STUDY

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Health effects of fine particles

Assessing the health burden of fine particles and options for stronger EU action

Policy Department for Transformation, Innovation and Health
Directorate-General for Economy, Transformation and Industry
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Abstract

This study examines the health effects of fine particulate matter ($PM_{2.5}$ and PM_{10}), trends in exposure, and the effectiveness of EU legal and policy frameworks. It draws on an umbrella review of 198 systematic reviews, quantitative analysis of exposure trends, stakeholder interviews, and comparative case studies across EU Member States. The study shows consistent health effects of $PM_{2.5}$ exposure across multiple disease categories and identifies persistent inequalities in exposure across populations and regions, with no safe threshold for $PM_{2.5}$ exposure identified. It proposes evidence-based policy recommendations to reduce health impacts across the EU.

The study was provided by the Policy Department for Transformation, Innovation and Health at the request of the Committee on Environment, Climate and Food Safety (ENVI) and the Committee on Public Health (SANT).

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LIST OF ABBREVIATIONS

AAQD	Ambient Air Quality Directive
ADHD	Attention Deficit/Hyperactivity Disorder
AFC	Antral Follicle Count
AMD	Age-related Macular Degeneration
AMH	Anti-Müllerian Hormone
ASD	Autism Spectrum Disorder
BAT	Best Available Techniques
CKD	Chronic Kidney Disease
COPD	Chronic Obstructive Pulmonary Disease
DALY	Disability-Adjusted Life Year
DED	Dry Eye Disease
EEA	European Environment Agency
EPBD	Energy Performance of Buildings Directive
FEV_1	Forced Expiratory Volume in one second
FVC	Forced Vital Capacity
FQD	Fuel Quality Directive
GBD	Global Burden of Disease
IHD	Ischaemic Heart Disease
IVF	In Vitro Fertilisation
LBW	Low Birth Weight
LGA	Large for Gestational Age
MI	Myocardial Infarction

NAFLD	Non-Alcoholic Fatty Liver Disease
PEF	Peak Expiratory Flow
PM	Particulate Matter
PPD	Postpartum Depression
PTB	Pulmonary Tuberculosis
SARS	Severe Acute Respiratory Syndrome
SIDS	Sudden Infant Death Syndrome
SLD	Steatotic Liver Disease
SLE	Systemic Lupus Erythematosus
TB	Tuberculosis
TLBW	Term Low Birth Weight
TRAP	Traffic-Related Air Pollution
WHO	World Health Organization

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EXECUTIVE SUMMARY

This study examines the health effects of fine particulate matter ($PM_{2.5}$ and PM_{10}), trends in exposure, and the effectiveness of EU legal and policy frameworks. It draws on an umbrella review of 198 systematic reviews, quantitative analysis of exposure trends, stakeholder interviews, and comparative case studies across EU Member States. The study finds no safe threshold for $PM_{2.5}$ exposure, shows consistent health effects across multiple disease categories, and documents persistent inequalities in exposure across populations and regions. It proposes evidence-based policy recommendations to reduce health impacts across the EU.

The study was prepared by Ecorys for the Policy Department for Transformation, Innovation and Health at the request of the Committee on Environment, Climate and Food Safety (ENVI) and the Committee on Public Health (SANT).

Background

Fine particulate matter, microscopic airborne particles known as $PM_{2.5}$ (particles smaller than 2.5 micrometres in diameter) and PM_{10} (particles smaller than 10 micrometres), is one of the most serious environmental threats to public health in the European Union (EU). These particles are small enough to pass deep into the lungs and enter the bloodstream, but they may also affect the body through other pathways, including direct transport via the olfactory system to the brain, where they trigger inflammation, damage blood vessels and organs, and disrupt the body's immune and nervous systems. These effects are not limited to the lungs: the same biological pathways explain why long-term exposure to fine particles is consistently linked to heart attacks, strokes, diabetes, dementia, cancer, and premature death. Critically, harmful effects are observed even at relatively low levels of exposure. Scientists have not identified any concentration of $PM_{2.5}$ below which there is no health risk.

