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, leading to 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.

World Health Organization

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 6.4 million deaths worldwide in 2021 *(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 µg/m^3) with 45 of these nations achieving IT4 (10 µg/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 µg/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.

[1] Science and Policy Summary

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 µg/m^3 24-hour average 45 µg/m^3
$PM_{2.5}$ (fine particulate matter)	Primary emissions from: • Residential combustion • Transport • Industry • 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	Annual average 5 µg/m^3 24-hour average 15 µg/m^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 average 100 µg/m^3
NO_2 (nitrogen dioxide)	Primary and secondary emissions from: • Transport • Industry • Energy production • Biomass burning • Residential combustion	Annual average 10 µg/m^3 24-hour average 25 µg/m^3
SO_2 (sulfur dioxide)	Primary emissions from: • Industry • Energy production • Natural sources	24-hour average 40 µg/m^3 10-minute average 500 µg/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.

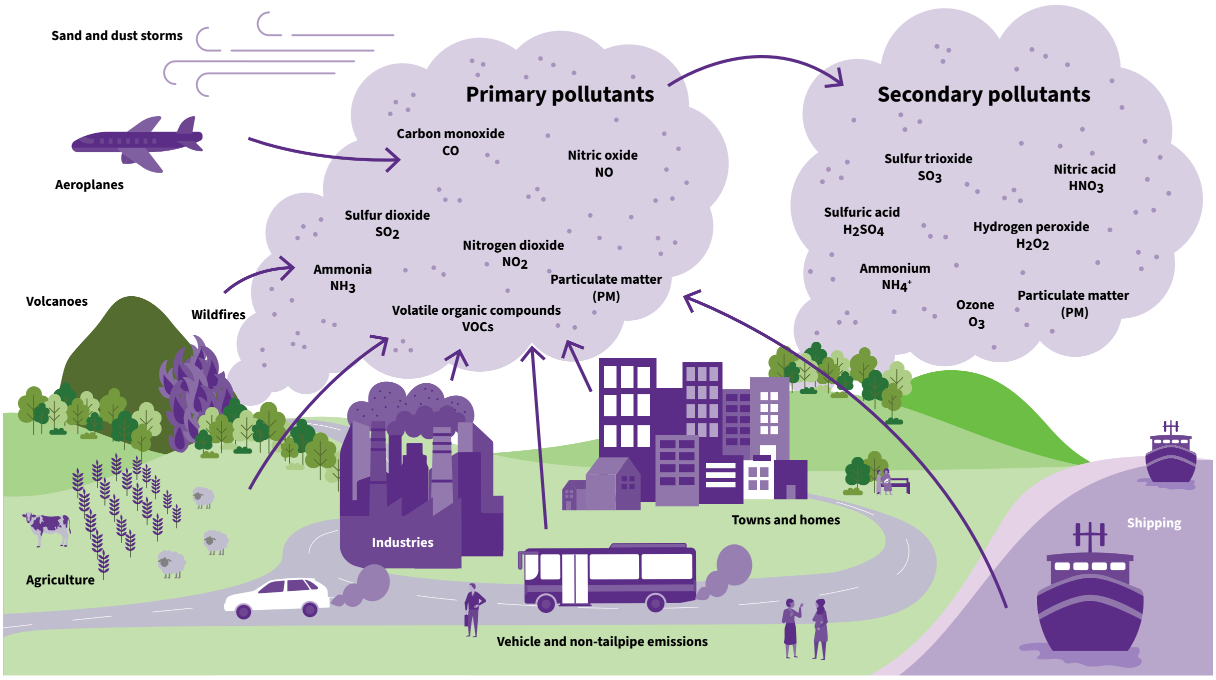
Pollutant characteristics and mixtures

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 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*

