution, there is potential to implement them further *(24).*

Complementary fora

United Nations Framework Convention on Climate Change (UNFCCC) and **Paris Agreement:** The 1992 UNFCCC and the 2015 Paris Agreement support the global response to the threat of climate change. The Paris Agreement's overarching goal is to hold "the increase in the global average temperature to well below 2°C above pre-industrial levels" and pursue efforts "to limit the temperature increase to 1.5°C above pre-industrial levels." In recent years, focus has been on the need to limit global warming to 1.5°C by the end of this century to prevent dangerous climate change. The three pillars of the Paris Agreement are mitigation, adaptation and finance, which also aims to increase the ability of countries to deal with the impacts of climate change, and making finance flows consistent with a low greenhouse gas and climate-resilient pathway. The ultimate objective of the UNFCCC system is to stabilize greenhouse gas concentrations in the atmosphere at a level that will prevent dangerous human interference with the climate system, in a timeframe which allows ecosystems to adapt naturally and enables sustainable development. Many actions to mitigate climate change have co-benefits in reducing the impacts of air pollution. Therefore, there is utility in taking an integrated approach to climate mitigation and action on air pollution to exploit co-benefits and manage any trade-offs in terms of impacts to human health and ecosystems *(25).*

Convention on Biological Diversity (CBD): The Kunming-Montreal Global Biodiversity Framework was agreed under the CBD during COP15 in 2022. This takes forward the achievement of the Sustainable Development Goals and builds on previous strategic plans to reach a global vision of a world living in harmony with nature by 2050. Target 7 of the Framework specifically calls for countries to strive to reduce pollution to levels that are not harmful to biodiversity. This gives the CBD a specific mandate and an opportunity to work with countries, existing agreements and nongovernmental organizations to work to reduce pollution from all sources, including fugitive emissions into the air *(26).*

Basel, Rotterdam and Stockholm conventions (BRS): These conventions, under the UN architecture, led global efforts towards the sound management of hazardous chemicals and waste, aiming to protect human health and the environment from their adverse effects at global, regional and national levels. Many chemicals are released into the atmosphere through industrial and other economic activities. Therefore, a close relationship between chemical and air pollution agreements is key to achieving joint benefits and limiting impacts on human health and ecosystems *(27).*

Leveraging the health voice for transboundary agreements on air pollution

Health sector role in tackling transboundary air pollution
Addressing environmental risks is key for primary prevention of diseases. With air pollution recognized as a major risk for noncommunicable diseases, the health sector can play an important role in transboundary agreements, beyond health impacts being mentioned in introductory texts. Yet the health workforce needs knowledge and tools to address the quantification of health risks and engage in multisectoral action. Understanding and capacity building for national and regional institutions to conduct health risk assessment of air pollution should be central to decision-making. This is even more important under a changing climate, as transboundary impacts of air pollution from wildfire smoke or sand and dust storms on health are likely to become more prominent, in addition to air pollution of anthropogenic origin.

Joint Task Force on the Health Aspects of Air Pollution (THF)
To date, there is only one regional agreement that has health specifically integrated in the science-policy framework – the UNECE Air Convention. The task force was established in 1997 within the UNECE Convention on Long-Range Transboundary Air Pollution to assess the health effects of such pollution and to provide supporting documentation *(28).* The WHO European Centre for Environment and Health (WHO ECEH) chairs the task force, which is composed of experts designated by most of the 51 countries that are parties to the convention. The TFH is a member of the family of task forces and international cooperative programmes dealing with different aspects of impacts of transboundary air pollution. The TFH works to quantify how long-range transboundary air pollution affects human health and helps define priorities to guide future monitoring and abatement strategies. It also advises on monitoring and modelling activities to improve the quality of assessments.

Through regular meetings and implementation of its work plan, the TFH and WHO ECEH have coordinated major international projects on air pollution and health and contributed to addressing the needs of the convention and its Parties in science, capacity building, communication and outreach.

