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Prioritizing Evidence Gaps: Air Pollution and Health Impacts of Climate Action

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People pass through the rising pollution on the Delhi-Jaipur Expressway. Gurgaon, Haryana, India. Photo: Sudarshan Jha, Shutterstock, 2021.

Executive Summary

Globally, around 8 million deaths are associated with air pollution each year.[1,2] The vast majority of these deaths are caused by anthropogenic sources of combustion, including energy production, power generation, transport, waste burning, industry and biomass burning (for household energy and agriculture). These activities result in a complex mixture of health- and climate-damaging pollutants with warming and cooling effects, including particulate matter, ground-level ozone, carbon dioxide, nitrogen dioxides and sulfur dioxides. Climate action to address these leading global sources of pollution in a way that results in net-cooling would offer short-term benefits to health while providing longer-term benefits to the planet.

Current evidence suggests climate actions will result in larger health gains via air pollution reductions than via CO_2 and temperature reductions[3]. At the same time, more research is needed to more precisely assess the effectiveness of clean air and climate actions being taken considering how actions reduce specific health-damaging source emissions or short-lived climate forcers (SLCFs). In addition, given the increasingly warming environment, more consideration needs to be given to the joint effects of air quality and heat.

We conducted a rapid scoping activity to identify and prioritize gaps in the evidence base that may be limiting cities' and countries' abilities to demonstrate the health impacts of climate mitigation actions targeting combustion source air pollution. Given the urgency of the issue, we focused on identifying evidence gaps that may be filled over roughly five years to inform action by 2030. To ensure that research results would have meaningful application to policy and regulation, we also considered critical evidence and data gaps that may hinder the robust linkage of routinely collected local data with the global evidence base. Opportunities to advance our ability to demonstrate the health and climate benefits of air quality actions were prioritized. In addition, as we considered the feasibility of applying research results to areas most affected by climate and air quality, we also considered how current levels of data and capacity could influence policy and looked at potential regulatory opportunities that could be unlocked by filling these gaps.

Approach

We took a systematic approach with mixed methods to identify and prioritize the research gaps in air pollution and health in the context of climate change. We conducted a comprehensive search of peer-reviewed systematic reviews and meta-analyses on the health effects of air pollution to establish the current state of knowledge. This was complemented by international consultations with researchers, policymakers, technical experts and government stakeholders to gather insights and identify areas where further research is needed. A global advisory panel provided additional expertise and guidance. Identified research gaps were prioritized, based on their scientific significance, policy relevance and feasibility, before we formulated recommendations to guide future research efforts and address the identified gaps.

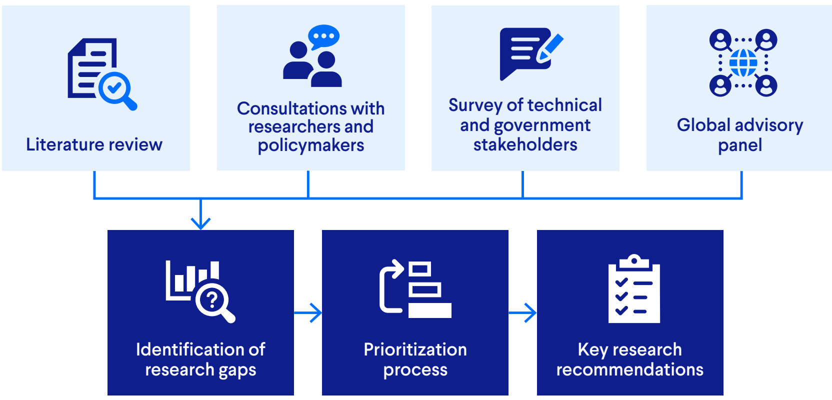

Figure 1. Summary of approach to identify and prioritize research gaps

Framing research priorities

We designed a rapid, two-stage pragmatic process to evaluate and prioritize research topics compiled through the literature review, stakeholder consultations and engagement with advisory panel members. Our goal was to prioritize research that would address critical climate, air quality and health issues in the context of broader considerations, such that research results would guide the development of effective, sustainable and ethically responsible solutions to mitigate the negative impacts of combustion.

Stage 1	Stage 2—Criteria		Priority score
Focus on combustion source pollution for greatest climate and air pollution mitigation potential Transport Industry Energy generation Wildfire Waste burning Agricultural burning Household energy	Scientific value	• filling critical gap • advancing knowledge	1 Little 2 Low 3 Medium 4 High
	Decision making value	• policy relevance • scalability • replicability	
	Feasibility/merit	• cost • timing	
	Capacity strengthening potential	• data systems strengthening • local opportunity	
	Public health potential	• emissions and/or exposure reduction potential • health mitigation potential • impact on cost to health system	
	Potential to advance equity	• filling critical gap • advancing knowledge	1 Yes 0 No
	Concern for unintended consequences	• filling critical gap • advancing knowledge	

Table 1. Overview of prioritization process used to identify research gaps for air pollution and health impacts of climate mitigation

From evidence to action: mapping research gaps along the chain of accountability

Researchers and policymakers consistently emphasize the need for evidence demonstrating the effectiveness of climate and clean air actions. Where efforts to promote clean air are in place, policymakers are keen to assess the extent to which improvements in air quality, and resulting impacts, may be quantified. Leaders who are currently weighing the feasibility and potential benefits of a suite of proposed measures would like to make decisions based on credible evidence that selected solutions will be effective.

However, even when health benefits are the ultimate aim, successful implementation involves consideration of the extent to which different control measures, such as transition to alternative energy sources, electrification of vehicle fleets or establishment of low-emission zones, may influence various points along the chain, from source control to emissions reduction, air quality/pollutant concentrations, exposure, dose and health effects. In addition, mediating factors along the chain, ranging from pollutant transport and transformation to key factors influencing susceptibility—such as nutrition or socioeconomic status—must be taken into account. As we consider the added complexity of a warming environment, the interaction of air quality and heat and their wide-ranging impacts on pollutant levels and health impacts also must be better characterized across the chain.

Research recommendations have been framed based on an adapted version of the chain of accountability[4] linking actions to health effects. This approach allows us to group priorities logically along this pathway so we can clearly articulate how research to fill fundamental knowledge gaps will support the design, implementation and evaluation of current and future climate and clean air policies.

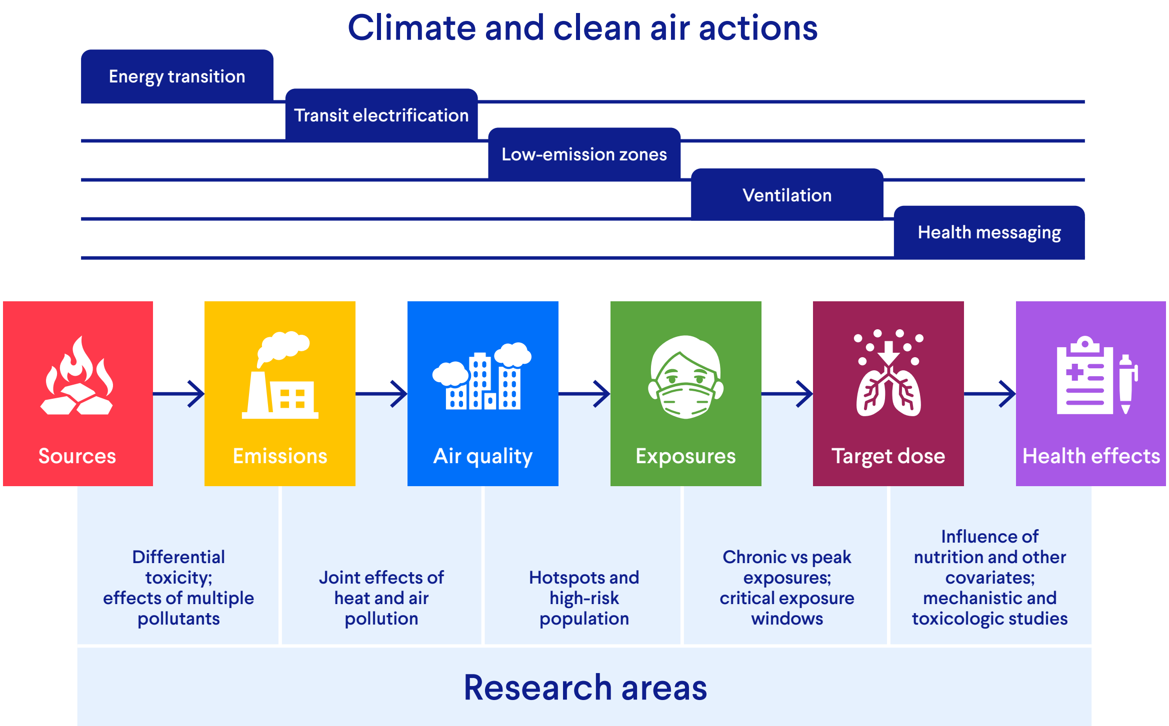

Figure 2. Modified chain of accountability for impact of climate and clean air action

Figure 2 depicts a refined chain of accountability for air pollution, expanding upon the traditional linear chain. It acknowledges the intricate interplay among sources, emissions, ambient air quality, exposures, target dose and health effects. Target clean air and climate actions (above) and illustrative examples of research areas (below) are provided along the chain.

While actions are generally intended to target a specific segment along this chain, from source reduction to health outcome mitigation, it is important to recognize that these actions often have cascading effects and may influence multiple stages. This approach also allows us to better synthesize recommendations, while it avoids artificially grouping recommendations by discipline. Where warranted, we flag research recommendations that may be of global priority and are of increasing and/or particular importance for selected regions or populations.

Sources: Priority sources identified are not necessarily global sources of pollution with key evidence gaps. Rather, they reflect leading regional sources of emissions. Location-specific source apportionment is also critical as pollution sources and their impacts vary significantly between urban, rural and industrial settings.

Emissions: Foundational gaps in our understanding of emissions and their broader implications for air quality, climate and health need to be filled in order to better evaluate the impact of actions being taken. This includes:

- development of updated emission inventories
- better data on how climate actions are influencing emission patterns

Also needed is a better understanding of the complex interactions between various emission sources and atmospheric processes to improve air quality management. One key priority is examining the joint effects of air pollution and climate drivers. This topic is vital because heat can worsen both air quality (e.g., impact on ozone formation) and its health impacts. Another essential area is the development of advanced atmospheric models that incorporate real-world conditions like changing meteorological patterns, urban heat islands and secondary pollutant formation. These models are critical for predicting how emissions evolve in the atmosphere and for devising effective mitigation strategies.

Air quality: Topics to directly inform policies aimed at reducing exposure disparities and improving public health outcomes were prioritized. Research priorities included a focus on how air quality is affected by temperature, especially temperature's impact during air pollution episodes versus its longer term effects given seasonal trends in temperature and air quality. Also of interest is the interaction of temperature on formation of secondary pollutants (e.g., ozone) which may result in even greater health impacts beyond those expected from primary pollutant emissions.

Exposures: Recommendations focus on gaining a better understanding of how exposures to air pollution translate into biological doses that directly affect human health, bridging the gap between environmental exposures and quantifiable health impacts, and enabling more precise risk evaluations and tailored interventions. A key priority is investigating the relationship between exposure duration, intensity and target dose to identify the most critical exposure windows that lead to adverse health effects. Another priority is studying the life-stage-specific exposure patterns of air pollution, particularly in vulnerable populations and older adults. Mechanistic studies to explain epidemiologic results are also prioritized here. Finally, examining the impact of cumulative and combined exposures to multiple pollutants is essential to understanding how these exposures interact biologically to produce additive or synergistic effects.

Target dose: Research in this area delves into how combined environmental stressors affect target doses. This also involves a focus on the combined impacts of air pollution and heat. Additionally, some source-specific studies may warrant a focus on specific diseases, as well as the compounded impact of wildfire smoke and heat, emphasizing the complexity of air pollution's health effects.

This area also includes a focus on dose-response relationships in vulnerable populations such as children, elderly people and those with preexisting health conditions, and research on socioeconomic modifiers of health outcomes as this is vital to address health disparities and to design equitable public health policies.

These topics must be prioritized because they provide a deeper understanding of how air pollution can manifest in diverse health outcomes on a warming planet, considering individual and contextual vulnerabilities.

Additional needs to advance climate and clean air policies for health

There were a few additional areas of research that were flagged by both technical and policy stakeholders as being of critical importance to 1) make the case for actions to be taken, and 2) marshal the widespread public support needed for successful implementation of actions to be taken. These include policy-relevant impact assessments to quantify the health and economic benefits of local actions using approaches that harness the best available global evidence and available local data. Also prioritized was social science research to promote increased awareness and behavior change. We would also recommend investing in the development of new methodologies or technical guidance that can direct the assessment of the health, climate and economic impacts of clean air and climate mitigation policies under consideration and/or in progress. This would help ensure the robustness of assessments to be undertaken, especially when coupled with efforts to strengthen local capacity to collect and integrate relevant data.

Pragmatic considerations

Addressing critical data and capacity gaps: Effective evaluations require clear baseline data on air quality and health outcomes. In some places this data may not be routinely collected or be readily accessible in an easily usable format. Many places with the greatest air quality concerns face capacity gaps in air quality data collection infrastructure, particularly for routinely updated emissions data, real-time air quality monitoring, and individual exposure assessment. Filling these gaps is essential to increase the global distribution of policy-relevant accountability research and help to ensure that interventions are evaluated rigorously.

Leveraging ongoing studies: Given the interest in generating evidence in the short term, opportunities to retrofit existing cohorts and other similar longitudinal studies are particularly valuable. The integration of routine and complete health data is also essential for understanding the relationship between pollution exposure and health outcomes. However, several gaps may hinder the ability to derive robust conclusions and implement effective interventions, due to fragmentation of health and exposure data sources, underrepresentation of vulnerable populations, and inconsistencies in data reporting and completeness. Impediments to timely data access and integration also need to be considered, including legal and ethical barriers, lack of interoperability between disparate data systems, and technological constraints to large-scale data integration.

Conclusion

Through this rapid scoping exercise, a common theme has emerged from our engagement with technical experts and policy stakeholders focused on air quality around the world: The priority should be to evaluate the effectiveness of climate actions taken, with a focus on assessing measurable impacts on public health. In order to do this effectively, there are critical and fundamental research gaps to be filled along the modified accountability chain linking climate and air quality action to health effects. This includes a range of epidemiologic and mechanistic studies focused on characterizing the impact of actions taken to address climate forcing emissions, and/or overall air quality on exposures and health effects. Mediating factors along the chain, ranging from pollutant transport and transformation to key factors influencing susceptibility, such as nutrition or socioeconomic status, need to be taken into account. New evidence emerging from targeted efforts to fill these gaps will serve as essential inputs to further research and practices as we aspire to maximize the measurable health benefits of climate and clean air action.

Given the urgency of this issue, for both people and the planet, we must prioritize research results that may be achieved over the short term, ideally over the next five years. At the same time, there are critical data and capacity gaps that are currently hindering ability to conduct research in a timely manner. Support to strengthen the research infrastructure, with a focus on the availability of routinely collected air quality and health data, will pave the way for a more robust research infrastructure moving forward.

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Introduction and objectives

Globally, around 8 million deaths are associated with air pollution each year, including 5.1 million deaths from burning of fossil fuels.[1a, 1b] The vast majority of these deaths are caused by anthropogenic sources of combustion, including energy production, power generation, transport, waste burning, industry, and biomass burning (for household energy and agriculture). These activities result in a complex mixture of health- and climate-damaging pollutants with warming and cooling effects, including particulate matter, ground-level ozone, carbon dioxide, nitrogen dioxides and sulfur dioxides. Climate action to address these leading global sources of pollution in a way that results in net cooling would offer short-term benefits to health while providing longer-term benefits to the planet.

Current evidence makes a strong case that from a health perspective, climate actions will result in larger health gains via air pollution reductions than via CO2 and temperature reductions.[2a] At the same time, more research is needed to precisely quantify the effectiveness of clean air and climate actions being taken. In addition, given the increasingly warming environment, more consideration needs to be given to the joint effects of air quality and heat.

We conducted a rapid scoping activity to identify and prioritize gaps in the evidence base that are limiting cities' and countries' abilities to demonstrate the health impacts of climate mitigation actions targeting combustion source air pollution. Given the urgency of the issue, we focused on identifying evidence gaps that may be filled over roughly five years to inform action by 2030, distinguishing among 1) universal evidence gaps, such as data directly linking exposures to health effects, and 2) key gaps in evidence associated with specific health-damaging source emissions or short-lived climate forcers (SLCFs). To ensure that research results would have meaningful application to policy and regulation, we also considered critical evidence and data gaps that may hinder the robust linkage of routinely collected local data with the global evidence base.

Opportunities to advance our ability to demonstrate the health and climate benefits of air quality actions were prioritized. We considered how current levels of data and capacity could influence the ability to fill in critical research gaps, particularly in geographies most affected by climate and air quality. We also explored potential regulatory opportunities that could be unlocked by filling these gaps.

Trends in air pollution, short-lived climate forcers and health effects

Regional trends in major pollutants and combustion sources of pollution

While air quality has improved in many high-income countries due to stringent regulations and the adoption of cleaner technologies, several countries continue to struggle with rising levels of air pollution from combustion sources. The major air pollutants of concern over the past 20 years include particulate matter (PM), nitrogen oxides (NO_x), sulfur dioxide (SO_2), carbon monoxide (CO), and ground-level ozone (O_3). The trends in these pollutants have been shaped by various socioeconomic, technological, and policy-driven factors. As seen in Figure 1, the emission sources vary considerably across regions, with industrialization, transportation and biomass burning serving as key drivers in different geographies. Unfortunately, comparable trends in wildfire emissions are not available.