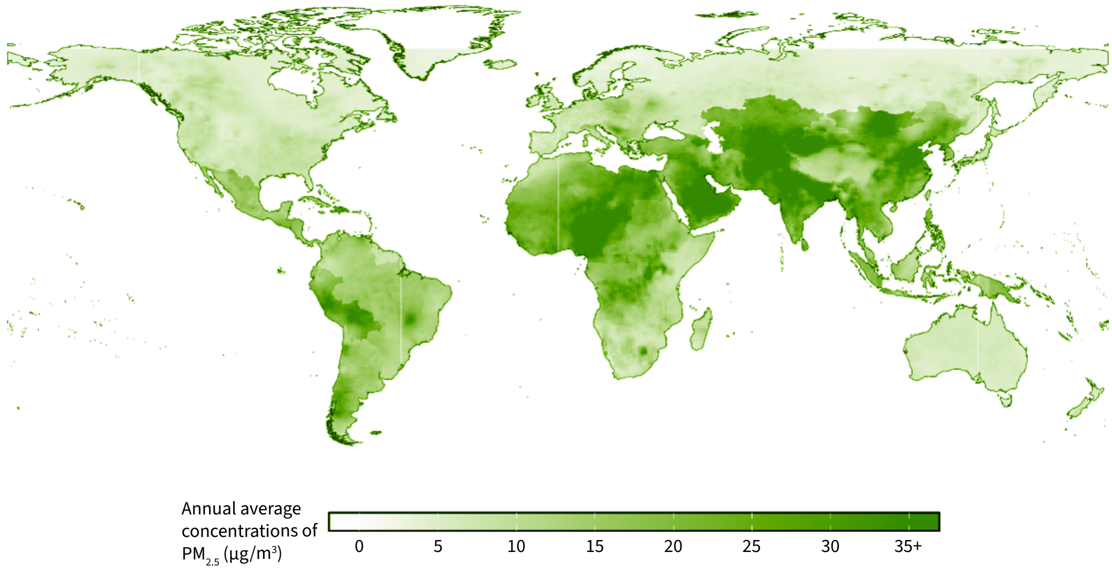
See SPS: *Household air pollution and related health effects*

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 m³)

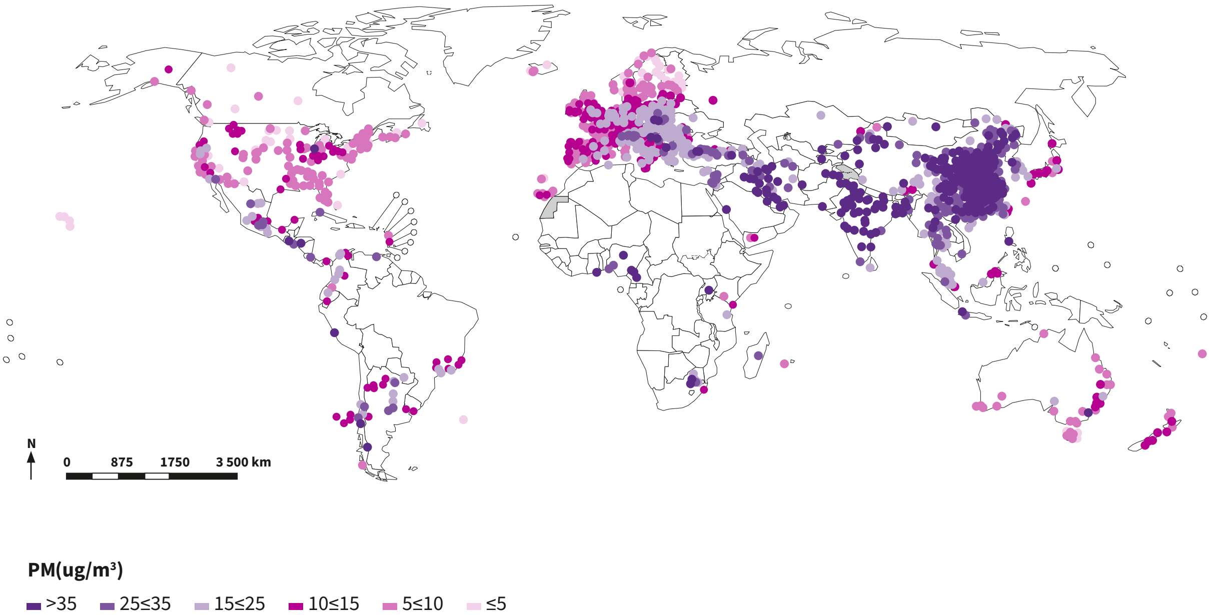


Source: Preliminary SDG 11.6.2 modelled estimates from the Data Integration Model for Air Quality *(7)*.