Notable outputs of the TFH include several health assessment reports consolidating evidence on health outcomes of exposure to air pollutants, such as persistent organic pollutants (2003), particulate matter (2006), heavy metals (2007), ozone (2008), black carbon (2012), pollution from solid fuel use for heating (2015) and polycyclic aromatic hydrocarbons (2021).

Health risk assessment within the TFH has been high on the agenda through various initiatives, such as publication of a report on general principles for health risk assessment in 2016. This has been complemented by the regular updates of WHO risk quantification tools like AirQ+[1] and CLIMAQ-H[2], as

[1] AirQ+ software allows the quantification of the health impacts of exposure to air pollution, including estimates of the reduction in life expectancy, for the most significant air pollutants.
[2] CLIMAQ-H software allows to calculate the health and related economic gains that can be achieved by implementing actions and measures aimed at mitigating climate change by reducing domestic carbon emissions.

well as the participation of TFH members in updating the Health Risks of Air Pollution in Europe (HRAPIE-2) project.

These scientific efforts of the TFH have been instrumental in informing major global projects led by WHO ECEH, including the updates of the WHO global air quality guidelines in 2005 and 2021. Additionally, the TFH's work has contributed to the development of policy instruments by WHO and UNECE, such as the WHA68.8 resolution on addressing the health impact of air pollution or amendments to the 1999 protocol to abate acidification, eutrophication and ground-level ozone (Gothenburg protocol).

Capacity building activities under the TFH have focused on quantifying the health impacts of air pollution at regional and subregional levels. Recently, there has also been attention on discussing effective communication of air pollution risks through tailored health messages.

Working with very limited resources, the TFH mobilizes the health and environment sectors to work together with the UNECE Secretariat, Member State representatives, the European Commission (also Party to the Convention), civil society and academia to address air pollution and protect human health, taking a multidisciplinary and multistakeholder approach. Originating from an environmental convention, the TFH is a well-established intersectoral platform, putting human health at the centre of its work; it has emerged as a valuable model for discussing and promoting these issues at the regional level *(29).*

Lessons learned and future opportunities for health leadership

The achievements of the UNECE Air Convention in the region have resulted in emission reductions of 50–80% since 1990, as well as health benefits *(30).*

From a health perspective, the THF has been instrumental as a platform for sharing knowledge among an extensive international network of multidisciplinary scientists, leading to the development of major publications on the health impacts of key pollutants, including the WHO global air quality guidelines and important health impact assessment and risk quantification tools, some of which are now integrated and used for local and national planning *(31).*

Way forward

Building collaboration and shared expertise

UNEA 6/10 resolution recognizes "the benefits of broadening the scope of existing geographical cooperation to address transboundary air pollution and bringing together regional and subregional bodies to mobilize new expertise, resources, and expanded capacity".

Although this document has outlined the positive steps being taken to establish regional air quality networks across the globe, there is even more scope for collaboration and cooperation across the current patchwork of agreements. There is much more we can do to share expertise and build capacity across regions to collectively improve global air quality and drive co-benefits for health and the climate.

AQMx repository of technical tools, models, data and knowledge

However, initiatives contributing to the implementation of UNEA 6/10 resolution are already available to enable key stakeholders around the world to enhance air quality management capacities. The Air Quality Management Exchange Platform (AQMx) exists as a repository of technical tools, models, data and knowledge to build capacity among air quality managers worldwide *(32).* It aims to serve as a reliable global resource hub, offering up-to-date information and guidance tailored to diverse capacities and local contexts.

UNEP Global Air Quality Cooperation Network
The UNEP Global Air Quality Cooperation Network aims to facilitate knowledge-sharing between participants from different regions and to empower governments at different levels and other key stakeholders to reduce air pollution by increasing the uptake of solutions from high-impact sectors, and improving access to finance, funding and other forms of support. Therefore, there are available resources which, if used effectively, could multiply the effect of efforts in different regions to address the significant impacts of air pollution to collectively achieve healthier environments for all.