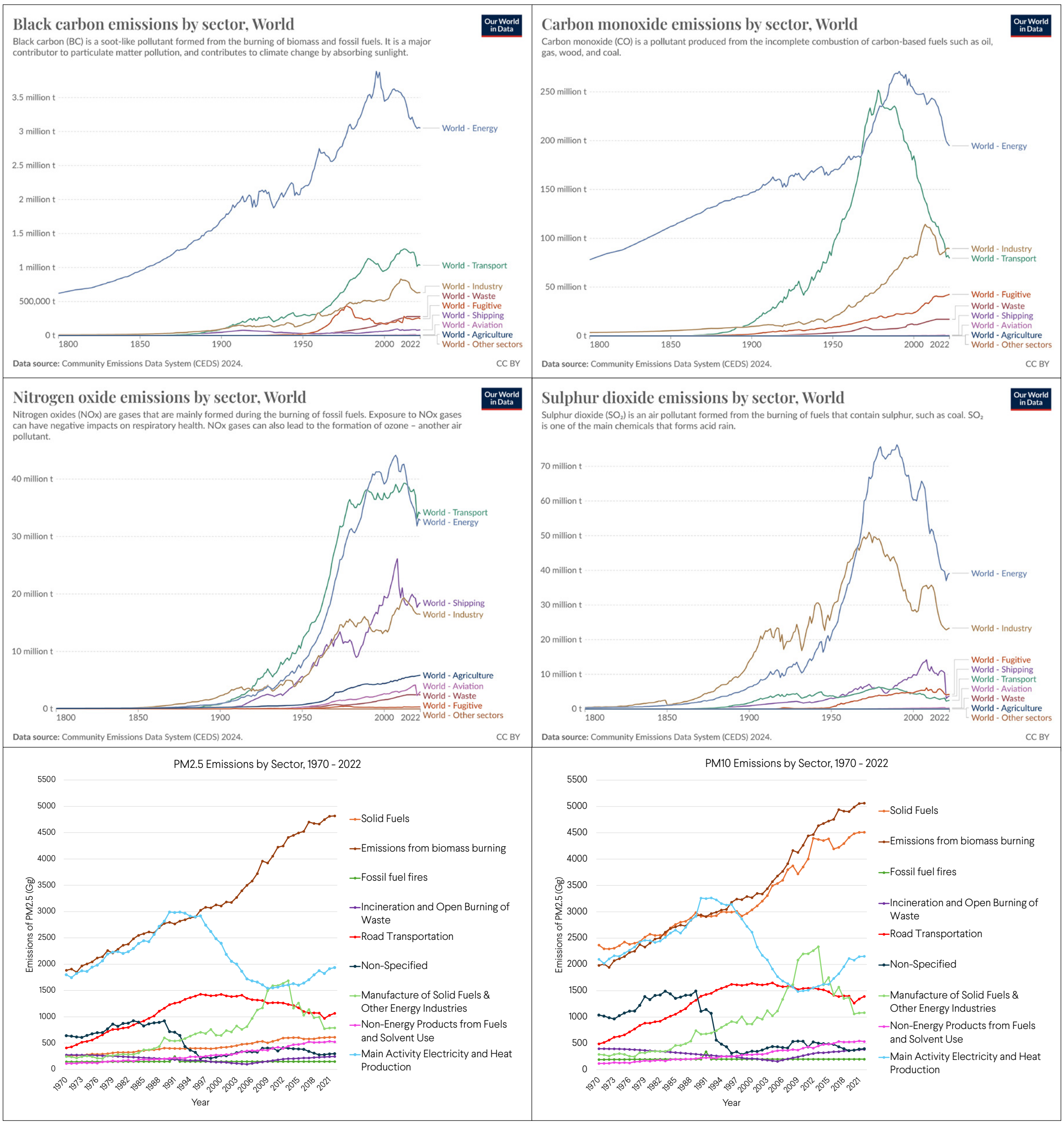


Figure 1. Global trends in pollutant emissions by sector source, 1800-2022

a. Black carbon (BC). Data source: Community Emissions Data System (CEDS) 2024[2]
b. Carbon monoxide (CO). Data source: Community Emissions Data System (CEDS) 2024[2]
c. Nitrogen oxide (NOx). Data source: Community Emissions Data System (CEDS) 2024[2]
d. Sulfur dioxide (SO2). Data source: Community Emissions Data System (CEDS) 2024[2b]
e. Particulate matter (PM): $PM_{2.5}$ and PM_{10}. Data source: Emissions Database for Global Atmospheric Research (EDGAR) – Global Air Pollutants[3]

Particulate Matter (PM): PM continues to be the most important indicator of health-damaging pollutant on a global scale and is the primary target of actions being taken. Rapid industrialization, increased vehicular emissions and biomass burning are significant contributors to elevated PM concentrations. IOver 90% percent of the world lives in areas exceeding World Health Organization's air quality guidelines, with severe implications for public health. The highest PM levels are experienced by residents of rapidly developing countries across South and Southeast Asia, and Sub-Saharan Africa. There has been a general decline in PM levels in high-income and some middle-income countries over the past two decades, due to the enactment of stringent air quality regulations and improvements in industrial technologies. For example, in China, $PM_{2.5}$ levels decreased by 40% between 2013 and 2020 due to the country's Action Plan for Air Pollution Prevention and Control.[4] However, in many low-income regions, particularly in Asia and parts of Africa, PM levels have remained high or continued to rise.

Black Carbon (BC): Black carbon is a key component of fine particulate matter as well as a short-lived climate pollutant. According to the World Bank data, global black carbon emission has been declining since 2012, following a period of rapid increase spanning several decades. However, levels often remain concerningly high even in places where substantial progress has been made. The largest emitters, such as China, the U.S., Brazil and Indonesia, have been experiencing overall reductions in BC emissions. However, several countries are seeing increases, including India, Pakistan and Nigeria.

Nitrogen Oxides (NO_x): Nitrogen oxides (NO and NO_2) are primarily emitted from combustion sources, such as vehicles, power plants and industrial facilities. Over the past 20 years, NO_x emissions have shown a mixed trend, with significant reductions in many high-income countries due to the adoption of stricter vehicle emissions standards and the transition to cleaner energy sources. In contrast, NO_x emissions in rapidly developing nations such as India have increased, driven by surging vehicle numbers, industrial expansion, and coal-fired power generation. For example, the U.S. reduced NO_x emissions by 50% from 2000 to 2020 due to cleaner vehicle technologies and fuel standards.[5] In contrast, NOx emissions in rapidly developing nations such as India have increased, driven by surging vehicle numbers, industrial expansion and coal-fired power generation.[6,7]

Ground-level ozone (O_3): ground-level ozone levels have increased globally due to rising temperature and rising emissions of precursors such as NO_x, methane, and volatile organic compounds (VOCs). In Europe, ground-level ozone levels increased by 20% from 2000 to 2020, even as NOx emissions declined, due to photochemical reactions influenced by higher temperatures.[8] Ground-level ozone is a secondary pollutant, so comparable data on emissions over time is unavailable. Figure 2 shows changes in ground-level ozone concentrations by region over the past decade.

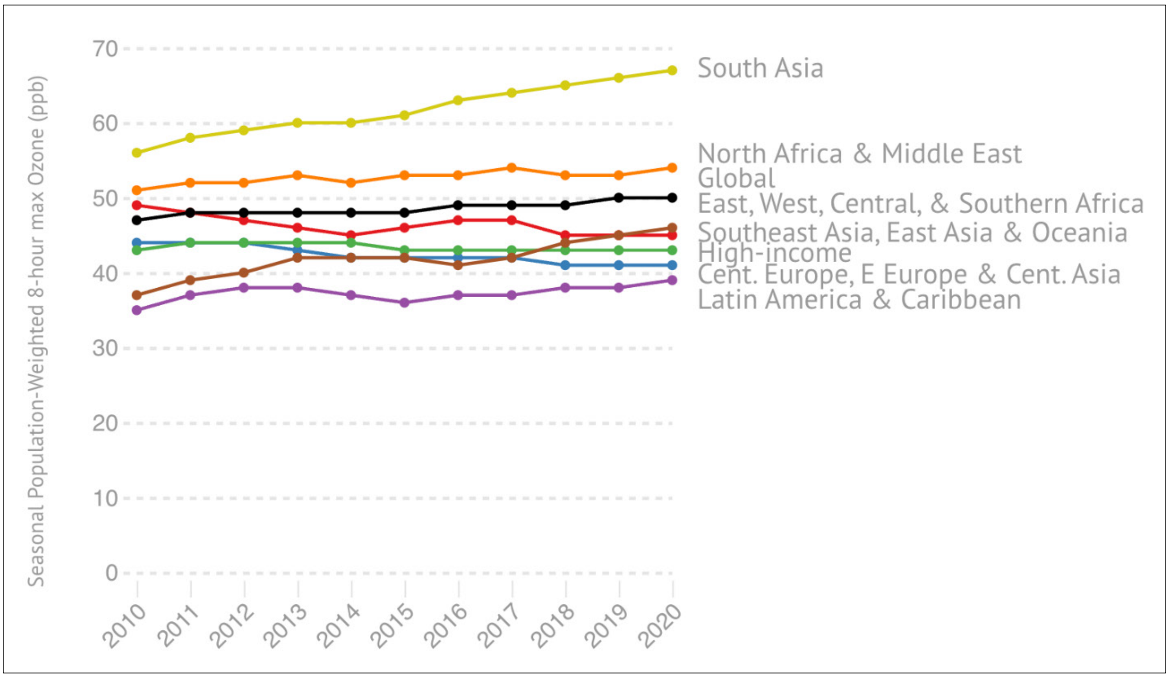


Figure 2. Trends in ground-level ozone levels by region, 2010-2020. Data source: State of Global[9]

Sulfur Dioxide (SO_2): From 1990 to 2015, global SO_2 emissions decreased by 31%.[10] This decline is largely attributed to the phasing out of high-sulfur fuels, the installation of flue gas desulfurization technologies, and tighter regulatory controls on emissions from power plants and industrial sources. In contrast, SO_2 emissions, especially in parts of Asia and Africa, have remained high or even increased, primarily due to the continued reliance on coal for energy generation and limited implementation of pollution control measures. In China, SO_2 emissions fell by 75% from 2000 to 2017, driven by a shift from coal-fired power plants to cleaner energy sources and advanced desulfurization technologies.[4] In India, SO_2 emissions increased by 40% between 2005 and 2015 due to continued reliance on coal.[11]

Carbon Monoxide (CO): Carbon monoxide emissions are related to combustion efficiency, i.e., better efficiency means lower CO emissions. CO has seen a general decline in most regions, particularly in high-income countries. This reduction is attributed to improvements in fuel quality, vehicle emissions standards, and the increased adoption of cleaner technologies. However, in regions with high levels of household biomass burning, such as sub-Saharan Africa and South Asia, CO remains a significant pollutant. In these regions, the use of traditional cooking and/or heating with wood, charcoal or animal dung continues to contribute to high levels of indoor and outdoor CO concentrations.

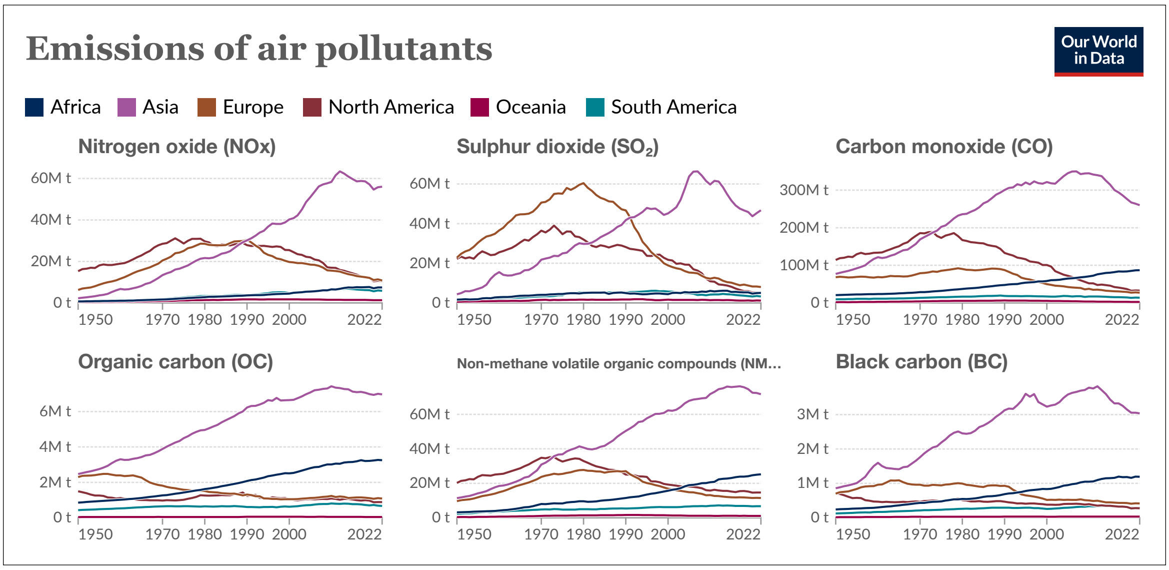


Figure 3. Trends in emission by region, 1950-2022. Data source: Community Emissions Data System (CEDS) 2024[2]

Figure 3 shows that the trends in air pollution over the past 20 years reflect a complex interplay of regional factors, including economic development, policy interventions, technological advancements and demographic shifts. In high-income countries, regulatory measures, technological innovation and a transition to cleaner energy have led to significant improvements in air quality. However, in many low- and middle-income countries, industrialization, urbanization and reliance on traditional energy sources continue to drive high levels of pollution.

In Asia, rapid industrialization and urbanization, coupled with high levels of coal consumption, have led to some of the highest levels of air pollution globally. In contrast, Europe and North America have generally seen declines in pollutant concentrations, although localized air quality issues persist in major urban centers. Sub-Saharan Africa and parts of South Asia continue to face significant challenges related to indoor air pollution from biomass burning, as well as outdoor air pollution from transportation and industrial activities. It should be noted that as the focus here is on combustion source pollution, so emissions from other leading anthropogenic sources of concern in some regions, including agriculture, construction, unpaved roads, desert dust, and chemical releases from industrial processes, were considered out of scope.

Trends in short-lived climate forcers

Climate change and air quality are deeply interconnected and policies to reduce air pollution can offer a "win-win" solution for clean air and climate. See Figure 4.

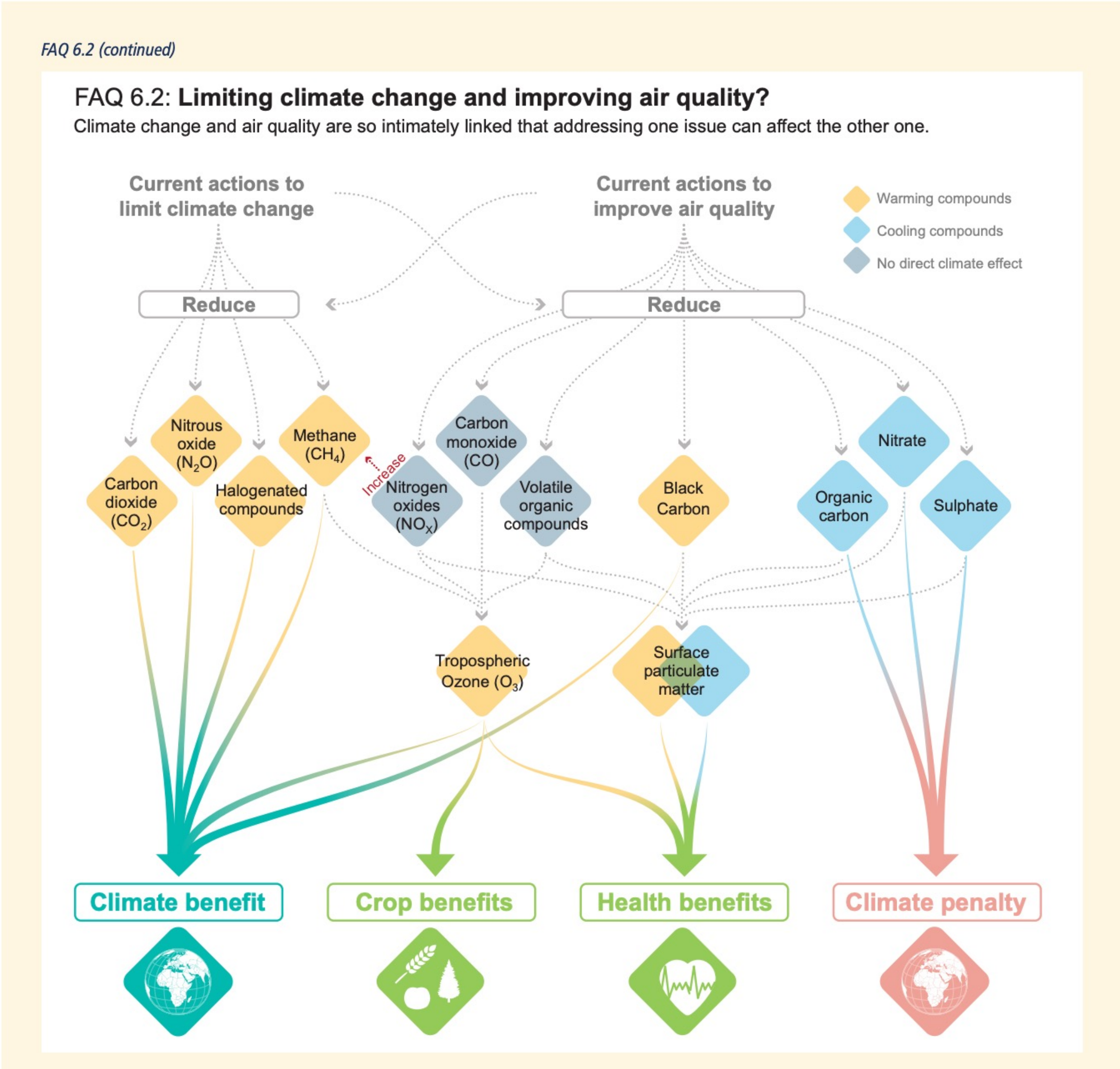


Figure 4. Links between actions aiming to limit climate change and actions to improve air quality. Greenhouse gases and aerosols can affect climate directly. Air pollutants (bottom) can affect human health, ecosystems and climate. All these compounds have common sources and sometimes interact with each other in the atmosphere, which makes it impossible to consider them separately (dotted grey arrows). Source: Intergovernmental Panel on Climate Change[13a]

Anthropogenic emissions of air pollution and greenhouse gases largely share the same sources. The same activities that emit health-damaging pollutants are also established sources of long-lasting greenhouse gases (Figure 5). And many of the health-damaging pollutants are also short-lived climate forcers (SLCFs) that affect climate on a relative shorter time scale (days to decades) compared to long-lived greenhouse gases like carbon dioxide. Anthropogenic SLCFs include aerosols like sulphates, nitrates and black carbon, and gases like methane, ground-level ozone, nitrogen oxides, carbon monoxide, nonmethane volatile organic compounds, sulphur dioxide and ammonia.