Despite significant improvements in EU air quality over the past two decades, around 182,000 deaths in the EU were still attributable to $PM_{2.5}$ in 2023. Most EU regions continue to exceed the World Health Organization's (WHO) recommended annual limit. The health burden is not evenly distributed: children, older adults, and people living in poorer regions and communities bear a disproportionate share.

This study was prepared by Ecorys on behalf of the Policy Department for Transformation, Innovation and Health at the request of the Committees on Environment, Climate and Food Safety (ENVI) and on Public Health (SANT). It provides a comprehensive and up-to-date assessment of the health impacts of fine particles, examines trends in exposure across EU Member States, reviews the effectiveness of EU and national legislation, and proposes evidence-based policy recommendations.

Aim

The study addresses four questions:

1) How does exposure to fine particles affect human health?
2) How have PM levels and their health impacts changed across EU Member States?
3) How effective is EU and national legislation in tackling exposure and health impacts?
4) What policy measures can best reduce exposure and protect health?

To answer these questions, the study combines four methods. First, a structured review of 198 peer-reviewed scientific studies (systematic reviews and meta-analyses), synthesising the best available evidence on health effects. Second, a quantitative analysis of EU-wide trends in air quality and health burden, drawing on data from the European Environment Agency (EEA), Eurostat, the World Health Organization, and the Global Burden of Disease study. Third, a review and assessment of the EU legislation and policy instruments relevant to particulate matter. Fourth, in-depth case studies of eight EU Member States (Poland, Bulgaria, Denmark, Finland, Spain, Italy, Germany, and France) and three non-EU countries (Norway, China, and the United Kingdom), supplemented by interviews with national authorities, EU institutions, and independent experts.

Key Findings

Health effects of $PM_{2.5}$ and PM_{10}

The scientific evidence on the health effects of fine particles is extensive and consistent. Long-term exposure to $PM_{2.5}$ is associated with a 6–10% increase in the risk of death from any cause for every 10 µg/m^3 increase in concentration. Short-term spikes in pollution, such as during heatwaves or high-traffic periods, also increase mortality by around 0.4–0.7% per 10 µg/m^3.

The health effects from long-term exposure extend across virtually every major disease category. Heart attacks and strokes are the most strongly affected conditions: both can be triggered by acute exposure episodes and are made more likely by years of chronic exposure. Lung disease, including asthma, chronic obstructive pulmonary disease (COPD), and lung cancer, is also consistently linked to particulate exposure.

There is now substantial evidence that fine particles affect the brain: long-term $PM_{2.5}$ exposure is associated with around a 49% higher risk of cognitive impairment and is consistently linked to dementia, depression, and neurodevelopmental conditions, including ADHD and autism in children. Exposure during pregnancy increases the risk of premature birth, low birth weight, and gestational diabetes.

Across all these outcomes, there is no evidence of a safe level of exposure. Health effects are observed at concentrations below the current EU legal limits (25 µg/m^3 for $PM_{2.5}$ and 40 µg/m^3 for PM_{10}) and even below the WHO's own recommended guideline values (5 µg/m^3 for $PM_{2.5}$ and 15 µg/m^3 for PM_{10}) (see Table 2).

Some groups are considerably more vulnerable than others. Children are at heightened risk because their lungs and brains are still developing; older adults face higher risks due to reduced physiological resilience and often multiple existing health conditions; and people in lower-income regions or households face both higher exposure levels and stronger health impacts per unit of pollution.

Trends in exposure and health burden

Air quality has improved significantly across the EU since 2005. $PM_{2.5}$-attributable premature deaths have fallen by approximately 57% over this period following decreases in PM burden, and every Member State has recorded declining $PM_{2.5}$ concentrations. This progress is a direct result of EU and national legislation covering vehicle emissions, industrial processes, and fuel standards.