Integrating the health argument
The integration of health into the science-policy interface of the UNECE Air Convention has resulted in a unique platform for discussions that have led to the development of key health risks quantification tools and health assessment reports of selected air pollutants. Other regional cooperation schemes can learn from the THF experience, its success and the need for dedicated resources. The health argument can also contribute to the harmonization of legislation and standards across countries.

These regional agreements and programmes, whether they start as scientific collaborations or are well-established legally binding agreements, are very important to ensure sustainable fora for scientific discussions and implementation of regional- and country-level actions. The commitment to the political and financial aspects that ensure their success should be preserved from short-term geopolitical pressures, to ensure a continuity in sharing global expertise and building capacity across regions to collectively achieve healthier environments for all.

Acknowledgements

This Science and Policy Summary (SPS) was coordinated by the WHO Air Quality, Energy and Health Unit.

WHO would like to thank the many individuals and institutions who contributed to the development of this document. This document was prepared by Anna Engleryd (Environmental Protection Agency, Sweden); Sophie Gumy and Kerolyn Shairsingh (WHO Department of Environment, Climate Change and Health); Dorota Jarosińska and Román Pérez Velasco (WHO European Centre for Environment and Health, Germany); John Salter and Anna Saunter (Department for Environment Food and Rural Affairs, United Kingdom of Great Britain and Northern Ireland); and Carolin Sanz Noriega (UNECE).

WHO also recognizes the helpful contributions provided by Bertrand Bessagnet and Isabella Koziell (ICIMOD); Dana Crawhall-Duk and James Morris (CCAC); Kevin Hicks and Alice Kaudia (Stockholm Environment Institute, Sweden); Lorenzo Labrador and Oksana Tarasova (WMO); Iyngararasan Mylvakanam (UNEP); Sangmin Nam (UNESCAP); Maria Katherina Patdu (EANET); Jordi Pon (LAC); Cristina Vert Roca (WHO Department of Environment, Climate Change and Health); and Simon Wilson (AMAP).

References[3]

1. Sustainable Development Goal indicator 3.9.1: mortality attributed to air pollution. Geneva: World Health Organization; 2024 (https://iris.who.int/handle/10665/379020). Licence: CC BY-NC-SA 3.0 IGO.
2. The global health cost of $PM_{2.5}$ air pollution: a case for action beyond 2021. Washington, DC: World Bank Group; 2022 (https://hdl.handle.net/10986/36501).

[3] Accessed 24 March 2025.