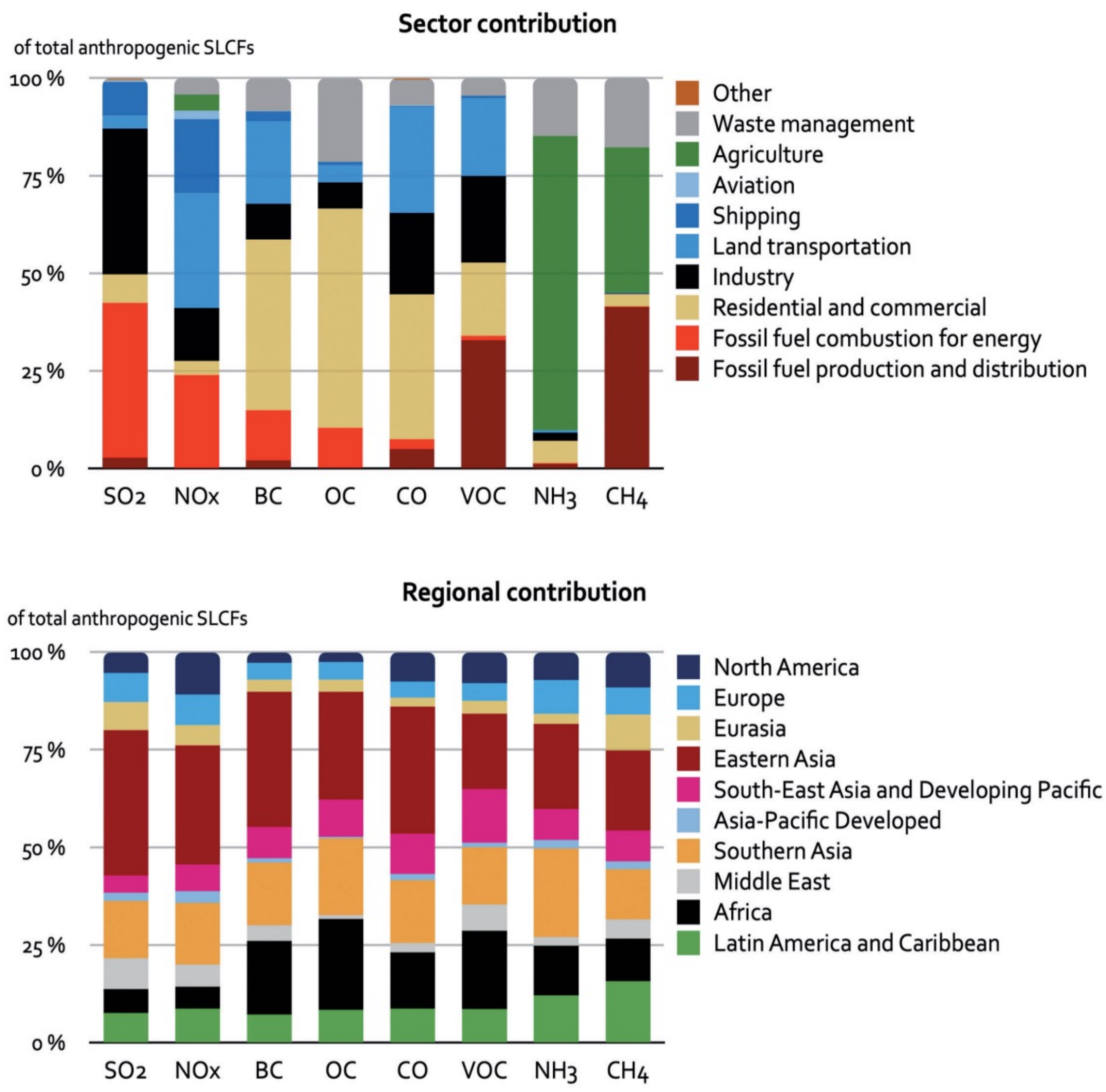


Figure 5. Relative regional and sectoral contributions to anthropogenic emissions of short-lived climate forcers (SLCFs), 2014. Source: Intergovernmental Panel on Climate Change[13a]

From climate change impacts to the impact of climate action

Evidence shows how climate change intensifies air pollution by altering atmospheric conditions that affect the formation, dispersion and persistence of pollutants such as ground-level ozone and fine particulate matter.[13] Researchers are currently exploring ways other climate change impacts (e.g., heat) may interact with air pollution and how this process affects human health.

Climate actions will result in larger health gains via air pollution reductions than via CO_2 and temperature reductions. The priority in the short term should be to evaluate the effectiveness of climate actions taken, with a focus on assessing measurable impacts on public health. For example, better ways are needed of quantifying the impact of national determined contributions on reducing health-relevant air pollutants, and then estimating the resulting impacts on public health.

Trends in health effects of air pollution

The regional burden of disease attributable to air pollution has evolved significantly over the past two decades, due to changes in exposure and age structures (e.g., increasing older age groups in many regions). The WHO Africa and the Eastern Mediterranean regions have seen slow but steady increases in air pollution-related deaths, while the region of the Americas has seen a very slight decrease. The Southeast Asian region has seen a dramatic rise in air pollution deaths, while the European region has seen a dramatic drop in air pollution deaths. Although the Western Pacific region saw a rise in air pollution deaths through the early 2000s, those began to decline until very recently.

Looking closer at Figure 6, ground-level ozone and particulate matter deaths have remained relatively stable in most regions. However, Southeast Asia has seen a large increase in ground-level ozone-related deaths; this is mainly due to increases in chronic diseases occurring as a result of the aging of the population. The Western Pacific has seen a decline in ground-level ozone-related deaths, with the burden now approaching the number of ground-level ozone-related deaths in 1990. Southeast Asia has experienced a rise in particulate matter deaths, compared to the decline in particulate matter deaths in Europe.

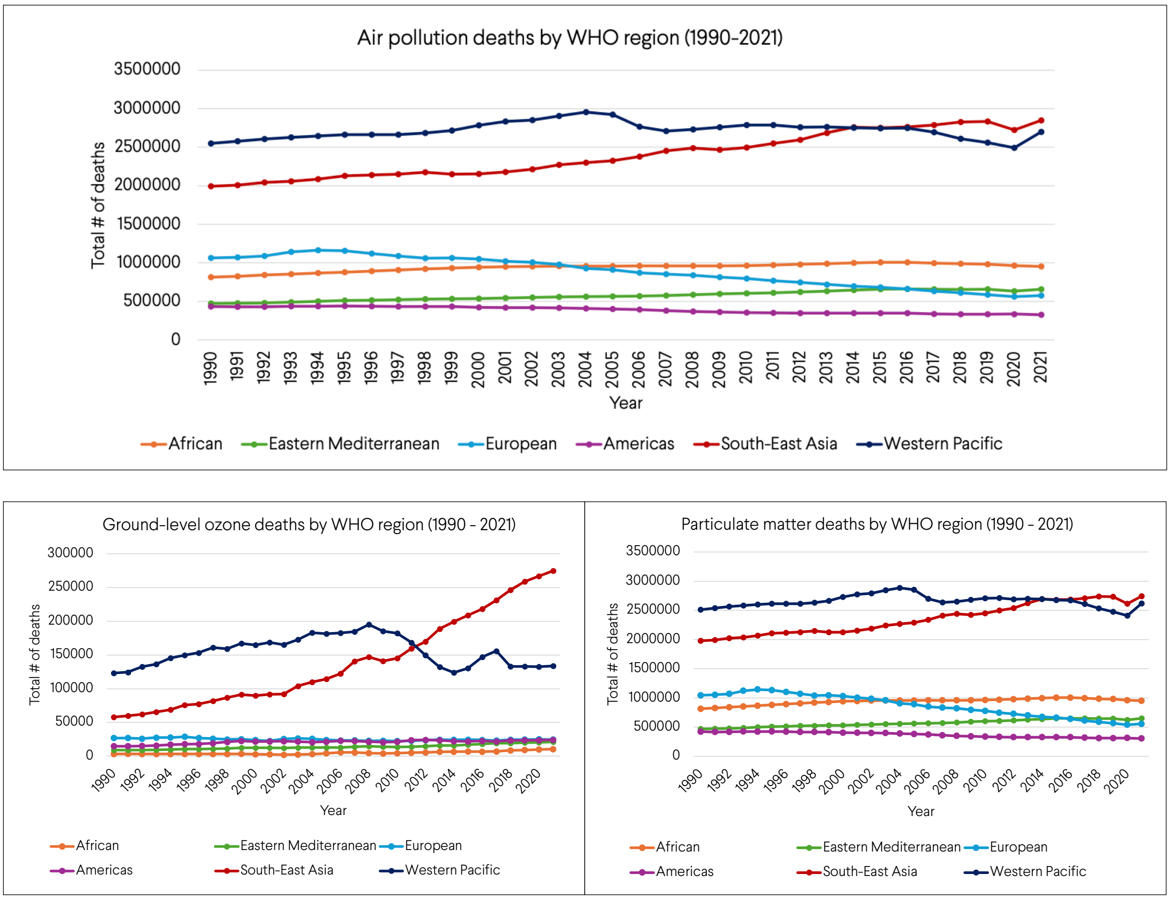


Figure 6. Top: Deaths attributable to air pollution by WHO region, 1990-2021. Bottom: Deaths attributable to ground-level ozone and particulate matter by WHO region, 1990-2021. Data source: Institute for Health Metrics and Evaluation 2024[1]

The pathway from air pollution exposure to health effects

The understanding of how air pollution affects health has advanced significantly over the past few decades. Originally, research focused mainly on the direct effects of individual pollutants, such as PM, NO_2, SO_3, O_3 and CO, linking them to acute health effects such as respiratory issues, cardiovascular diseases and mortality. However, advancements in environmental health sciences, epidemiology and toxicology have increasingly shown that these relationships are more complex than previously thought. Initially, exposure-response relationships were typically assessed through cross-sectional studies, often focusing on observable, short-term effects like asthma exacerbations or respiratory infections. The assumption was that higher concentrations of pollutants led directly to higher incidences of specific health outcomes. As evidence accumulated, researchers began to realize that health impacts of air pollution could be attributed not only to short-term, high-level exposures but also to long-term, low-level exposures. Chronic exposure to even moderate concentrations of pollutants over years can lead to the development and exacerbation of diseases such as cardiovascular disease, stroke, lung cancer and even neurodegenerative disorders. Furthermore, studies highlighted that certain vulnerable populations, such as children, elderly people and those with pre-existing health conditions, are disproportionately affected by long-term exposure.

Advances in modeling and epidemiological studies have revealed that exposure-response relationships for air pollutants are often nonlinear. In addition, while low levels of pollutants may cause subtle or undetectable health effects, small increases in pollution levels can have disproportionately large effects on health, particularly in vulnerable groups. Emerging evidence continues to suggest the absence of an “exposure threshold” effect: There is no safe level below which health effects would not occur as a result of exposure to air pollution. In other words, any measurable improvements in air quality should provide benefits to public health.

Recent studies have expanded the understanding of exposure-response pathways by considering complex interactions between pollutants, environmental factors and human biology. For example, air pollution’s impacts on health are not just limited to direct respiratory or cardiovascular outcomes, but also include diabetes and dementia—diseases with rapidly increasing prevalence globally, which will mean even more dramatic reductions in air pollution exposure needed to reduce the burden of disease in the future. Other key health indicators include immune system modulation, inflammation and oxidative stress. There is growing evidence that pollutants such as $PM_{2.5}$ and O_3 influence the body’s inflammatory response, which in turn triggers or exacerbates a range of diseases. In addition, pollutants interact with other environmental stressors—some of which are caused by climate change, like temperature fluctuations—and socioeconomic factors, making it more difficult to establish clear-cut exposure-response pathways.

A more nuanced understanding has emerged regarding individual and population-level susceptibility. Genetic factors, lifestyle and pre-existing health conditions (such as asthma, heart disease or diabetes) influence how a person responds to exposure. Children are particularly vulnerable, because their developing respiratory and immune systems are more susceptible to pollutants. Pregnant women and older people are also considered particularly susceptible groups. Similarly, socioeconomic factors like living conditions and access to health care mediate the effects of air pollution on health.

In conclusion, the understanding of exposure-response pathways between air pollution and health has shifted from simple, direct correlations to complex, multifactorial interactions. The field has expanded from studying individual pollutants to understanding how multiple pollutants and environmental factors interact and affect human health over the long term. The evolving understanding of the cumulative, nonlinear and often delayed health impacts of exposure underscores the need for continued research and stronger regulatory measures to protect vulnerable populations.

Trends in clean air and climate mitigation actions

Spurred by growing concerns over air pollution, public health and climate change, there has been a global shift toward more aggressive and comprehensive clean air and climate mitigation policies over the past two decades. These policies, which range from local air quality regulations to international climate agreements, have been implemented in varying degrees across different countries, with notable impacts on public health and environmental sustainability.

The last decade saw more than 1,200 climate and clean air policies enacted globally, addressing sectors like transportation, energy production and industrial emissions.[4] It should be noted, however, that policies must be effectively implemented in order for measurable clean air and climate mitigation progress to be achieved.

- European Union: As a frontrunner for clean air and climate action, the EU adopted the European Green Deal (2020) and numerous related policies, targeting net-zero emissions by 2050. Over 300 clean air regulations were adopted across member states.
- United States: The U.S. implemented more than 200 policies under initiatives like the Inflation Reduction Act (2022), emphasizing clean energy investments and emissions reduction.
- China: China enacted 150 clean air policies, including its 2021 commitment to carbon neutrality by 2060, focusing on renewable energy and industrial emission controls.
- India: With more than 100 policies introduced, the National Clean Air Programme (2019) aims to reduce $PM_{2.5}$ levels by 20% to 30% in cities that exceed national ambient air quality standards.
- Ghana: Ghana's national action plan to mitigate short-lived climate pollutants outlines 16 mitigation measures covering household energy and transportation, that if fully implemented could cut methane and black carbon concentrations by more than half.[14]
- Brazil: Brazil's National Air Quality Policy that came into effect last year introduces national targets for air quality consistent with 2021 WHO guidelines.[15]

The evolving nature of air pollution, its shifting components and its complex interactions with climate change make it essential to evaluate the current research gap in climate, air pollution and health. Air quality measures may impact climate goals, and vice versa. As climate mitigation actions to reduce combustion sources have potential co-benefits for public health, understanding these linkages is crucial. Maximizing benefits to both climate and air quality will require an intentional consideration of the synergies between local pollution and global greenhouse gas emissions during the policy development process. Additionally, the changing patterns in disease burden and considerations of how to minimize disparities in air pollution exposure and its impacts necessitate equity-focused and region-specific research gap analysis.

Approach

We took a systematic approach with mixed methods to identify and prioritize the research gaps in air pollution and health in the context of climate change. Figure 7 outlines the approach. It begins with a comprehensive literature review to establish the current state of knowledge. This is complemented by consultations with researchers, policymakers, technical experts and government stakeholders to gather insights and identify areas where further research is needed. A global advisory panel provides additional expertise and guidance. The identified research gaps are then prioritized, taking into account their scientific significance, policy relevance and feasibility. The final step involves formulating key research recommendations to guide future research efforts and address the identified gaps. By following this structured process shown in Figure 7, researchers and policymakers can ensure that research investments are focused on the most critical areas, leading to more effective air pollution control strategies and improved public health.

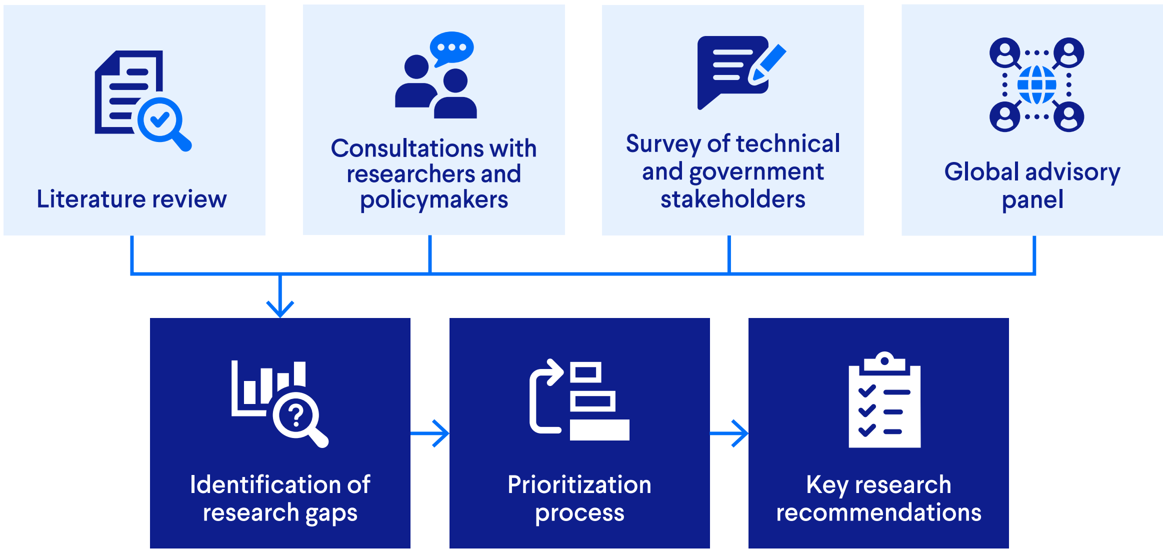


Figure 7. Summary of approach to identifying and prioritizing research gaps

Literature reviews

Review of reviews

We reviewed the existing peer-reviewed systematic reviews and meta-analyses on the health effects of air pollution, with a focus on systematic reviews and meta-analyses using the following search equation:

> "Soot"[MeSH] OR "Particulate Matter"[MeSH] OR "Ozone"[MeSH] OR "Nitrogen Dioxide"[MeSH]) AND "Health Status"[Mesh]

To allow for disaggregation of results by priority geographic areas, we also added country/region names—China, India, sub-Saharan Africa and Latin America—to the search equation. Any articles that did not belong to the priority regions were tagged as "Global."

The evidence gap analysis only included systematic reviews with at least one pollutant-outcome pair.

For each systematic review or analysis, we extracted the specific health outcome, pollutant and strength of association between the health outcome and the pollutant (risk ratio or odds ratio). In cases where a quantitative value was not mentioned, we extracted qualitative information for the analysis, such as positive association or inconclusive evidence.

We included studies with PM (including PM_1, $PM_{2.5}$, PM_{10}), BC, NO_x, SO_x, O_3 and CO. Pollutant mixtures were excluded from the gap analysis. Notably, all pollutant mixture studies were from China. We also excluded region-specific pollutants that could not be easily categorized, for example pond ash (India), Saharan dust (sub-Saharan Africa), etc. Citations for studies identifed in the literature review are provided as a separate reference list. A full list of excluded pollutants is presented in Appendix 1.

For ease of visualization, all the extracted health outcomes were grouped into fewer broad categories using the International Classification of Disease (ICD-10) codes.