However, progress is uneven and, in recent years, diverging. Between 2013 and 2023, some Member States, including Luxembourg, Belgium, Czechia, Austria, Germany, and Slovakia, reduced $PM_{2.5}$ concentrations by 40–50%. Others, including Greece, Spain, Malta, and Italy, achieved far smaller reductions of 10–22%. More recently, between 2021 and 2023, five Member States; Portugal, Italy, Greece, Slovenia, and Spain, actually recorded an increase in the health burden attributable to $PM_{2.5}$.

Significant regional hotspots persist even where national averages have improved. In 2023, 56 EU regions still exceeded the 2030 EU legal limit for $PM_{2.5}$, and 210 of 234 EU regions exceeded the WHO-recommended guideline. The highest concentrations were recorded in and around Bucharest, Venice, Silesia, Zagreb, and Athens.

The health burden is concentrated in older adults, who account for the large majority of the 182,000 $PM_{2.5}$-attributable deaths in 2023. Dementia, included in EU burden-of-disease estimates for the first time in 2025, is now the single largest individual disease contributing to $PM_{2.5}$-attributable ill health in people aged 60 and over, a finding that substantially increases previous estimates of the total health burden. The gap between the richest and poorest EU regions has not narrowed: the poorest fifth of EU regions are exposed to around 30% more $PM_{2.5}$ than the wealthiest, and the risk of death from a given level of pollution is up to twice as high in disadvantaged regions.

EU legal and policy frameworks

The EU has a comprehensive set of laws addressing particulate matter, spanning air quality standards, vehicle emission limits, industrial emissions rules, fuel standards, and national emission reduction commitments. The evidence shows that this framework has worked: the majority of PM reductions since 2005 are attributable to legally binding standards covering vehicles, large industrial sources, and fuel quality.

However, the framework has significant gaps. Agricultural emissions, specifically ammonia, which is the main ingredient in the formation of a large share of fine particles, have barely changed since 2005. EU legislation sets national targets for ammonia reductions but includes no binding sector-level measures, and the main EU regulation governing agricultural nitrogen (the Nitrates Directive) contains no reference to air quality. Residential wood-burning, a major and growing source of $PM_{2.5}$ in many Member States, falls entirely outside EU sustainability and product standards. EU renewable energy legislation does not regulate emissions from household wood stoves, and no EU-level product standards limiting PM emissions from domestic heating appliances have yet been adopted.

Legal flexibility provisions also risk weakening effective ambition. Under the revised EU Air Quality Directive (adopted in 2024), Member States can apply for a delay of up to 10 years in meeting the 2030 $PM_{2.5}$ limit. This postponement is conditional on Member States demonstrating, via an air quality roadmap assessed by the Commission, that the limit value will be met by the end of the postponement period. Eligible grounds include a high share of low-income households in the zone if the Member State has a national GDP per capita lower than the EU average, or modelling results showing the limit values cannot be attained within the attainment date, as well as unfavourable dispersion conditions linked to topography or climate, and significant transboundary pollution contributions. Case study evidence suggests this is a likely outcome for Poland, Bulgaria, and parts of Italy, precisely the regions with the highest health burden.

Case studies of eight Member States confirm a wider pattern: having laws on paper does not automatically translate into health improvements on the ground. Air quality plans often lack concrete targets, assigned responsibilities, and dedicated funding. Low-emission zones, which restrict the most polluting vehicles from urban areas, are legally required in many Member States but inconsistently enforced. No case study country has adequately addressed agricultural ammonia as a source of $PM_{2.5}$.

Policy recommendations

The study presents 17 recommendations, grouped into five themes.

On strengthening EU air quality standards: the EU should use the review mechanism built into the 2024 Air Quality Directive to commit to a binding pathway towards the WHO $PM_{2.5}$ guideline of 5 µg/m³ by 2040, with an interim target of 7.5 µg/m³ by 2035. The postponement provisions that allow Member States to delay compliance should be restricted and subject to mandatory public reporting on the health costs of any delay.