3. Resolution 1/7: strengthening the role of the United Nations Environment Programme in promoting air quality. Report of the Executive Director. United Nations Environment Assembly. United Nations Environment Programme; 2016 (https://wedocs.unep.org/20.500.11822/34316).
4. Resolution WHA68.8: health and environment: addressing the health impacts of air pollution. World Health Assembly 68. Geneva: World Health Organization; 2015 (https://iris.who.int/handle/10665/253237).
5. Global Atmospheric Watch programme (website). Geneva: World Meteorological Organization; 2025 (https://community.wmo.int/en/activity-areas/gaw).
6. Updated road map for an enhanced global response to the adverse health effects of air pollution. EB156/24. Geneva: World Health Organization; 2025 (https://apps.who.int/gb/ebwha/pdf_files/EB156/B156_24-en.pdf).
7. Resolution 6/10. Promoting regional cooperation on air pollution to improve air quality globally. United Nations Environment Assembly. United Nations Environment Programme; 2024 (k2400831.pdf).
8. Air quality (website). Nairobi: United Nations Environment Programme; 2025 (https://www.unep.org/topics/air).
9. CCAC (website). Climate and Clean Air Coalition; 2025 (https://www.ccacoalition.org).
10. Air pollution. Geneva: World Health Organization; 2025 (https://www.who.int/health-topics/air-pollution#tab=tab_1).
11. Health. Geneva; World Meteorological Organization (https://wmo.int/topics/health).
12. UNECE Convention on Long-Range Transboundary Air Pollution. United Nation; 1979 (https://treaties.un.org/pages/ViewDetails.aspx?src=TREATY&mtdsg_no=XXVII-1&chapter=27&clang=_en).
13. Arctic Council – 2017 Fairbanks Declaration. Arctic Council; 2017 (https://oaarchive.arctic-council.org/items/57b4cb2e-5a1c-4eeb-a1c5-65298006f3f7).
14. Regional action programme on air pollution. United Nations Economic and Social Commission for Asia and the Pacific; 2022 (https://www.unescap.org/sites/default/d8files/event-documents/AP.pdf).
15. ASEAN Agreement on Transboundary Haze Pollution. ASEAN Haze Portal; 2015 (https://hazeportal.asean.org/action/asean-agreement-on-transboundary-haze-pollution/).
16. Acid Deposition Monitoring Network in East Asia (website). Acid Deposition Monitoring Network in East Asia: Bangkok; 2025 (https://www.eanet.asia/).
17. Malé Declaration on Control and Prevention of Air Pollution and Its Likely Transboundary Effects for South Asia. Colombo: South Asia Co-operative Environment Programme; 2024 (http://www.sacep.org/programmes/male-declaration).
18. International Centre for Integrated Mountain Development. Kathmandu: International Centre for Integrated Mountain Development; 2025 (https://www.icimod.org/).
19. Science policy and finance dialogue on air quality management in the Indo-Gangetic Plain and Himalayan Foothills, 26–27 June 2024. Kathmandu: International Centre for Integrated Mountain Development; 2025 (https://www.icimod.org/event/climate-environment-risks/air-quality-management-in-the-indo-gangetic-plain-and-himalayan-foothills-2024/).
20. South Asia Co-operative Environment Programme (website). Colombo: South Asia Co-operative Environment Programme; 2025 (http://www.sacep.org/).
21. Regional cooperation for better air quality in West Asia. United Nations Iraq; 2023 (https://iraq.un.org/en/244749-regional-cooperation-better-air-quality-west-asia).
22. Intergovernmental Air Pollution Network for Latin America and the Caribbean. United Nations Environment Programme; 2023 (https://www.unep.org/intergovernmental-air-pollution-network-latin-america-and-caribbean).
23. Integrated assessment of air pollution and climate change for sustainable development in Africa. Climate and Clean Air Coalition; 2023 (https://www.ccacoalition.org/resources/full-report-integrated-assessment-air-pollution-and-climate-change-sustainable-development-africa).

24. ECOWAS CCAC partner since 2017. Climate and Clean Air Coalition; 2025, (https://www.ccacoalition.org/partners/ecowas).
25. The Paris Agreement. United Nations Climate Change; 2025 (https://unfccc.int/process-and-meetings/the-paris-agreement).
26. Convention on Biological Diversity. United Nations Environment Programme; 2025 (https://www.cbd.int/).
27. Basel, Rotterdam and Stockholm conventions. United Nations Environment Programme; 2025 (https://www.brsmeas.org/Home/tabid/10038/language/en-US/Default.aspx).
28. Joint Task Force on the Health Aspects of Air Pollution. Copenhagen: WHO Regional Office for Europe; 2025 (https://www.who.int/europe/groups/joint-task-force-on-the-health-aspects-of-air-pollution).
29. Historic 20th meeting of the Joint Task Force on the Health Aspects of Air Pollution [website]. Copenhagen: WHO Regional Office for Europe; 2017 (https://www.who.int/europe/news/item/16-05-2017-historic-20th-meeting-of-the-joint-task-force-on-the-health-aspects-of-air-pollution).
30. In times of tension, look to 45 years of cooperation for clean air. United Nations Economic Commission for Europe; 2024 (https://unece.org/media/environment/Air-Pollution-Convention/press/397637).
31. [Test d'AirQ+, un Outil d'évaluation quantitative des impacts de la pollution de l'air sur la sante]. French Agency for Ecological Transition (ADEME); 2019 (https://librairie.ademe.fr/56-test-d-airq-un-outil-d-evaluation-quantitative-des-impacts-de-la-pollution-de-l-air-sur-la-sante.html).
32. Air Quality Management Exchange Platform [website]. Climate and Clean Air Coalition; 2025 (https://aqmx.org/).