Review of studies on inequities in air pollution and impacts

To look at the inequities of air pollution and its health impacts, we used the following equation to search through the PubMed database to find related articles.

(((("Health Inequities"[MeSH]) OR "Socioeconomic Disparities in Health"[MeSH])
OR "Health Status Disparities"[MeSH]) AND "Air Pollution"[MeSH])
NOT "Tobacco Smoke Pollution"[MeSH]

Defined and analyzed inequities included race, socioeconomic status, distance from traffic/transportation pathways, neighborhood-level poverty, access to green space, access to healthcare and segregation.

Stakeholder insight

We sought several rounds of insight from technical and policy stakeholders through consultations, an online survey and a global advisory panel.

Stakeholder consultations

We organized three group consultations with experts at the intersection of air pollution, climate and health to help refine our thinking and help identify and prioritize gaps in the evidence base that were limiting the ability to measure the health benefits of climate mitigation actions targeting air pollution.

- On Aug. 25, 2024, a workshop was hosted in Santiago, Chile, ahead of the global International Society of Environmental Epidemiology (ISEE) Conference. Participants included representatives from the National Institutes of Environmental Health Sciences (NIEHS) of the United States, Harvard University, the University of Georgia, the Kintampo Health Research Centre, the Berkeley Air Monitoring Group, the Institute of Epidemiology at Helmholtz Munich, and the Health Effects Institute.
- On Sept.17, 2024, we led a discussion with Indian researchers, as well as representatives from leading public health research agencies and policymakers, in New Delhi. Participants included representatives from the National Programme on Climate Change and Human Health, the Energy Policy Institute at the University of Chicago, the Lung Care Foundation, CAPHER/AIIMS New Delhi, the Council on Energy Environment and Water, the Indian Council of Medical Research, and the Sustainable Futures Collaborative.

- On Oct. 14, 2024, we co-hosted a technical consultation with the AiR-Climate-Health (ARCH) Integrated Study and Exchange Platform, an air pollution research platform led by Dr. Tong Zhu of the Center for Environment and Health at Peking University, Beijing. Participants included representatives from the Institute of Atmospheric Physics at the Chinese Academy of Sciences, Fudan University, Peking University and the University of Science and Technology Beijing.

Stakeholder survey

A survey was created to send to a wide group of technical and government stakeholders to help us pinpoint critical gaps in the evidence base. Stakeholders were asked to provide insight on source-specific, pollutant-specific and toxicological/mechanistic air pollution research gaps related to health, gaps in research by life stage, gaps in data availability and capacity, and mitigation measures. We received 21 responses from stakeholders based in the United States, Ethiopia, Brazil, Germany, Portugal, South Africa, the United Kingdom, Uganda, Denmark, Poland, Canada, Romania, Rwanda and Switzerland. Respondents were affiliated with academia, national research institutes, local city governments and WHO. For a copy of the survey instrument, see Appendix 2.

Global advisory panel

We formed a global advisory panel comprising 11 experts in causal mechanisms, epidemiology and exposure assessment, toxicology and risk assessment to help refine and shape our work. This included experts from low-, middle- and high-income countries who possess, beyond subject matter expertise, an intimate understanding of how emissions patterns and research gaps vary geographically or are influenced by competing priorities. A graphical summary of the meeting is provided in Appendix 3.

Framing research priorities

We designed a rapid, two-stage pragmatic process to evaluate and prioritize research topics compiled through the literature review, stakeholder consultations and engagement with advisory panel members. Our goal was to prioritize research that would address critical climate, air quality and health issues in the context of broader considerations, such that research results would guide the development of effective, sustainable and ethically responsible solutions to mitigate the negative impacts of combustion.

In brief, we screened identified topics for relevance, then rated them across seven key dimensions in order to come up with a list of policy-relevant topics most likely to advance scientific knowledge while informing improvements in public health. For a summary of the research prioritization process, see Table 1.

Stage 1	Stage 2—Criteria		Priority score
Focus on combustion source pollution for greatest climate and air pollution mitigation potential	Scientific value	• filling critical gap • advancing knowledge	1 Little 2 Low 3 Medium 4 High
Transport	Decision making value	• policy relevance • scalability • replicability	
Industry	Feasibility/merit	• cost • timing	
Energy generation	Capacity strengthening potential	• data systems strengthening • local opportunity	
Wildfire Waste burning	Public health potential	• emissions and/or exposure reduction potential • health mitigation potential • impact on cost to health system	
Agricultural burning	Potential to advance equity	• filling critical gap • advancing knowledge	1 Yes 0 No
Household energy	Concern for unintended consequences	• filling critical gap • advancing knowledge	

Table 1. Overview of prioritization process used to identify research gaps for air pollution and health impacts of climate mitigation

Stage 1: Prioritize combustion sources

To ensure a focus on climate mitigation that would offer maximum benefits to air quality, we limited the scope to research topics related to emissions from leading combustion sources of pollution. This included emissions from transport, industry, energy generation, wildfires, waste burning, agriculture and household energy.

Stage 2: Criteria for ranking research questions

Each research topic was ranked along seven dimensions according to the following criteria to consider scientific rigor, feasibility, social responsibility and policy relevance. Concerns about advancing equity, avoiding unintended consequences, and strengthening local data and technical capacity were also taken into account.

Dimension 1: Scientific value

Scale: 1 Little 2 Low 3 Medium 4 High

Key focus: Filling critical gaps and advancing knowledge

Assess how this research question will address important gaps in existing evidence base.

- Does it have the potential to lead to a breakthrough in understanding a key issue or problem?
- Does the research advance or challenge existing scientific paradigms or theories?
- Does the research build on existing evidence in a meaningful way?

Consider the novelty of the research and its potential to generate new scientific insights.

Dimension 2: Public health potential

Scale: 1 Little 2 Low 3 Medium 4 High

Key focus: Burden on health and health systems, exposure potential, health mitigation potential

Evaluate the relevance of the research to public health. Assess how the study can inform efforts to reduce health burdens. Consider the exposure potential and how the research might help in health mitigation strategies (e.g., interventions and policies). Also, consider the potential impact on health care systems, including how the research could reduce costs or strain on health care services. Also, assess the external validity, i.e., how the research can be generalized beyond the study context.

Questions to consider:

- Does the research address a significant public health issue?
- Does the research have the potential to reduce exposure to harmful factors or mitigate the effects of diseases?
- How might the findings affect the capacity of the health care system or lead to cost savings?
- How much impact would the research have on improving the health outcomes?

Dimension 3: Decision-making value

Scale: 1 Little 2 Low 3 Medium 4 High

Key focus: Scalability/replicability, policy relevance, opportunity for action, ramifications elsewhere

Assess how the research will influence decision-making processes, particularly in policy or practice. Consider whether the results can be scaled up or applied in different contexts. Is the research relevant to policymakers, public health agencies or other decision-makers? Evaluate whether the findings have broad applicability or specific relevance to particular settings or populations.

Questions to consider:

- Can the findings be applied on a large scale or in other geographic locations?
- Does the research have direct relevance to current policy debates or public health priorities?
- What practical actions or interventions might emerge from the findings?
- Will the research help policymakers make more informed decisions?

Dimension 4: Feasibility

Scale: 1 Little 2 Low 3 Medium 4 High

Key focus: Cost of filling the gap, timing

Evaluate the practicality of conducting the research. Consider the resources required, including funding, time, personnel and infrastructure. Assess whether the research is feasible within the proposed time frame and budget. What are the risks to successful implementation (e.g., political sensitivity, data security, methodological challenges, access to populations)? Consider whether the costs are justified relative to the expected outcomes or benefits.

Questions to consider:

- Is the proposed research feasible within the available budget and timeline?
- Are there significant barriers or challenges that could delay or prevent the research from being completed successfully?
- How does the feasibility compare to the potential impact or value of the research?

Dimension 5: Capacity-strengthening potential

Scale: 1 Little 2 Low 3 Medium 4 High

Key focus: Local research capacity strengthening, data system strengthening

Consider whether the research will help build local capacity for future research, particularly in under-resourced or low- and middle-income settings. Does the research enhance local researchers' skills, foster local collaboration, or strengthen data systems (e.g., data collection, management and analysis)? Will the research leave a lasting infrastructure or knowledge base that supports future public health or scientific work?

Questions to consider:

- Does this research build the skills and capabilities of local researchers or institutions?
- How will the research strengthen local data systems or other infrastructure?
- Will the research lead to long-term improvements in local research capacity?

Dimension 6: Equity

Scale: 1 Yes 0 No

Evaluate the research qualitatively on whether it will contribute to promoting health equity.

Key focus: Advancing equity, exposure inequities, vulnerable groups

Assess whether the research addresses equity issues, particularly in terms of health disparities or access to resources. Does the research focus on vulnerable or marginalized groups (e.g., racial/ethnic minorities, low-income populations, children, elderly, disabled, etc.)? Does it seek to better understand the causes of health inequities or provide solutions to reduce them? Consider how the research might inform policies or interventions aimed at improving health equity.

Questions to consider:

- Does this research focus on populations that are disadvantaged or vulnerable?
- Will the research advance understanding of the factors contributing to health inequities?
- How will the research influence decision-making or interventions that aim to improve equity?

Dimension 7: Evaluating unintended consequences

Scale: 1 Yes 0 No

Where relevant, we also considered the extent to which research, or the actions being evaluated, could have unintended consequences. These could be positive or negative, and might relate to social, ethical, political or environmental issues. What are the potential risks of the research not being fully understood or misapplied? Consider any ethical concerns, especially regarding vulnerable populations or communities. For example, could the research unintentionally exacerbate inequalities or harm vulnerable groups? We also considered the appropriate boundaries of research, considering what should be addressed, what might be appropriate limits of inquiry, and how this would help frame assumptions underlying the study and/or interpretation of results.

Prioritizing recommendations

To further narrow down research priorities, we worked with advisory panel members to rank and prioritize recommendations using a prioritization exercise rating methodology developed during the workshop. Core technical team members then compiled the final list of recommended areas for research.

Summary of review and consultation processes

Epidemiologic evidence

The evidence base on air pollution and health is rapidly growing. We identified a total of 182 systematic reviews focused on the health effects of air pollution published between 1970 and 2024. Temporal trends illustrate how the peer-reviewed literature on air pollution and health continues to increase on a global and regional scale. See Figure 8.

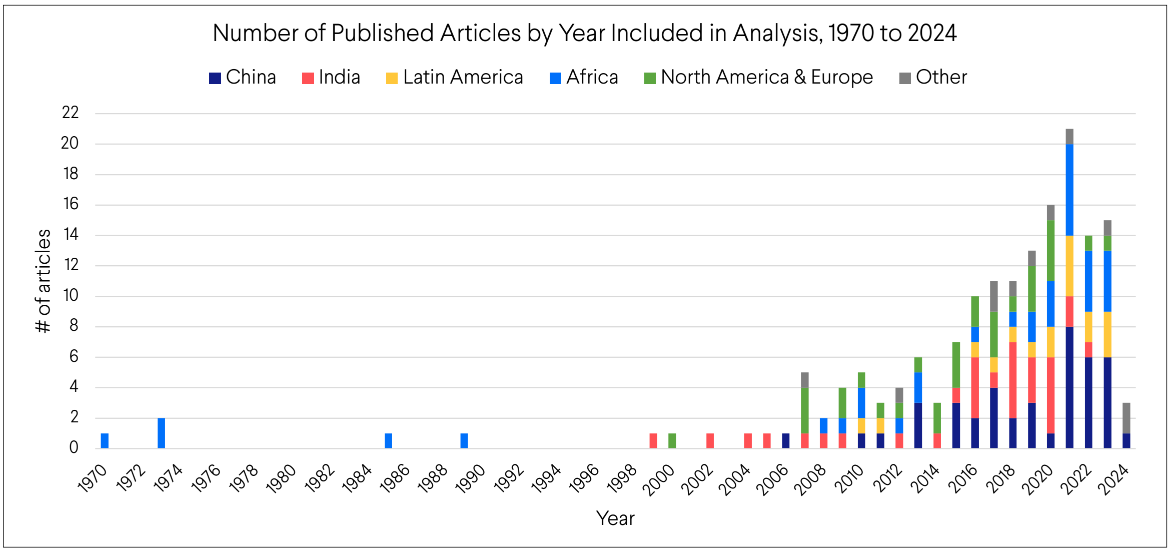


Figure 8. Trends in publications of systematic reviews of air pollution and health, 1970-2024

Beginning in the 2010s, reviews from China increasingly dominated the evidence base. There were relatively fewer reviews focused on India, Latin America and sub-Saharan Africa, likely reflecting the smaller number of region-specific studies motivating regional systematic reviews (Figure 9). For some geographies, this may reflect the limited availability and/or accessibility of high-quality, routinely collected data needed to sustain a robust air pollution and health research community. The articles spanned a broad range of exposures like air pollution in general, particulate matter, gases, pollutant mixtures, volatile organic compounds, and indoor and outdoor pollution. Most review studies focused on epidemiologic studies of air pollution.

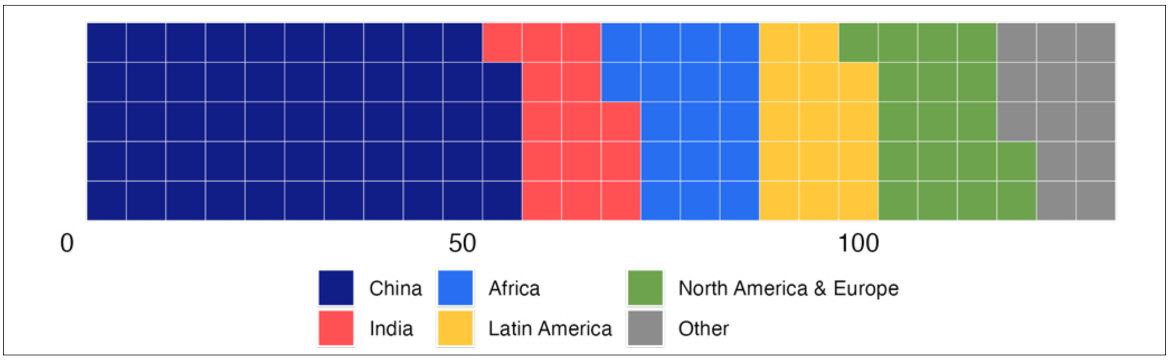


Figure 9. Number of epidemiologic reviews identified, by region, 1970-2024

A total of 26 review articles focused on mortality alone. Other reviews focused on a broad range of health outcomes across the life span. Cardiovascular disease and respiratory disease were the most studied health outcomes, with at least 35 reviews each. All reviews under the infectious disease category reported associations between air pollution exposure and COVID-19. Five of the reviews focused on lung cancer, and six articles reported associations with cerebrovascular diseases. A total of nine reviews were under the mental health category, including outcomes such as behavioral disorders, dementia, depression, Parkinson's disease and schizophrenia. Finally, a total of 15 reviews focused on fertility and outcomes of pregnancy, including developmental anomalies, fetal growth and fetal death. Table 2 shows the health outcomes under each category and the corresponding number of review articles.

Category	Outcome	# of Articles
Mortality	Mortality	26
Malignant neoplasm	Cancer	1
	Lung cancer	5
Mental, behavioral or neurodevelopmental disorder	Behavioral disorder	1
	Dementia	3
	Depression	2
	Parkinson's disease	2
	Schizophrenia	1
Nervous system disease	Cerebrovascular disease	6
Circulatory system disease	CVD	35
Endocrine, nutritional and metabolic diseases	Cystic fibrosis	1
	Diabetes	2
	Obesity	1
	Thyroid dysfunction	1
Systemic inflammation	Systemic inflammation	1
Lung infection	Lung infection	7
Lower respiratory tract disease	Asthma	14
	COPD	14
Upper respiratory tract disease	Allergic rhinitis	2
Respiratory disease	Respiratory disease in general	37
Allergy	Allergy	2
Infectious disease	Covid-19	4
Developmental anomalies	Developmental anomalies	1
Prenatal condition	Disorders of newborn related to length of gestation or fetal growth	5
	Fetal death	2
	Spontaneous abortion	1
Complications of labor or delivery	Preterm delivery	5
Female infertility	Female infertility	1

Table 2. Summary of health outcomes addressed in epidemiologic reviews, 1970-2024

The gap analysis heat map below in Figure 10 summarizes data from 78 systematic reviews and meta-analyses included in the final database (including 43 from China, three from India, six from Africa and 10 from Latin America). Grey cells represent evidence gaps where there were no studies examining the association between the pollutant and the corresponding health outcome. All but three reviews confirmed positive association, i.e., exposure to the pollutant leading to higher risk of the studies. No negative association was found. Asterisks (*) show pollutant-outcome pairs where one study reported inconclusive results. The colored cells indicate that robust evidence of association between air pollution exposure and health outcomes exists throughout the life course. The darker colors in the top panel confirm that the methodology to estimate all-cause mortality and strong association with exposure to specific air pollutants is well established. We also found several reviews and meta-analyses confirming association between air pollution exposure and adverse respiratory and cardiovascular outcomes. These include COPD, upper and lower respiratory infections, lung infections and circulatory system diseases. While reviews for pregnancy and birth outcomes look sparse (one or two reviews), evidence does exist of positive associations between most pollutants and adverse outcomes. Throughout the life course, association between $PM_{2.5}$ exposure (~17 systematic reviews) and adverse health outcomes are most studied, followed by PM_{10} exposure (~16 systematic reviews). One pollutant that stands out for lack of evidence is black carbon. Only one review focused on black carbon, and looked at the impact of exposures on systemic inflammation. The limited number of epidemiologic studies focused on black carbon exposure is likely driven by the tendency to focus on routinely monitored pollutants rather than PM components.

Despite its significance in climate change, and growing concerns of its health effects, we found only one systematic review from China on health impacts.[16] Similarly, there were limited studies on allergy and inflammation, perhaps because the studies tend to focus on direct health effects (as opposed to indicators) and more severe outcomes.