To close the agricultural ammonia gap, binding sector-level ammonia reduction obligations should be introduced through targeted amendments to EU legislation governing national emission ceilings and agricultural nitrogen management.

To improve implementation and enforcement, air quality roadmaps required under the 2024 Directive should include concrete, funded, and enforceable measures; the framework for low-emission zones should be strengthened; and EU-level support for monitoring and best-practice sharing should be expanded.

On closing sectoral policy gaps: the regulatory gap for residential wood-burning should be addressed through both renewable energy legislation and product standards for heating appliances; and EU policy should accelerate the turnover of older, more polluting vehicle fleets to realise the health benefits of the latest emission standards.

On integrating health into air quality policy: health authorities should be systematically involved in air quality policy design at national level; EU burden-of-disease estimates should be expanded to include morbidity costs and economic impacts; public information on air quality should meet common EU standards; and equity, ensuring that the most disadvantaged communities benefit from air quality improvements, should be explicitly addressed in air quality plans and health assessments.

1. INTRODUCTION

1.1. Background of the study

Air pollution, and in particular fine particulate matter ($PM_{2.5}$ and PM_{10}), remains one of the most significant environmental threats to public health in the European Union, contributing to substantial premature mortality and preventable disease burden each year. Despite regulatory progress, health effects are observed even at concentrations below current EU limit values, and exposure disproportionately affects vulnerable and socioeconomically disadvantaged populations. In the context of the revised Ambient Air Quality Directive and the European Green Deal, a clear and up-to-date assessment of the health impacts of particulate matter is essential to inform ambitious, evidence-based policy decisions.

1.2. Scope and objectives of the study

This study has been commissioned by the European Parliament. The ultimate aim of this study is to provide Members of the ENVI and SANT Committees with comprehensive and up-to-date evidence on the health effects of fine particulate matter ($PM_{2.5}$ and, where relevant, PM_{10}) and on the effectiveness of EU legislation addressing these pollutants. It will also offer policy recommendations, including potential legislative measures to support EU decision-making. Specifically, the research questions are:

1) How does exposure to $PM_{2.5}$ and PM_{10} affect human health?
2) What are the trends in $PM_{2.5}$ and PM_{10} concentrations and their associated health impacts across EU Member States?
3) How effective are the legal and policy frameworks of the EU, Member States and non-EU countries in addressing $PM_{2.5}$ and PM_{10} exposure and its health impacts?
4) What evidence-based policy options and recommendations can be proposed to reduce $PM_{2.5}$ and PM_{10} exposure and mitigate health impacts in the EU?

While the primary focus is on the EU as a whole, the study also maps selected measures at the Member State level to reduce the health impacts of $PM_{2.5}$. In addition, it provides comparative insights from non-EU countries with advanced regulatory frameworks or successful strategies to reduce particulate matter and mitigate its health effects.

This study is structured to address each of the four research questions in turn.

Table 1: Study structure

Chapters		Research questions
1	Introduction and methodology	
2	$PM_{2.5}$/PM_{10} and human health	RQ1: health effects of exposure
3	Trends across the EU	RQ2: Trends in concentration and health impacts
4	Legal and policy frameworks	RQ3: Effectiveness of EU and national frameworks
5	Case studies	RQ3 and RQ4: national examples and lessons learned
6	Conclusions and recommendations	RQ4: evidence-based policy options

The detailed methodology for this study is provided in **Annex 1**.

1.3. Analytical scope and limitations

Several limitations of the analytical approach of this study, as detailed in **Annex 1,** warrant acknowledgement.