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



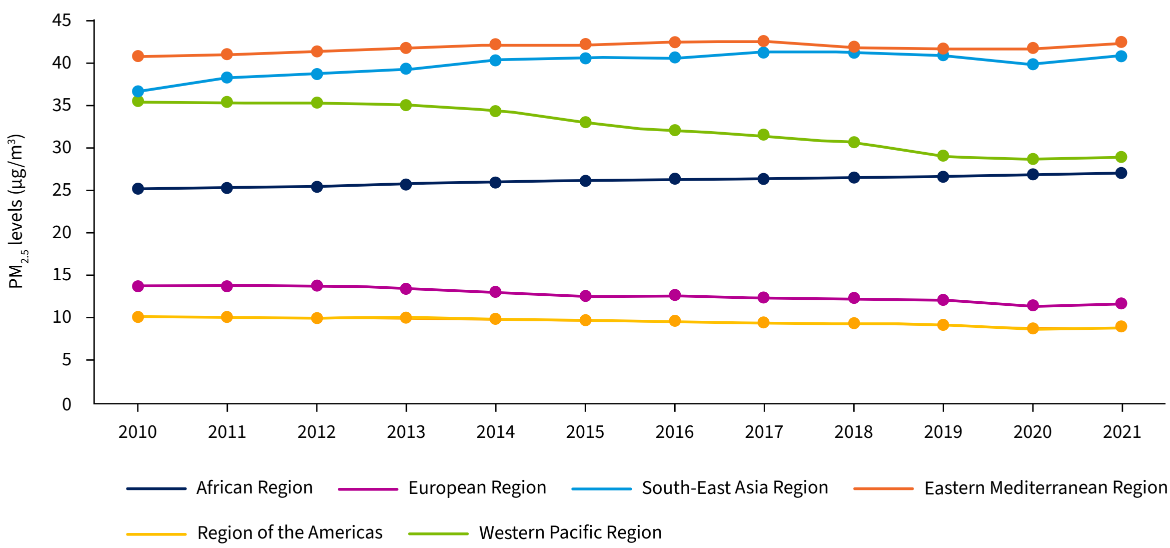
Notes: There is a large disparity in monitoring density in different regions of the world with particular gaps in parts of Africa, Latin America and Asia.

Source: WHO Ambient Air Quality Database *(8)*.

Trends and sources in world regions

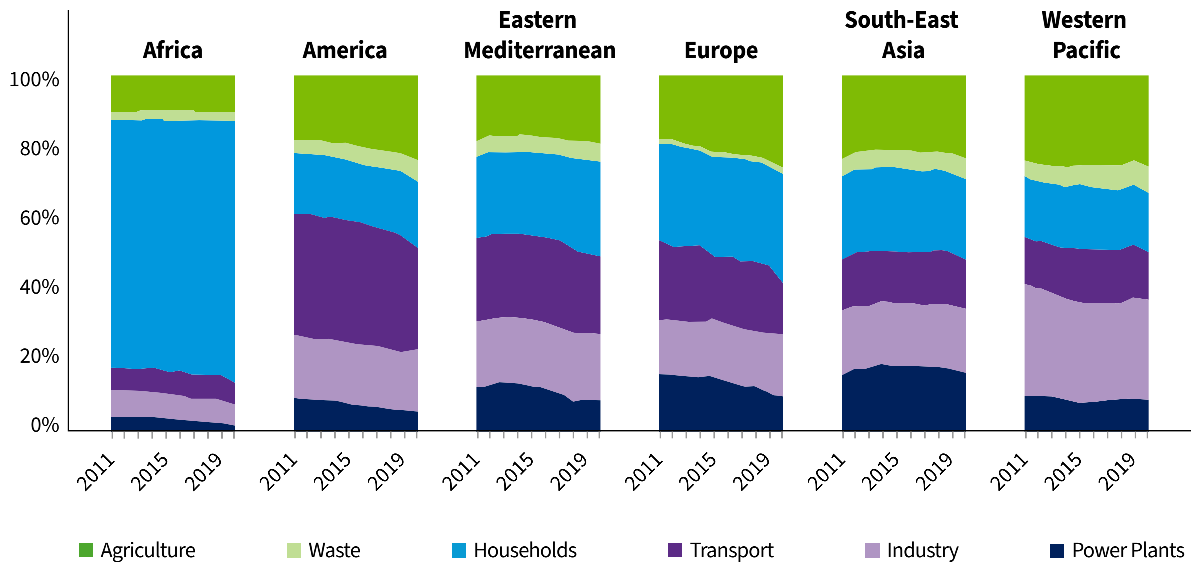
From 2010 to 2021, concentrations of $PM_{2.5}$ showed diverse trends across the regions, with levels decreasing in the WHO European, American and Western Pacific regions (see Fig. 4).

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 are 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 sources

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

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. We consulted with the following experts in the field (ambient and household air pollution exposure and epidemiology, air pollution policies, atmospheric modelling) to obtain recommendations for relevant articles, ensuring access to pertinent literature for this document. This consisted of exploring the most recent evidence and selecting key documents as a reference for the development of the SPS, prioritizing published systematic reviews and metanalyses.

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 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.

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