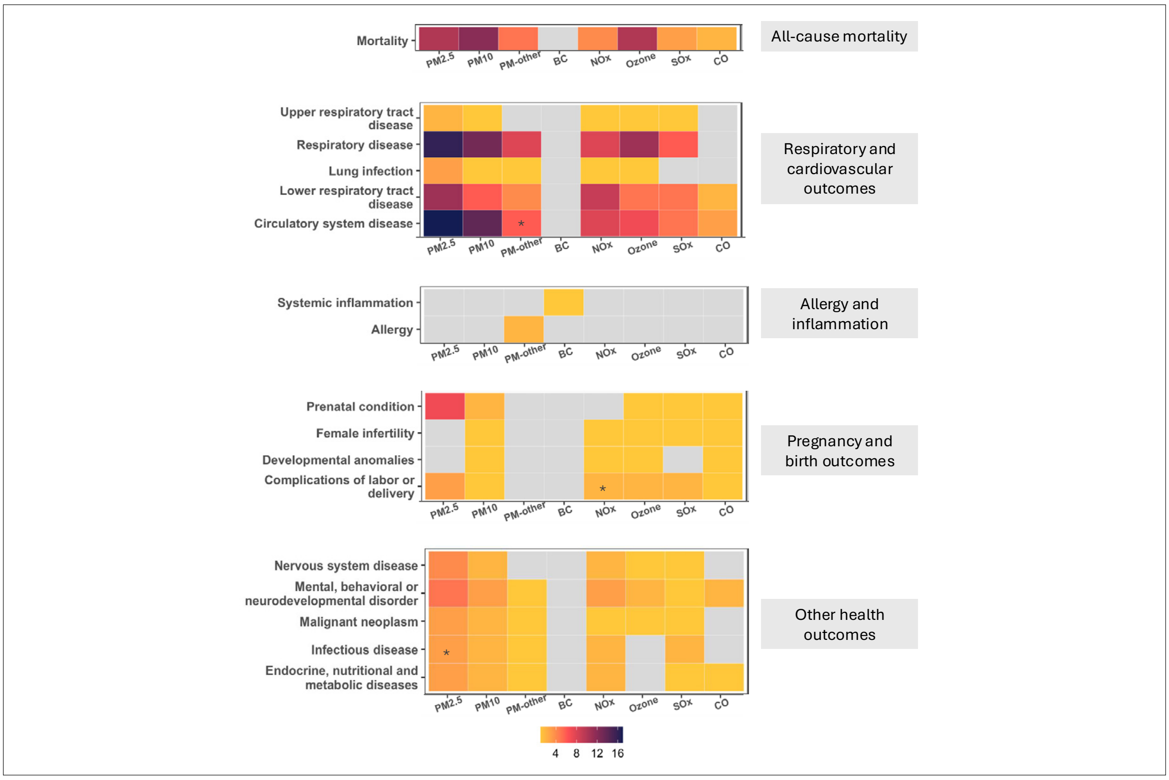


Figure 10. Evidence gap analysis of epidemiologic reviews of air pollution and health, 1970-2024. Color of cells indicates the number of systematic reviews or meta-analyses for the particular health outcome-pollutant pair. Grey cells indicate the absence of any reviews or meta-analysis. Asterisk indicates that one review was inconclusive.

It should be noted, however, that even though some areas may appear understudied based on a systematic review of the literature, not all gaps need to be filled. This is particularly true in cases where a complete chain of evidence is not needed to inform action. For example, we already have a substantial body of knowledge on the general health impacts of air pollution, particularly regarding common pollutants like $PM_{2.5}$, NO_2 and O_3. The evidence clearly links these pollutants to a variety of health conditions, including respiratory diseases, cardiovascular issues and premature mortality.

Characterizing inequities in air pollution exposure and impacts

The systematic review of studies on inequities of air pollution's health impact yielded 119 results published between 2007 and 2024. Of those, 39 articles were excluded for lack of relevance or having no clearly defined inequity, leaving 80 studies eligible for review. Publications on this topic have remained relatively low (10 or fewer articles each year) until a recent increase in the past two years.

- Exposure can lead to adverse birth outcomes.[17-23] Children[24-30] and older adults[31-33] tend to bear more air pollution related health burdens as they are more susceptible to the health impacts of air pollution.
- The most commonly analyzed inequities focused on differences by race or socioeconomic status. Among racial groups, non-white populations, particularly Black and Hispanic populations, face greater air pollution-related health inequities compared to their white counterparts.[34-37] This includes typically living closer and being more exposed to transportation pathways,[35-36,38-40] living closer to industrial air pollution sources,[40-45] and having less access to health care.[46-48] Populations with low socioeconomic status also face greater air pollution-related health inequities, and experience an increased burden of disease regardless of race or marginalization.[48-53]
- Health inequities faced by the above populations include cardiovascular disease,[31,54-56] respiratory illnesses[29,34,46-47,51,57-60] and adverse birth outcomes.[17-23] Lack of timely access to health care and treatment can also increase the impacts of air pollution exposure.[32,44,59-61]
- Environmental and social inequities, like availability of green space, neighborhood poverty levels, proximity of residence to main roads[18,36-39] and segregation[17,39-40,56,58-60,62] can also contribute to health disparities.

Consultations with local stakeholders emphasized the rural and urban disparities in air pollution and health research. For example, data availability may be more limited in rural areas due to a lack of monitoring and/or limited availability of complete, routinely collected health data. Rural and urban areas also have different sources of air pollution, which can influence exposure patterns.

The existing evidence base highlights the need to consider how inequalities play out differently in different places, i.e., the feasibility of generalizing results from one geography to another needs to be carefully considered. As a result, while publications in this area have been increasing over time, additional studies to provide more geographic variability in results are needed. There is particular need to increase the evidence base in Asia and Sub-Saharan Africa. This will necessarily involve a focus on characterizing the impacts of different leading sources of exposure. It will also involve a careful consideration of how the exposures of different groups are influenced by very different mixtures of traditional (e.g., household energy and waste burning) and modern (e.g., transport and industry) sources of pollution.

It will be important to maintain an active dialogue with key local stakeholders, including those in civil society. This will help ensure a clear understanding of how climate policies can effectively reduce inequities in air pollution and its impacts within any given context.

Local evidence gaps

While global studies may be used to assess the consistency of the evidence base, the translation of air pollution evidence into effective policies also depends on local context, as well as the ability to connect local and global data. As air pollution levels, sources and health impacts can vary significantly by region, consideration of local data is critical for informing effective policy. Stakeholder consultations revealed several areas where local evidence is needed to make the case for action:

- Leading regional sources of pollution: Evidence on the health effects of specific pollution sources like waste burning, biomass burning, industrial emissions and transportation is still limited. This lack of evidence hampers efforts to regulate or target interventions at the most harmful sources of pollution.
- Susceptibility and social determinants: There is a need for a deeper understanding of how social determinants—such as socioeconomic status, education, and access to health care—interact with envi- ronmental exposures to modify health outcomes. Understanding the social and behavioral vulnerabilities of certain populations, such as elderly people or low-income groups, will help refine policies that protect the most at-risk communities.
- Policy development and implementation: More nuanced local data is required to inform policies that are contextually relevant and feasible. For instance, climate and local health co-morbidities (e.g., asthma or cardiovascular disease) should be factored into air quality regulations to avoid unintended health disparities. Evidence on how policy changes translate into actual health improvements remains limited, so a better understanding of the policy process and how evidence can be effectively used in the media to influence both public opinion and policymakers is crucial.

Toxicology and mechanistic evidence

Unlike epidemiologic studies, toxicologic and mechanistic studies do not easily lend themselves to comparative systematic reviews or meta-analyses. However, it is widely acknowledged that an understanding of the underlying mechanistic pathways and toxicology from basic research is paramount for informing policy. Increasing the scientific knowledge of toxicological and mechanistic evidence influences the demand for clean air.

Some key mechanistic gaps were raised in stakeholder consultations. These are summarized below:

- The chemical profiles and toxicology of particles collected from different places at the same time could reveal as-yet-unidentified differences in the health impacts of pollution from different sources.
- Elucidating the external exposome (the totality of exposure throughout a person's life course). This would include toxicology studies that quantify and take into account the effects of multiple exposures, e.g., air, noise and temperature.
- Studying multiomics and mixtures of pollutants/multipollutants. The impacts of pollutant mixtures have not been studied as well as individual pollutants have.
- Research to profile pollutants by source type, and to understand their toxicological impact, is considered by some to be critical for improving public health policy. At the same time, nearly all exposures are mixtures, and a focus on differential toxicity may be used as an excuse for inaction. A focus on identifying the leading sources contributing to warming and air pollution would be the most pragmatic approach to be taken.

Stakeholder survey

In this section, we summarize key findings from the stakeholder survey about critical data gaps and insights from a local/regional perspective. A full copy of the survey is in Appendix 2. Responders highlighted source-specific evidence gaps with respect to residential burning like cooking with solid fuels, local traffic emissions and wildfires. When asked about pollutant-specific data gaps, most respondents highlighted the lack of evidence base for black carbon, ultrafine particles and pollutant mixtures. When asked about research gaps throughout life stages, nearly half of the respondents (11 out of 21) acknowledged that the prenatal stage is the least studied.

We also found that a variety of evidence is being prioritized by policymakers and implementers (Figure 11). While health outcomes and exposure evidence would be an obvious choice, more than 40% of the respondents confirmed the importance of effectiveness of previous action taken as part of key evidence needed for policymakers and implementers.

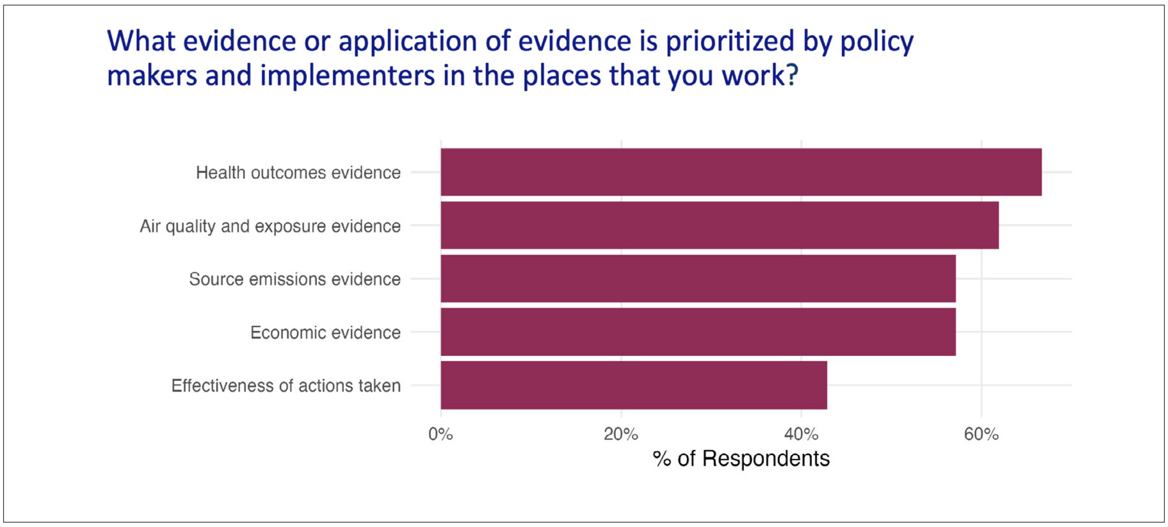


Figure 11. Evidence prioritized by policymakers reported by stakeholder survey respondents (n = 21)

Data gaps in health outcomes, source emissions and exposure stood out as the most frequently encountered evidence gaps in the survey, as shown in Figure 12.

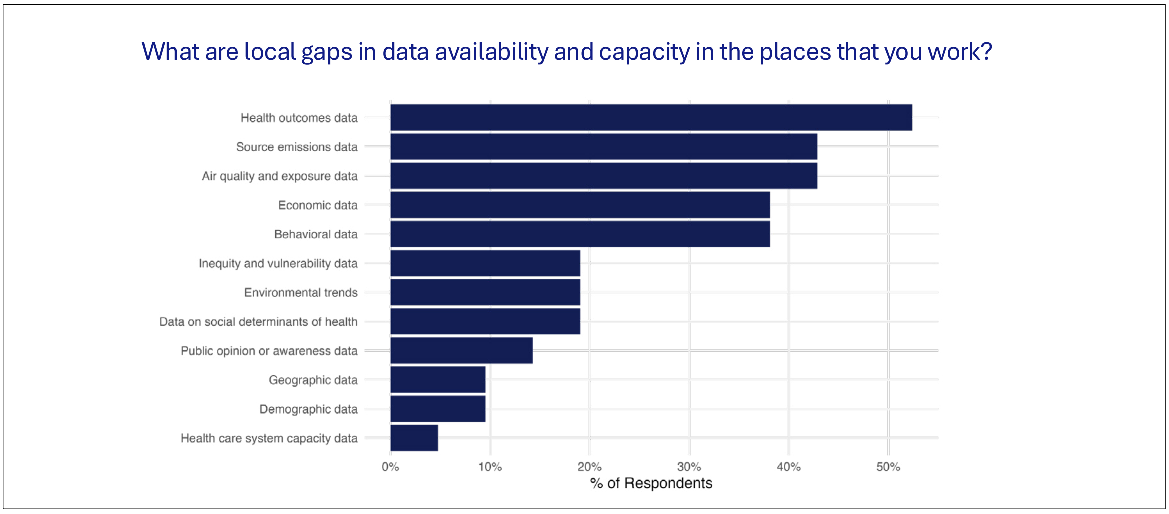


Figure 12. Local data gaps identified by stakeholder survey respondents (n = 21)

We also asked stakeholders about specific mitigation measures under consideration in their regions that could require baseline and follow-up data for implementation and evaluation.

Type of baseline/follow-up data needed according to the respondents:

- Health co-benefits of mitigation strategies, for example low-emission zones or bike lanes, to help with the uptake and to increase demand for these polices.
- Changes in exposure as a result of mitigation strategies.
- Specific population-level data on biomarkers of different exposures would also aid in the evaluation of the impacts of such mitigation measures.

The mitigation measures themselves that would benefit from such data fell within three broad categories as follows:

Transportation and urban planning

- Promotion of electric vehicles and nonmotorized transport
- Restricting old vehicles
- Developing bike lanes, green quarters and efficient public transport
- Implementation of low-emission zones, congestion charges and parking regulations

Technological solutions

- Retrofitting vehicles and ships with emission-reducing technologies
- Transition household heating away from coal and wood burning
- Geothermal network installations (ground source heat pumps)

Other policy and advocacy measures

- Implementing wood-burning bans and agricultural regulations
- Potential impacts of remote work/home office policies
- Advocating for environmentally sustainable health care and resilient health systems

From evidence to action

Evaluating the effectiveness of actions taken was consistently the highest priority identified across all research approaches during stakeholder consultations. This includes evaluating how the intended benefits of policies align with real-world outcomes, particularly with respect to achieving intended health impacts. For example, accountability studies on climate policies and the electrification of vehicles need to determine whether these initiatives have measurably reduced emissions or merely shifted pollutants geographically or temporally. Similarly, evaluating the health impacts of transitioning to electric vehicles requires examining not only reductions in tailpipe emissions but also potential upstream pollution from energy generation, especially in regions reliant on fossil fuels.

Framing research gaps along the chain of accountability

Researchers and policymakers consistently emphasize the need for evidence demonstrating the effectiveness of climate and clean air actions being taken. Where efforts to promote clean air are in place, policymakers are keen to assess the extent to which improvements in air quality, and resulting impacts, may be quantified. Leaders who are currently weighing the feasibility and potential benefits of a suite of proposed measures would like to make decisions based on credible evidence that selected solutions will be effective. However, even when health benefits are the ultimate aim, successful implementation involves consideration of the extent to which control measures may influence various points along the chain, from source control to emissions reduction, air quality/pollutant concentrations, exposure, dose and health effects. In addition, mediating factors along the chain, ranging from pollutant transport and transformation to key factors influencing susceptibility—such as nutrition or socioeconomic status—must be taken into account. As we consider the added complexity of a warming environment, the complex interaction of air quality and heat and their wide-ranging impacts on pollutant levels and impacts also must be better characterized across the chain.

Research recommendations have been framed based on an adapted version of the chain of accountability[63] linking actions to health effects. This approach allows us to group priorities logically along this pathway so we can clearly articulate how research to fill fundamental knowledge gaps will support the design, implementation and evaluation of current and future climate and clear air policies. See Figure 13.

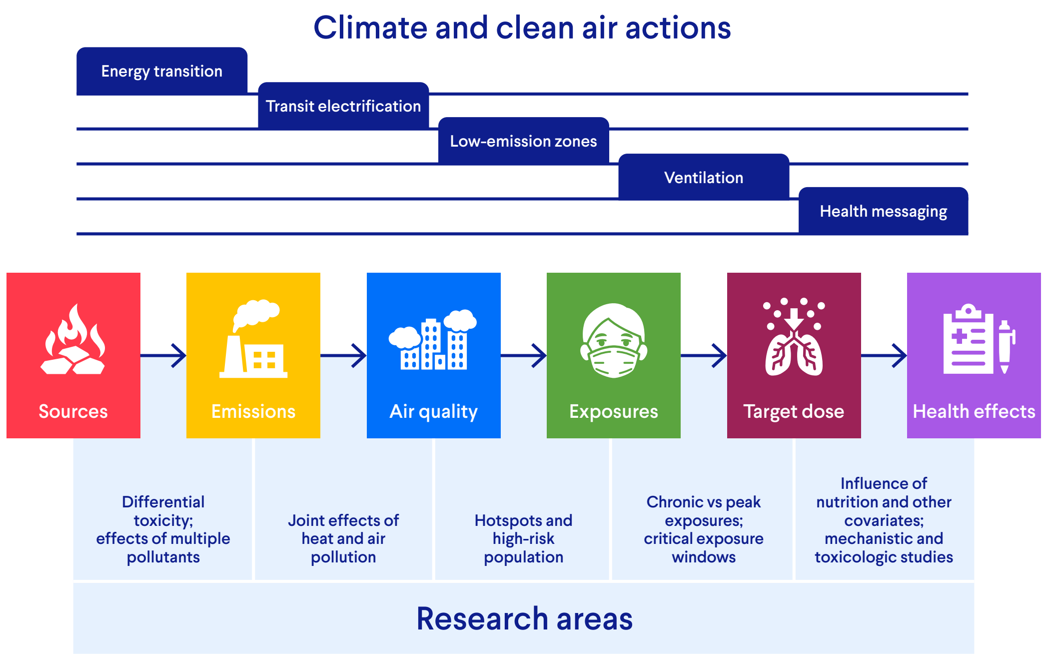


Figure 13. Modified chain of accountability for impact of climate and clean air action

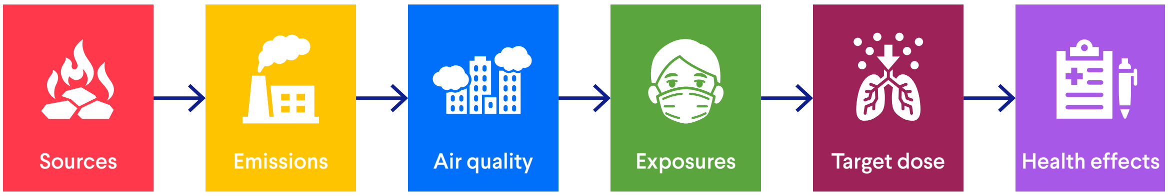
Figure 13 depicts a refined chain of accountability for air pollution, expanding upon the traditional linear chain. It acknowledges the intricate interplay between sources, emissions, ambient air quality, exposures, target dose and health effects. Target clean air and climate actions (above) and illustrative examples of research areas (below) are provided along the chain.

- **Sources:** This area focuses on understanding the impact of changes in types and quantities of pollutants emitted from various sources, such as industrial facilities, vehicles and power plants. Research in this area can inform strategies to reduce emissions at the source.
- **Emissions:** This area examines how emissions from various sources contribute to the overall air quality. It involves modeling atmospheric dispersion and chemical transformations of pollutants to assess their impact on ambient concentrations.
- **Air Quality:** This aims to quantify human exposure to air pollution, both indoors and outdoors. It involves measuring pollutant concentrations in different microenvironments and linking them to individual exposure patterns.
- **Exposures:** This area investigates critical exposure windows, determining exposure-response relationships, and understanding the mechanisms by which air pollution causes adverse health outcomes.
- **Target doses:** This area focuses on individual intake susceptibility as well as the quantification of the impacts of air pollution.

While actions are generally intended to target a specific segment along this chain, from source reduction to health outcome mitigation, it is important to recognize that these actions often have cascading effects and may influence multiple stages. Indeed, some experts have recently recommended that this “chain” be extended to a “web” of accountability.[63]

This approach also allows us to better synthesize recommendations, while it avoids artificially grouping recommendations by discipline. Where warranted, we flag research recommendations that may be of global priority and are of increasing and/or particular importance for selected regions or populations.

Summary of air pollution accountability studies to date



	Policy/study	Location	Implementation/ study period	Results
Sources	**1990 Hong Kong Legislation for Restriction on Sulfur Content in Fuel:** mandatory limit of 0.5% sulfur by weight in fuel[62]	Hong Kong, China	Five years before and after the institution of the ban (1985-1995)	Decreases in NO_2 and SO_2 concentrations, no consistent changes in PM_{10} concentrations. Increased excess risks for mortality due to all natural causes for both SO_2 and NO_2, cardiovascular causes for SO_2, respiratory causes for NO_2, and O_3 for both all natural causes and respiratory disease; PM_{10} was not consistently or statistically associated with increased excess risk.
Sources	**School Bus Rebate Program:** replacement of old diesel school buses with new, lower-emitting buses across the United States[63]	USA-wide	2012	Community-level fine particle air pollution concentrations improved in school districts that had been selected for funding, with the largest gains in districts that replaced the oldest buses. Student educational performance and school attendance improved in districts that were selected for funding to replace old buses, and improved the most in districts that replaced the oldest (pre-1990) diesel-powered school buses.
Sources	**Smoky coal ban:** prohibits the sale and burning of high-smoke-emitting coal in all cities and towns[64]	Dublin (and 11 additional cities)	1990	Decreases in black smoke concentrations (45-70%), particularly during the heating season, after each ban. Respiratory mortality decreased significantly, by 17%, after the 1990 ban and, to a lesser extent, after the 1995 and 1998 bans; no reduction in total or cardiovascular mortality after either ban.

Sources	**Beijing household energy transitions:** bans coal use in the greater-Beijing area and offers a subsidy for transitioning to a new clean heating policy (CHP)[65]	Beijing	2016	Preliminary (unadjusted) results indicate that treated households had greater increases in average indoor temperatures and greater reductions in mean indoor $PM_{2.5}$ than untreated households between baseline and follow-up seasons. Overall reduction of 6.6% in the incidence of acute myocardial infarction from before to after rollout of the CHP in exposed townships relative to those not exposed to the policy.
	Wood stove change-outs: replacement of older wood stoves with newer, certified ones[66]	Libby, Montana	2005-2008	Ambient winter concentrations of $PM_{2.5}$ gradually declined over the study period and were 30% lower in the final winter after the changeout program (year 4) than in the baseline years. There was a significant reduction in childhood wheezing associated with lower winter ambient $PM_{2.5}$ concentrations; the most robust associations were for itchy or watery eyes, sore throat, bronchitis, influenza and throat infection.
	Brief closing of steel mill: the closure and reopening of the local Geneva steel mill, the primary source of PM_{10}[67]	Utah Valley, Utah	1987-1988	During the winter months when the steel mill was open, PM_{10} levels were nearly double the levels experienced during the winter months when the mill was closed. Children's hospital admissions for pneumonia, pleurisy, bronchitis and asthma were two to three times higher during the winters when the mill was open compared to when it was closed; PM_{10} levels were strongly correlated with hospital admissions.
	Industrial air pollution and children's respiratory health: comparison of wheezing occurrence in children below age 2 in an area near the factory (Călăraşi) and in a village 10 km from the factory (Roseți) after the factory closed[89]	Călăraşi and Roseți, Romania	1998	After adjusting for possible confounders, factory closure resulted in a significant decrease in wheezing incidence rates near the factory, while an increase in rates was observed 10 km away
Emissions	**Transit:** assessing the effects of emission-control measures on birth outcomes associated with traffic-related air pollution (TRAP)[68]	Texas	1996-2016	70% decrease in NO_2 levels observed over this period. The results were mixed on whether associations between TRAP exposures and birth outcomes became weaker over time.

Emissions	**London Congestion Charging Scheme (CCS): fees** for travel into central London to reduce traffic volume[69]	London	2001-2002	Little evidence that air quality was improved. In the study of the oxidative potential of PM_{10}, investigators were unable to identify a temporal, CCS-related change during the six-year period during which the scheme was implemented.
	1996 Summer Olympic Games: short-term, temporary intervention to reduce traffic congestion during the Olympic Games[70]	Atlanta	1996	Significant decline in ground-level ozone concentrations of 20% to 30% during the Olympic Games, with less pronounced decreases in concentrations of CO, PM_{10}, and NO_2. No significant reductions in the number of emergency department visits for respiratory or cardiovascular health outcomes in adults or children.
	Estimating model-based marginal societal health benefits of air pollution emission reductions: simulating the potential health benefits of reducing emissions from transportation and other sources at locations across the United States and Canada[71]	USA, Canada	2016	The greatest estimated annual monetary benefit of averted premature mortality associated with long-term fine particulate matter exposure linked to primary emissions of fine particulate matter, ammonia, nitrogen oxides and sulfur dioxide came from reducing primary fine particulate matter emissions. The combined health burden of all domestic emissions totaled US$805 billion in the United States and CA$77 billion in Canada in 2016.
	Effects of policy-driven air quality improvements on children's respiratory health: nearly 20 major policy actions were implemented in Southern California from 1993-2012 to reduce pollution from transportation and other sources[72]	Southern California, USA	1993–2012	Total emissions of NO_x, reactive organic gases (ROG), $PM_{2.5}$, PM_{10} and SO_x, and emissions in nearly all major categories (stationary, area-wide, on-road and other mobile sources) decreased between 1993 and 2012. Decreases in air pollutants were associated with decreased prevalence of respiratory symptoms (bronchitis, cough and phlegm), particularly in children with asthma, as well as increased growth of children's lung function.

Emissions	**2008 Beijing Olympic Games:** interventions focused on traffic and industrial emissions, e.g., both long-term closures of polluting factories and upgrading of vehicle emissions requirements, along with short-term measures restricting traffic, power generation and other emissions[73]	Beijing	Pre-Olympics (June 2–July 20, 2008), during-Olympics (July 21-Sept. 19) and post-Olympics (Sept. 20-Oct. 30)	Reductions in levels of air pollutants, including statistically significant reductions ranging from 40% to 60% for NO_2, SO_2 and CO; ground-level ozone concentrations were found to have increased. During-Olympics levels of several cardiovascular markers decreased compared with pre-Olympic levels.
	Ultra-low emission zone (ULEZ): a 12-month natural experimental study of the effects of the Ultra Low Emission Zone on children's travel to school[74]	London	Baseline (2018-19) and one-year follow-up (2019-20)	Implementation of clean air zones can increase uptake of active travel to school and was particularly associated with more sustainable and active travel in children living farther from school.
	1990 Clean Air Act Amendments: reductions in pollutants from power plants and in fine particulate matter ($PM_{2.5}$) concentrations in the eastern United States[75]	USA	1999-2005	Title IV of the Clean Air Act resulted in an estimated reduction in ambient $PM_{2.5}$ concentrations (averaged across the eastern United States) of 1.07 µg/m3 between 1999 and 2005 (or 0.89 µg/m3 on a population-weighted basis).
	1990 German reunification: stricter environmental controls and modernization of industry, transportation and household heating after the German reunification[76]	Erfurt, Germany	1990	Overall air-pollution concentrations decreased during the study period, with SO_2 going from 64 µg/m3 in 1992 to 4 µg/m3 in 2000, and PM_{10}, $PM_{2.5}$ and CO concentrations decreasing by more than 50%. Over the study period as a whole, risk ratios for all-cause mortality varied substantially from little or no association at some lags (the number of days between exposure and death) to significant associations at selected lags with an interquartile range (IQR) change in pollutant concentrations.

Emissions	**Impacts of regulations on air quality and emergency department visits:** examining the extent to which national and state regulations targeting power plants and mobile sources were effective in reducing pollutant emissions, improving air quality and reducing cardiorespiratory emergency department visits[77]	Atlanta	1999-2013	Air pollutant emissions and ambient concentrations decreased over the study period 1999-2013 for most pollutants evaluated, and pollutant levels were lower than what would have been expected without regulatory actions. The observed improvements in air quality were associated with fewer emergency department visits for asthma and other respiratory diseases compared with what would have been expected without the regulations.
	Transportation limits for Asian Games: reduced traffic flow during a citywide intervention for the 2002 Summer Asian Games[78]	Busan, South Korea	2002	The estimated relative risk of hospitalization for childhood asthma during the post-Games period over the baseline period was 0.73.
	Huai river policy: provision of free winter heating via coal for boilers in cities north of the Huai River but denial of heat to the south[79]	China	1950s	Ambient concentrations of TSPs total suspended particles) were found to be about 184 μg/m^3 or 55% higher in the north. The results indicate that life expectancy is about 5.5 years lower in the north owing to an increased incidence of cardiorespiratory mortality.
Air quality	**California Goods Movement Plan:** series of actions to reduce air pollution from the movement of traded goods (e.g., requiring electric shore power for ships, switching cargo handling equipment to low-sulfur fuels, and offering incentives for retrofitting truck fleets for higher efficiency)[80]	Los Angeles	2006	Compared with the pre-policy period, there were statistically significant reductions in NO_2 and $PM_{2.5}$ concentrations across all 10 counties in the post-policy period. There were statistically significantly greater improvements in health outcomes for Medi-Cal beneficiaries suffering from respiratory-related chronic conditions who were living in goods movement and non-goods-movement corridors when compared with control areas.

Air quality	**London Low Emission Zone (LEZ):** restricted entry of older, more polluting vehicles into Greater London[81]	London	2008	The modeling studies predicted modest reductions in total emissions of PM_{10}, NO_x and NO_2 associated with the LEZ. Oxidative potential appeared to be greater in PM from roadside locations than from urban background locations.
	Evaluating air pollution source regulations: evaluation of the major national regulatory policies that were implemented in China[82]	China	2008-2018	From 2008 to 2019, there was an estimated overall approximately 40% reduction in $PM_{2.5}$ as compared to a no-control scenario, but with regional heterogeneity. Associations were observed between $PM_{2.5}$ and mortality rates in both cohorts.
	Impact of transportation changes on air quality: Analysis of the effect of different transportation changes on air quality in two similarly sized cities: Granada (Spain) and Ljubljana (Slovenia)[83]	Granada, Spain and Ljubljana, Slovenia	Before restriction: Aug. 24, 2013, to Sept. 21, 2013 After restriction: Sept. 29, 2013, to Oct. 23, 2013	Black carbon concentrations were reduced by limiting traffic to public transport.
	NO_x Budget Trading Program (NBP): a cap-and-trade program created to reduce the regional transport of NO_x emissions from power plants and other large combustion sources[84]	New York, USA	2003 - 2008	Implementation of EPA's NBP policy resulted in significant reductions in mean ground-level ozone levels (-2% to -9%) throughout New York state. Significant post-intervention declines in respiratory admissions were observed in the central, lower Hudson Valley, and New York City metro regions.
	Geographic variation in pollution shocks induced by a recession: the recession-induced drop in industrial activity with substantial variation across sites in air pollution reductions[85]	USA	1981-1982	A 1% reduction in total suspended particles (TSPs) resulted in a 0.35 percent decline in the infant mortality rate, implying that 2,500 fewer infants died from 1980-1982 than would have in the absence of the TSP reductions.

Exposures	**Residential indoor air filtration:** using low-cost $PM_{2.5}$ and O_3 air monitors to measure indoor and outdoor pollutants and personal exposure[86]	Shanghai	2017	Indoor $PM_{2.5}$ concentrations were reduced substantially with the use of air cleaners, with more modest reductions in personal exposure.
	Reducing Air Pollution in Detroit Intervention Study (RAPIDS): evaluation of cardiovascular health benefits and personal fine-particulate-matter exposure reductions via portable air filtration units (PAFs) among older adults[87]	Detroit	2014-2016	Intervention with portable air filters was able to significantly decrease indoor $PM_{2.5}$ derived from outdoor and indoor $PM_{2.5}$ sources and significantly reduce the infiltration of outdoor $PM_{2.5}$.
	Portable HEPA air cleaners: effectiveness of portable HEPA air cleaners on reducing indoor $PM_{2.5}$ and NH_3 in an agricultural cohort of children with asthma[88]	Yakima Valley, Washington, USA	2015-2017	HEPA cleaners effectively reduced $PM_{2.5}$ levels in the child's bedroom and living room by 60% and 42% respectively, compared to asthma education alone.
	Industrial air pollution and children's respiratory health: comparison of wheezing occurrence in children below age 2 in an area near the factory (Călăraşi) and in a village 10 km from the factory (Roseți) after the factory closed[89]	Călăraşi and Roseți, Romania	1998	After adjusting for possible confounders, factory closure resulted in a significant decrease in wheezing incidence rates near the factory, while an increase in rates was observed 10 km away

Table 3. Summary of existing accountability studies of clean air action and impacts on air quality and health

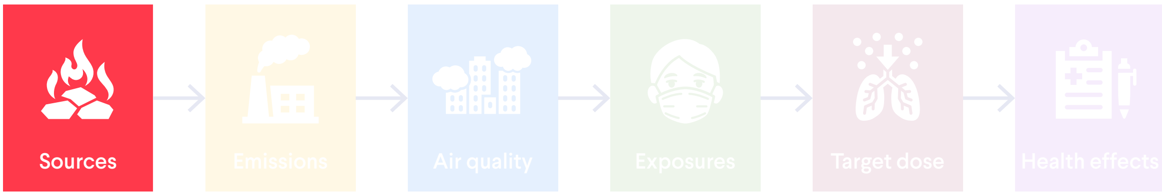
The accountability studies highlighted here are those focused on the effectiveness of actions taken. The studies are heavily weighted toward the left side of the accountability chain. Most of the studies evaluate the impact of clean air action on source-specific emissions and/or air quality. Studies demonstrating the measurable health impacts of actions taken are far more limited.

Recommendations

This section provides a summary of recommendations for research along the modified chain of accountability. Once again, it should be noted that even when health benefits are the ultimate aim of climate and clean air actions taken, successful implementation requires effective measures to be taken along various points of the chain, from sources to emissions all the way to health impacts.

We also discuss the role of policy assessments, building on the evidence base, which may provide support for clean air and climate policies. Here, we also consider the extent to which local exposure-response relationships are needed to inform timely action. In addition, we discuss several pragmatic considerations for obtaining results in the short term, including specific considerations to overcome data and capacity gaps.

Research priorities: sources



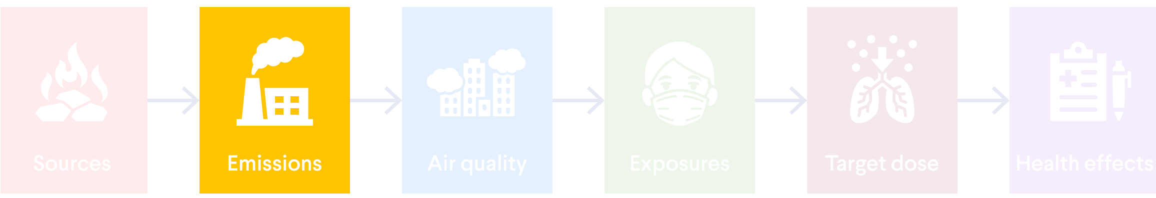
Priority sources identified are not necessarily global sources of pollution with key evidence gaps. Rather, they reflect perceptions of **leading regional ambient sources of emissions**. Priority sources that are suggested by the advisory panel for more research include the following:

- biomass burning
- waste burning
- transport

Source-specific biomass or waste burning are important contemporary sources but are not well-inventoried. Research that may better characterize how local combustion patterns contribute to local (e.g., waste burning or household energy) and regional (forest fires or agricultural burning) emissions, and hence provides foundations for further research on their climate and health impact. Studies may also uncover differences in emissions by urbanicity. Transport emissions research may focus on how location-specific traffic density or vehicle types influence emissions of multiple pollutants, which may not have been routinely measured until recently, helping to prioritize mitigation strategies.

We would also suggest prioritizing **location-specific source apportionment.** This is critical as pollution sources vary significantly between urban, rural and industrial settings. By pinpointing the major contributors in specific regions—such as transportation in cities or biomass burning in rural areas—this research enables targeted mitigation strategies tailored to local conditions, maximizing efficiency and effectiveness.

Research priorities: emissions



Foundational gaps in our understanding of emissions and their broader implications for air quality, climate and health need to be filled in order to better evaluate the impact of actions being taken.This includes:

- development of updated emission inventories
- better data on how climate action is influencing emission patterns

Routinely updated, complete emission inventories, including chemical and physical properties of emissions, are essential since comprehensive, high-resolution data on trends in emissions is the cornerstone of air quality modeling and policy formulation. Concentration data alone does not provide information on how source-specific policies are affecting air quality; information is needed on trends in progress associated with clean air and climate solutions—this is where emissions data is of critical importance. Including chemical and physical characteristics of pollutants, such as particulate size distribution or chemical composition, allows for better predictions of their behavior in the atmosphere, their toxicity and their potential to form secondary pollutants like ground-level ozone and particulate matter. This detailed understanding is necessary to address both immediate air quality issues and long-term public health risks.

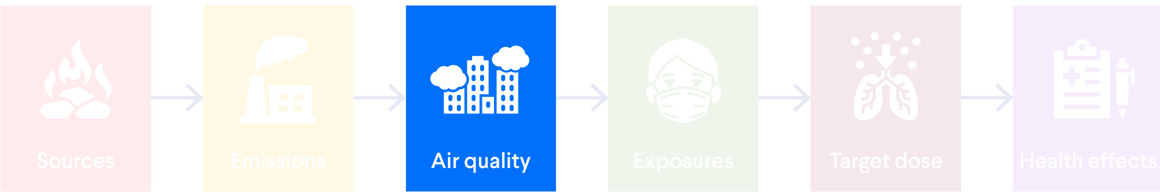
Changes in emission patterns as a result of climate change represent a pressing research priority due to the increasing influence of climate variability on emissions. For example, climate change can exacerbate the frequency and intensity of wildfires, releasing vast quantities of pollutants and altering regional air quality. Similarly, temperature and humidity changes can affect emissions from natural and anthropogenic sources, creating feedback loops that amplify climate and health impacts. Understanding these dynamics is critical for developing adaptive strategies to manage emissions in a changing climate and mitigate their cascading effects on human and ecological health.

To better characterize health benefits, we need better to consider how climate action affects emissions and air quality. One key priority is examining the **joint effects of air pollution and climate actions**. This topic is vital because emissions such as greenhouse gases (e.g., methane) and pollutants like particulate matter interact synergistically, worsening both air quality and climate conditions. These intertwined effects necessitate an integrated approach to simultaneously address air pollution and global warming, enabling more sustainable interventions.

Another essential area is the **development of advanced atmospheric models** that incorporate real-world conditions like changing meteorological patterns, urban heat islands and secondary pollutant formation. While relatively sophisticated models are available in North America and Europe, more robust models are urgently needed in other regions, especially those with high levels of air pollution and rapidly changing climates. These models are critical for predicting how emissions evolve in the atmosphere and for devising effective mitigation strategies. Research in this area enables policies based on robust scientific evidence and remains adaptive to future environmental changes.

These topics are essential for addressing growing concerns about air quality deterioration and its cascading effects on climate, ecosystems and human health. Prioritizing these areas fosters better prediction of air pollution trends and creates pathways for comprehensive and actionable air quality solutions.

Research priorities: air quality

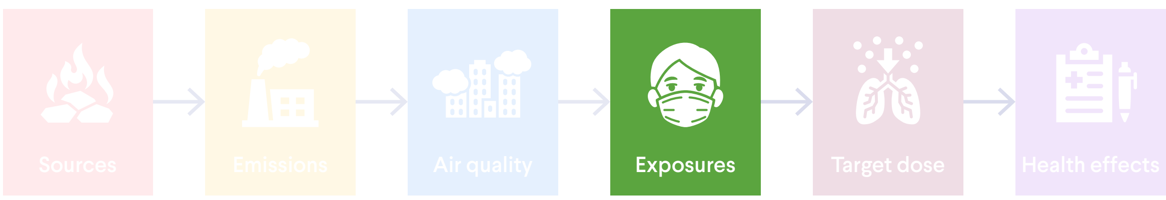


Research questions on air quality included a focus at the intersection of air quality and temperature, as well as the differential impact of peak (e.g., from air pollution episodes) versus chronic exposures to air pollution. Priority research areas proposed by the advisory panel included the following:

- **Impact of air pollution (wildfire, agricultural burning) episodes on development of chronic disease.** Studies in this category examine how air pollution episodes such as wildfires or agricultural burning contribute to chronic diseases. This requires advanced methodologies such as longitudinal studies to track health outcomes over time.
- **Impacts faced by vulnerable populations.** A better understanding is needed of population-level exposure disparities, including the degree to which vulnerable groups such as children, elderly people and low-income communities experience disproportionately higher exposures due to socio- economic factors and geographic proximity to pollution sources. In addition, more evidence is needed to characterize the interaction of air pollution and heat on people with mental health challenges. This research is essential because exposure inequality exacerbates health inequities, necessitating targeted interventions to protect these at-risk groups. More research on different exposure patterns, access to health care, and resulting outcomes among vulnerable populations is also needed, particularly in low- and middle-income regions of the world.
- **Influence of temporal and spatial exposure variability and disparity,** particularly during extreme pollution events such as wildfires or smog episodes. This includes understanding how people's daily activities, such as commuting or outdoor labor, interact with fluctuating air quality levels to create peak exposure moments. Such insights are vital for developing real-time risk communication systems and personalized exposure reduction strategies.
- **Chronic versus episodic exposure impacts.** Research into whether prolonged low-level exposure or short-term high-level exposure poses greater health risks can guide air quality standards and public health policies more effectively. This is crucial in regions with seasonal pollution fluctuations, where populations face both chronic background pollution and acute episodic spikes. This is also especially relevant in the context of a changing climate where seasonal wildfire episodes and/or heat events are becoming more common, more widespread and more extreme.

These topics were prioritized because they directly inform policies aimed at reducing exposure disparities and improving public health outcomes. By focusing on the interplay between air quality levels and exposure patterns, researchers can develop nuanced interventions that protect populations under diverse environmental conditions, across varying socioeconomic contexts.

Research priorities: exposures



This area links individual exposure to physiological outcomes. Many of the recommendations focus on gaining a better understanding of how exposures to air pollution translate into biological doses that directly affect human health.

A key priority is investigating the relationship between exposure duration, intensity and target dose to identify the most critical exposure windows that lead to adverse health effects. This research is crucial because not all exposures result in equivalent internal doses due to individual variability in metabolism, activity patterns and physiological responses. Such studies can refine public health guidelines and exposure limits.

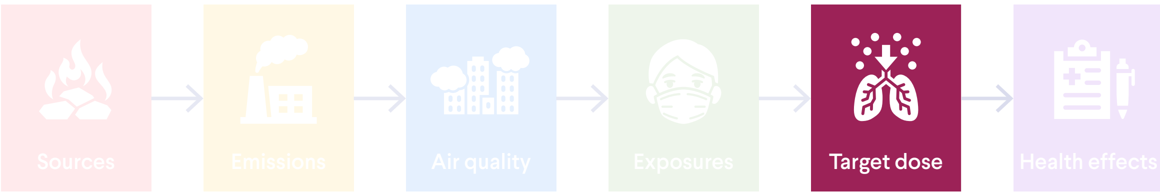
Another priority is studying the **life-stage-specific impacts of air pollution**, particularly in vulnerable populations and among elderly people. For example, research on how in-utero exposure to air pollutants influences fetal development and long-term health outcomes such as cognitive and metabolic disorders can reveal critical windows of susceptibility.

Mechanistic studies to supply context and support plausibility are also prioritized here. These studies will bring the "how" to the observational and epidemiologic studies— a critical link needed by policymakers to make the case for action. This includes a focus on assessing the impact of pollution on oxidative stress. Given the warming planet, a focus on the interactions of air pollution and heat on oxidative potential is also a priority.

Examining the impact of **cumulative and combined exposures to multiple pollutants** is essential to understanding how these exposures interact biologically to produce additive or synergistic effects. For example, exposure to both $PM_{2.5}$ and NO_2 may have compounded effects on respiratory and cardiovascular systems. Such research is critical for developing comprehensive risk assessment models that account for real-world exposure scenarios.

These topics were prioritized as they bridge the gap between environmental exposures and quantifiable health impacts, enabling more precise risk evaluations and tailored interventions. By focusing on how exposure patterns translate into target doses, researchers can advance strategies to mitigate long-term health risks associated with air pollution.[92]

Research priorities: target dose



Research in this area delves into how combined environmental stressors affect health.

This also involves a focus on the combined impacts of air pollution and heat, especially given the interaction of temperature on formation of secondary pollutants (e.g., ground-level ozone). Additionally, some source-specific studies may warrant a focus on specific diseases, as well as the compounded impact of wildfire smoke and heat, emphasizing the complexity of air pollution's health effects.

This area also includes a focus on **dose-response relationships in vulnerable populations** such as children, elderly people and those with preexisting health conditions. For instance, research on how air pollution exacerbates nonsmoking-related lung cancer risk in populations exposed to wildfire smoke, heat and humidity can offer insights into compounded environmental health risks. These findings can guide more accurate risk assessment models and tailored interventions.

Research should also prioritize **socioeconomic modifiers of health outcomes**, examining how factors like poverty, access to health care and occupational exposure influence the health effects of target doses. Understanding these modifiers is vital to address health disparities and to design equitable public health policies.

These topics must be prioritized because they provide a deeper understanding of how air pollution can manifest in diverse health outcomes on a warming planet, considering individual and contextual vulnerabilities. This knowledge forms the basis for designing precise interventions, refining health guidelines and creating targeted public health strategies to minimize the global burden of air pollution-related diseases.

Additional needs to advance climate and clean air policies for health

Nearly all of the research priorities identified could be placed within the modified chain of accountability described earlier. There were, however, a few additional areas that were flagged by both technical and policy stakeholders as being of critical importance to 1) make the case for actions to be taken, and 2) marshal the widespread public support needed for successful implementation of actions to be taken. These include impact assessments and social science research to promote increased awareness and behavior change. While these are not considered research priorities, they are critically related to the increased use of research and data to support the prioritization and evaluation of clean air and climate policies.

Policy assessments: Beyond scientific evidence from mechanistic and epidemiologic studies, policymakers need to understand 1) the magnitude of the current situation, in terms of the burden of disease, i.e., the ill health and deaths associated with air pollution at present, along with the economic impact of that burden, and 2) the potential health and economic benefits of the proposed actions. These types of policy assessments typically integrate data on changes in emissions and air quality and exposure data associated with proposed interventions, exposure-response functions from the existing global evidence base, and local data on air quality, health outcomes, and costs to estimate the relative effectiveness of actions. Results of these assessments are regularly used to prioritize actions to be taken on a local scale.

Policymakers often inquire about whether concentration-response functions used in health impact assessments should be based on local research, given concerns about differences in leading sources, pollution concentrations, and competing risk factors. In addition, the advantages of using concentration-response functions which integrate the best available global evidence have several advantages, including the narrowing of uncertainty around global estimates, the ability to estimate health impacts in various locations, and their suitability for generating recommendations for widespread application.[92]

There are certainly different underlying assumptions about the shape of the concentration-response function, particularly at lower concentrations. At the same time, most geographies currently lacking sufficient evidence to generate localized concentration-response functions routinely experience higher levels of air pollution exposure. Where these geographies fall along the curves will have a more substantial influence on results than the choice of exposure-response curve selected, i.e., expected changes in risk for any given outcome are mainly driven by levels of pollution experienced by the population of interest. See Figure 14 for an illustrative example. As such, the application of available global functions to local data on exposure and health outcomes is recommended, rather than delaying action until more local research results are available.

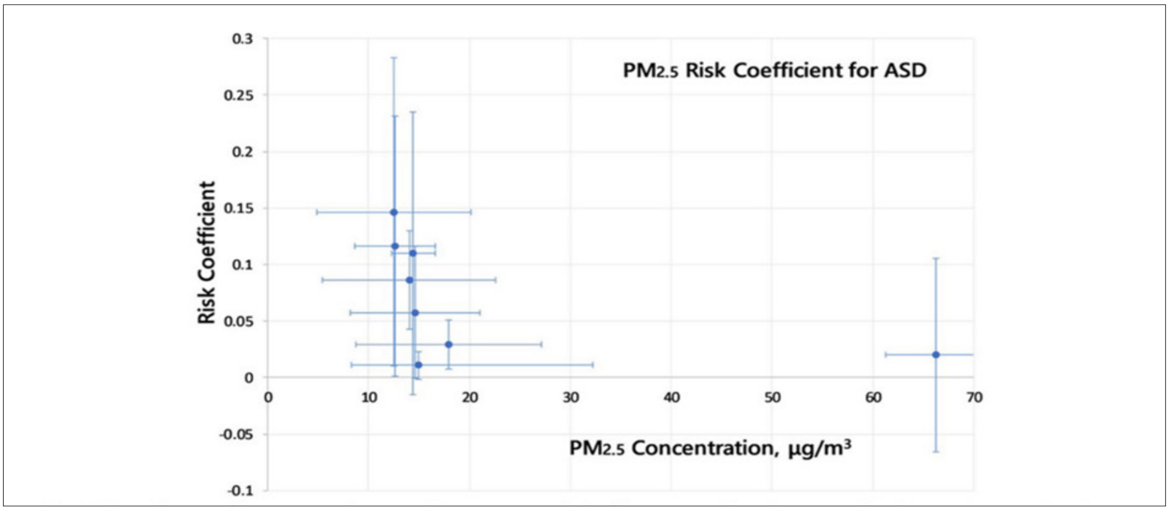


Figure 14. Risk coefficients of the association between $PM_{2.5}$ exposure and risk of Autism Spectrum Disorder Incidence, by range of concentrations in various studies. Source: Forastiere et al.[92]

Given the widespread and increasing interest in strengthening the integration and use of routinely collected local data to conduct these impact assessments, we recommend investing in the development of new methodologies, practical tools and provision of technical guidance needed to support the assessment of the health, climate and economic impacts of clean air and climate mitigation policies under consideration and/or in progress. This would help ensure the robustness of assessments to be undertaken, especially when coupled with efforts to strengthen local capacity to collect and integrate relevant data. In many cases, this would likely need to be coupled with efforts to strengthen local capacity to collect and integrate relevant data. This would help to ensure that local researchers are equipped with the robust data and tools needed to conduct assessments required to advance local polices. This would also result in robust results that are more comparable across various studies and contexts.

Social science research: There is a need for better communication and social science research to 1) raise awareness of sources of air quality and its impacts, 2) increase support for effective solutions, and 3) promote successful implementation of clean air and climate actions. A detailed prioritization of specific research objectives for social science is beyond the expertise and scope of this project, however.

Pragmatic considerations

Effective evaluations require clear baseline data on air quality and health outcomes. In some places this data may not be routinely collected or be readily accessible in an easily usable format.

Leveraging ongoing studies and existing datasets

Given the interest in generating evidence in the short term, e.g., over the next five years or so, opportunities to **retrofit existing cohorts and other similar longitudinal studies** are particularly valuable. These cohorts may provide a comparatively low-cost, robust framework for assessing the long-term health impacts of policies like low-emission zones or active mobility initiatives (e.g., increased walking and cycling). Opportunities to leverage ongoing studies and expanded analysis of existing datasets are a strategic way of filling key evidence gaps.

Retrofitting existing cohorts with new data on air pollution exposure, physical activity levels and health outcomes will allow an assessment of how these interventions influence chronic diseases, mental health and overall well-being over time. This approach also helps address the challenge of attributing health improvements directly to specific policies versus broader societal changes.[93]

Results of accountability studies will enable policymakers and stakeholders to design and implement more effective air quality interventions, providing clear evidence of their benefits while identifying areas needing improvement. By integrating theoretical models with real-world data and leveraging existing cohorts, researchers can develop a comprehensive understanding of how air pollution and health policies translate into tangible outcomes.

Addressing critical data and capacity gaps

Air quality data: Robust air quality data is pivotal in environmental and public health research, serving as a foundation for analyzing trends, developing policy and assessing risk. Routinely collected air quality data typically includes measurements of pollutants such as PM, NO_x, SO_2, O_3, and CO. These pollutants are monitored through fixed-site monitoring networks operated by governmental and independent organizations. However, pollutant-specific gaps in this data, particularly for less comprehensively monitored pollutants like black carbon, hinder the development of evidence-based conclusions and interventions. Many places with the greatest air quality concerns face capacity gaps in air quality data collection infrastructure, particularly for routinely updated emissions data, real-time air quality monitoring and individual exposure assessment. Filling these gaps is essential to increase the global distribution of policy relevant accountability research so that interventions are evaluated rigorously.

Specifically, there are a number of challenges reported regarding collection of air pollution data:

- **Spatial and temporal coverage:** Air quality monitoring networks are often unevenly distributed, leading to underrepresentation in rural and underserved regions. Routine undermonitoring of rural areas may lead to underestimation of exposures from biomass burning, especially in parts of Asia and Africa. Urban areas, typically prioritized due to higher pollution levels, may still experience limited site coverage for specific pollutants like NO_x. In addition, a disproportionate focus on measuring air pollution hot spots may limit the availability of data to represent population-level exposures.
- **Measurement limitations:** Certain pollutants, such as VOCs or NO_x, require specialized, high-resolution instruments. Data collection for NO_x can be inconsistent due to variations in instrumentation and calibration across monitoring stations. This leads to discrepancies in data quality and reliability. In addition, some sources of pollution, and indicator pollutants associated with these sources, such as NO_x for traffic, require more localized monitoring to accurately characterize differences in exposure.
- **Frequency of monitoring:** Some stations record data at hourly intervals, while others aggregate data monthly or annually. This inconsistency affects the capacity to assess acute exposure events, such as spikes in NO_x levels due to traffic congestion.

There are different approaches to collect or estimate air pollution data at different geographic scales. Data from different approaches may be integrated. Figure 15 illustrates the hierarchy of air pollution monitoring and modeling approaches.

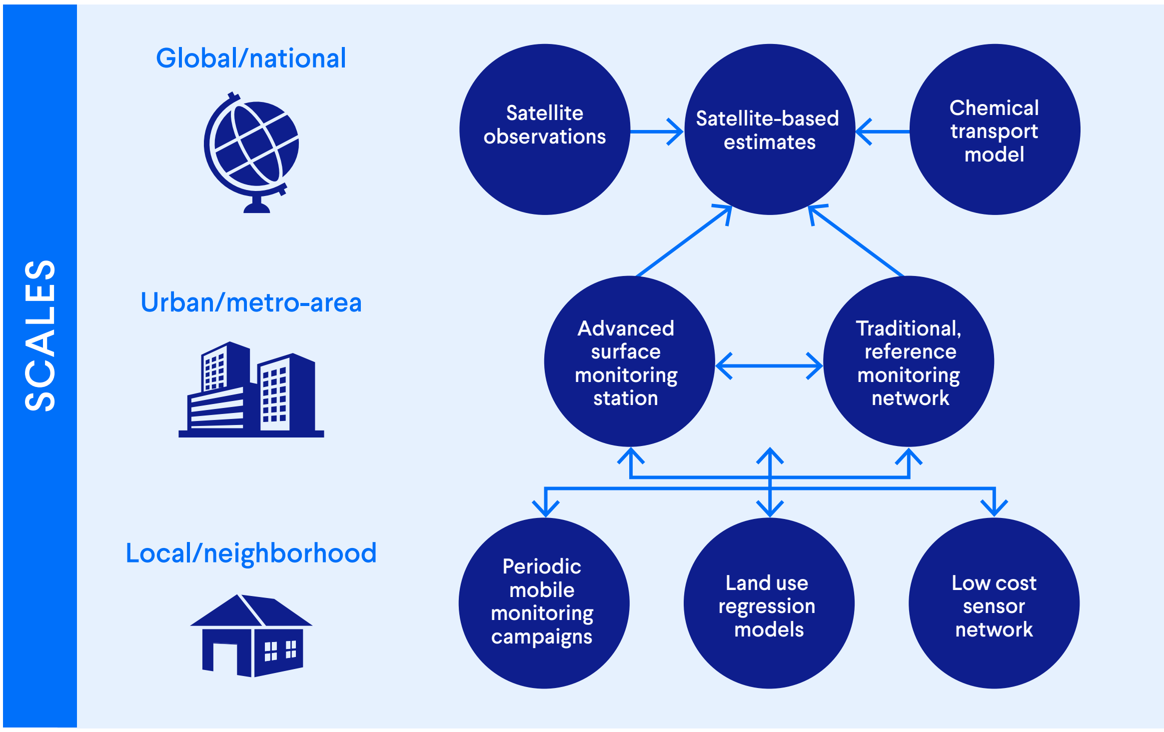


Figure 15. Integrated air pollution monitoring system to assess air pollution variation at different spatial and temporal resolution, inform additional reference monitor placements and incorporate new innovations over time. Source: Vital Strategies

Health data:

The integration of routine and complete health data is essential for understanding the relationship between pollution exposure and health outcomes. However, several gaps may hinder the ability to derive robust conclusions and implement effective interventions.

1. **Fragmentation of health and exposure data sources** Health data relevant to air pollution research is often collected across disparate institutions, including hospitals, insurance databases and public health agencies, each with their own reporting standards. For example, respiratory disease admissions may be recorded in hospital datasets, while broader population health trends are tracked by representative surveys by public health departments. This fragmentation makes it challenging to link health outcomes with pollution exposure consistently.

2. **Underrepresentation of vulnerable populations** Rural areas, low-income groups and marginalized communities are often underrepresented in health data, despite evidence that these populations are disproportionately affected by air pollution. For instance, rural residents exposed to agricultural burning may experience elevated respiratory risks, yet their health outcomes are infrequently recorded in urban-centric datasets.

3. **Temporal gaps in health data collection** The intermittent nature of health data collection, such as annual aggregation of disease incidence, limits the ability to analyze short-term health effects of acute pollution events such as wildfires or smog episodes. This temporal mismatch with high-frequency air quality data impedes the assessment of time-sensitive exposure impacts.

4. **Inconsistencies in reporting and completeness** Health outcomes such as emergency room visits for asthma or chronic obstructive pulmonary disease (COPD), are often underreported or lack granularity in time and location. When strengthening the routine collection of health data, it may be pragmatic to focus first on health effects or populations of greatest concern to the public or policymakers, such as young children. In addition, datasets may lack details needed to establish precise exposure-response relationships, for example, data on patient residential proximity to pollution hotspots, such as highways or industrial zones.

Data access and integration:

There are additional impediments to data integration and sharing and impact on research that need to be considered.

- **Legal and ethical barriers:** Privacy concerns and restrictive regulations, such as those under the General Data Protection Regulation (GDPR) or the Health Insurance Portability and Accountability Act (HIPAA), limit data sharing between air quality researchers and health data custodians. These barriers often prevent the linking of air pollution exposure datasets with health outcomes, creating gaps in longitudinal studies. Researchers focused on small area studies may have to address additional privacy concerns to ensure the anonymity of study participants.
- **Lack of interoperability:** Disparate data systems used for health and air pollution monitoring often lack standardized formats or metadata, complicating integration. For instance, combining spatially resolved air quality data with geographically referenced health records is hindered by inconsistent geocoding practices.
- **Technological constraints:** Many public health agencies lack the infrastructure for large-scale data integration. The absence of advanced analytical platforms capable of handling diverse datasets (e.g., hospital records, air quality monitoring, satellite data) limits the potential for innovative research approaches such as machine learning-based exposure modeling.

These integration barriers reduce the granularity and validity of evidence used to inform policy. For example, the inability to analyze granular health data in conjunction with air quality exposure has slowed progress in understanding the long-term effects of pollutants like fine PM and NO_2 on chronic conditions such as cardiovascular diseases.

While these challenges may seem daunting, the good news is that through active engagement with data owners, targeted technical assistance, and coordination of key technical climate, air quality and health stakeholders, there are innovative solutions available. Moreover, the process of filling in data gaps strategically would serve to reinforce the foundation for future research.

Conclusion

While there will always be scope for research to better quantify the health effects of climate actions targeting air quality, given trends in climate and clean air action, we should prioritize research to:

- fill in critical gaps with respect to characterizing the impact of addressing leading sources of pollution, including biomass burning
- consider the joint effects of air pollution and heat, studying multiple pollutants as well as particularly vulnerable populations
- inform policymakers about climate and air quality actions likely to provide maximum, equitable and measurable health benefits

Through this rapid scoping exercise, a common theme has emerged from our engagement with technical experts and policy stakeholders focused on air quality around the world: **The priority should be to evaluate the effectiveness of climate actions taken, with a focus on assessing measurable impacts on public health.** In order to do this effectively, there are critical and fundamental research gaps to be filled along the modified accountability chain linking sources of air pollution to health effects. This includes a range of epidemiologic and mechanistic studies focused on characterizing the impact of actions taken to address climate forcing emissions, and/or overall air quality on exposures and health effects. Mediating factors along the chain, ranging from pollutant transport and transformation to key factors influencing susceptibility, such as nutrition or socioeconomic status, need to be taken into account. New evidence emerging from targeted efforts to fill these gaps will serve as essential inputs to further research and practices as we work to maximize the measurable health benefits of climate and clean air action.

In addition, robust methodological approaches and practical tools are needed to conduct rigorous assessments of the health and economic benefits of climate and clean air actions, especially given the need to integrate global evidence with local data. These assessments have substantial policy relevance, and will also be informed by evidence generated when filling many of the research gaps identified here. While some social science priorities were duly noted, these are beyond the scope and expertise of our project team.

Given the urgency of this issue, for both people and the planet, we must prioritize research results that may be achieved over the short term, ideally over the next five years. At the same time, there are critical data and capacity gaps that are currently hindering the ability to conduct research in a timely manner. Support to strengthen the research infrastructure, with a focus on the availability of routinely collected air quality and health data, will pave the way for a more robust research infrastructure moving forward.

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Appendices

Appendix 1. Pollutants excluded from evidence gap analysis

EXCLUDED from the analysis	Number of articles (Region)
Air pollution	11 (China), 1 (Latin America)
Fly ash	7 (India)
AQI	1 (China), 1 (India), 1 (Latin America)
CO_2	2 (India)
HAP	2 (China), 2 (India), 1 (Africa), 1 (Latin America), 3 (Global)
TVOC	1 (China), 1 (India)
Phthalates	1 (China), 1 (India), 1 (Global)
Dust/Saharan dust	2 (Africa)

Individual studies — China
Pollutant mixtures: Ground-level ozone+$PM_{2.5}$, Ground-level ozone+$PM_{2.5}$+NO_2, PM_{10}+NO_2, PM_{10}+SO_2, $PM_{2.5}$+SO_2, $PM_{2.5}$+NO_2
Others: Benzene, PAH, coal burning, cooking oil vapor, domestic coal, haze, indoor coal
Individual studies — India
Coal, cotton dust, dust, HCHO, mercury, pond ash
Individual studies — Global
Carbon particles, elemental carbon, H_2S

Appendix 2.

Survey Instrument: Research priorities on health impacts of climate mitigation actions targeting air pollution

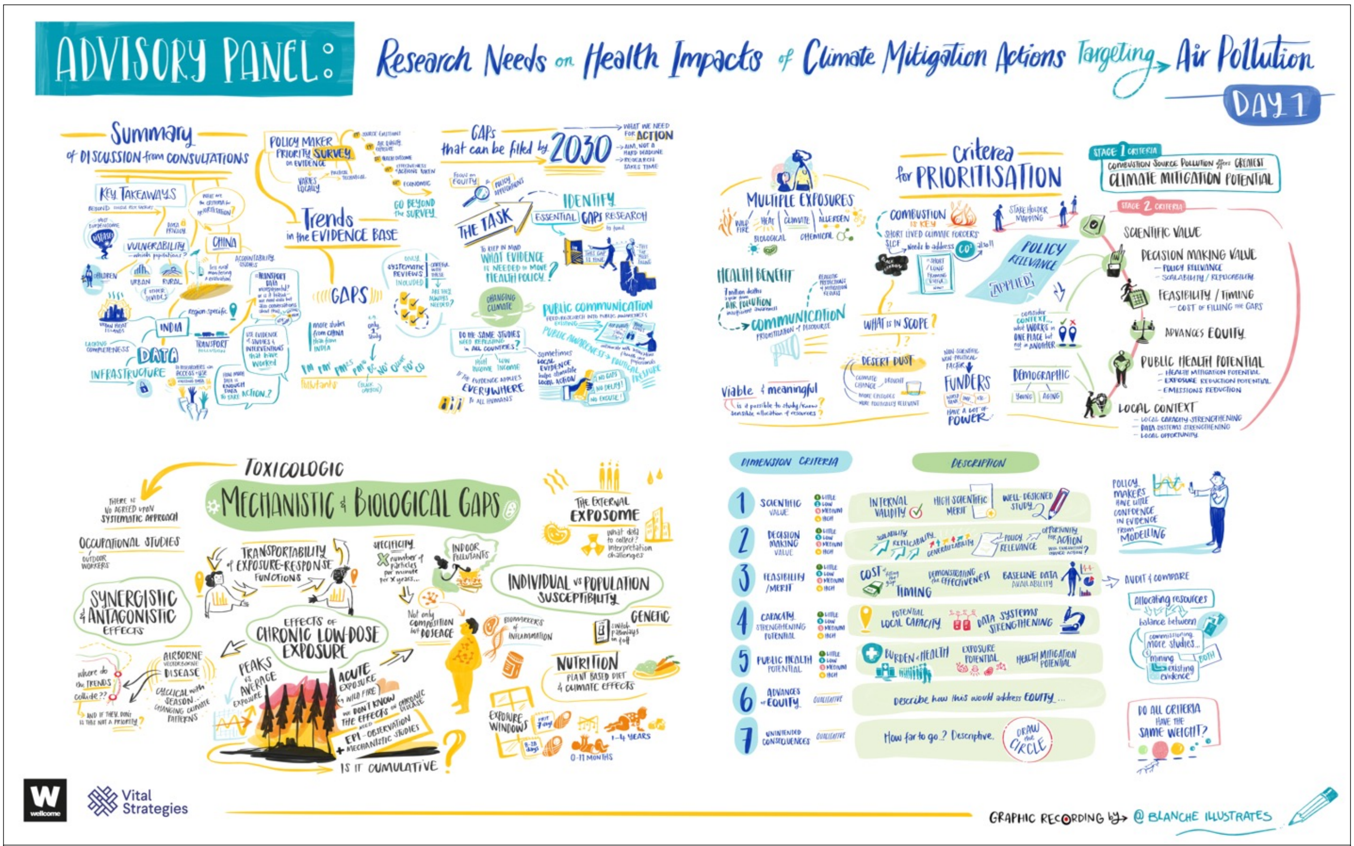
General questions

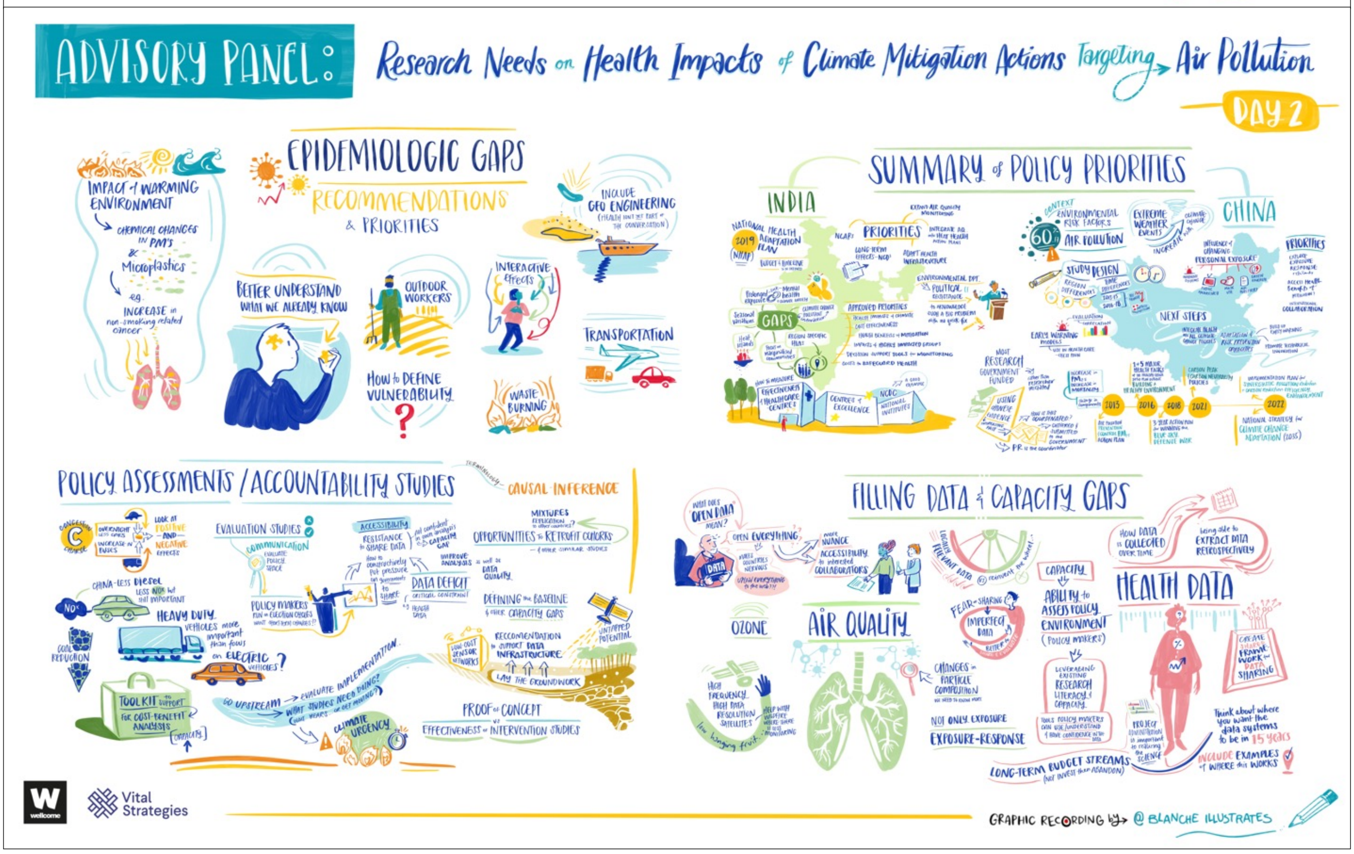
1. Name
2. Email
3. Gender: *cis-male, cis-female, non-binary/queer*
4. Country you are based in
5. Countries you work in
6. Affiliation
7. Area of expertise: *epidemiology, exposure assessment, risk assessment, biostatistics, toxicology, policy, physiology, clinical medicine, other (specify)*
    a. If other, specify
8. *Focus within expertise: adolescent/child health, non-communicable diseases, infectious diseases, reproductive health, mental health, maternal health, natural/climate disasters, occupational health, community health, chronic diseases, pregnancy outcomes, social determinants of health, other (specify)*
    a. If other, specify

Research questions

1. What are the most pressing SOURCE-specific research gaps in terms of how they are damaging to health?
2. What are the most pressing POLLUTANT-specific research gaps in terms of how they are damaging to health?
3. What are the key knowledge gaps in understanding the MECHANISMS of how air pollution impacts health?
4. What are the key knowledge gaps in understanding the TOXICOLOGY of air pollution?
5. Are there on-going studies (e.g., cohort) where air pollution may be added to expedite availability of results?
6. What age group/life stage is missing key evidence? (check all that apply): *prenatal, early neonatal (within first 7 days), late neonatal (8-28 days), 0-11 months, 1-4 years, 5-14 years, 15-49 years, 50-69 years, 70+ years*
7. What evidence or application of evidence is prioritized by policymakers and implementers in the places that you work? (check all that apply): *Source emissions evidence (e.g., pollution levels, types of pollutants, emission trends), Air quality and exposure evidence (e.g., concentration of pollutants, population exposure levels), Health outcomes evidence (e.g., mortality, morbidity, DALYs, disease incidence), Economic evidence (e.g., cost-benefit analysis, economic burden of disease, cost of interventions), Effectiveness of actions taken (e.g., consistency, reach, effectiveness of interventions), Other (specify)*
    a. If other, specify
8. What are local gaps in data availability (sources, exposures, impacts, etc.) and capacity (technical, measurement, laboratory, monitoring, etc.) in the places that you work? (check all that apply): *Health outcomes data (e.g., mortality, morbidity, DALYs, disease incidence), Source emissions data (e.g., pollution levels, types of pollutants, emission trends), Air quality and exposure data (e.g., concentration of pollutants, population exposure levels), Environmental trends (e.g., climate change, deforestation, urbanization), Economic data (e.g., cost-benefit analysis, economic burden of disease, cost of interventions), Geographic data (e.g., regional variation, urban vs. rural data, specific hot spots), Demographic data (e.g., age, gender, socioeconomic status, vulnerable populations), Social determinants of health (e.g., housing, access to clean water, education, income levels), Inequity and vulnerability data (e.g., by gender, socioeconomic status, geographic location), Healthcare system capacity data (e.g., health infrastructure, access to services, healthcare workforce), Behavioral data (e.g., cooking practices, transportation habits, waste management), Public opinion or awareness data (e.g., surveys on public concerns, awareness of pollution issues), Other (specify)*
    a. If other, specify
9. What are leading mitigation measures currently underway in the places where you work which need evaluation?
10. What are leading mitigation measures under consideration in the places where you work which would require robust baseline data and then follow up?
11. Would you be willing to be contacted for a brief follow-up interview?: *Yes, No*

Appendix 3. Graphic notes summarizing advisory panel meeting





Graphic recording by Blanche Ellis, 2024.

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