- First, the health evidence base (Chapter 2) draws on existing meta-analyses and systematic reviews, which vary in the exposure metrics used, the populations studied, and the health outcomes assessed. Heterogeneity across studies means that findings should be interpreted as associations rather than definitive causal relationships, and where inconsistency persists, the study presents ranges rather than single-point estimates.
- Second, the trends analysis (Chapter 3) relies primarily on EU-level datasets from EEA, Eurostat, and WHO, which differ in territorial scale, reporting years, and definitions across Member States, limiting strict comparability.
- Third, the assessment of legal and policy frameworks (Chapter 4) is constrained by uneven availability of national implementation and enforcement data, particularly for subnational measures and non-EU countries.
- Finally, the stakeholder consultation, while broad in scope, may not fully capture all relevant perspectives, and divergent views are reported transparently where they arise. Where data gaps or uncertainties are significant, they are explicitly flagged in the relevant chapters.

2. $PM_{2.5}$/PM_{10} AND HUMAN HEALTH

KEY FINDINGS

A consistent pattern emerges across the evidence: particulate matter exposure is associated with adverse health outcomes across multiple organ systems, with certain population groups facing particularly high risks.

Health impacts have been observed even at low concentrations, with no clear safe threshold of exposure identified. The underlying biological mechanisms, including oxidative stress, inflammation, and vascular damage, are consistently observed across a wide range of health outcomes.

The strongest and most consistent evidence relates to respiratory and cardiovascular disease, with exposure linked to increased risks of asthma, COPD, lung cancer, heart attacks, stroke, and premature mortality. Growing evidence also points to important effects on brain health, including cognitive decline, dementia, depression, anxiety, and neurodevelopmental disorders.

Vulnerability is not evenly distributed across the population. Children, older adults, individuals with pre-existing health conditions, and socioeconomically disadvantaged groups consistently experience greater risks, reflecting a combination of biological susceptibility, underlying health status, and higher levels of exposure. Pregnancy and early childhood emerge as particularly sensitive periods, with evidence linking exposure to adverse pregnancy outcomes and impacts on child health and development.

Across health outcomes, $PM_{2.5}$ generally shows stronger and more consistent associations than PM_{10}, reinforcing its importance as a priority target for public health and air quality policy.

Particulate matter is the collective term for the mixture of solid particles and liquid droplets suspended in the air we breathe. Particles vary enormously in size, and size determines how far they can travel through the body. PM_{10} refers to particles with a diameter of 10 micrometres or less (roughly one-seventh the width of a human hair), small enough to be inhaled and to reach the upper airways and lungs. $PM_{2.5}$ refers to the finer fraction: particles of 2.5 micrometres or less, which penetrate deeper still, reaching the smallest air sacs of the lung (the alveoli) and, in some cases, crossing into the bloodstream. These fine particles come from a wide range of sources, including vehicle exhausts, industrial processes, residential heating (particularly wood and coal burning), agricultural emissions, and chemical reactions between atmospheric gases that produce secondary particles, and other sources. Because they are invisible to the naked eye and remain suspended in the air for hours or days, people are exposed continuously and often unknowingly. The combination of their ability to penetrate deeply into the body, the novel effects they have on different organs, their diverse origins, and the chronic exposure of the population makes particulate matter one of the most studied and consequential environmental health risks of our time.

This chapter synthesises current scientific and epidemiological evidence on the health impacts of exposure to $PM_{2.5}$ and PM_{10}. It examines how fine particulate matter contributes to premature mortality, defined as death occurring earlier than would be expected in the absence of a given risk factor, and to a broad spectrum of infectious and chronic diseases, assessing its impacts across different life stages and among vulnerable groups.

Exposure to fine particulate matter ($PM_{2.5}$ and PM_{10}) triggers a set of well-established biological mechanisms that affect multiple organ systems. Fine particles penetrate deeply into the lungs, inducing oxidative stress and systemic inflammation. Oxidative stress is a process in the body that causes harmful molecules to damage cells and tissues faster than the body can repair them, and systemic inflammation is a widespread immune response that affects the entire body rather than a single site. Together, these processes damage blood vessels, disrupt heart function, and impair the body's ability to regulate itself. These wide-ranging effects explain why particulate matter is consistently associated not only with respiratory disease, but also with cardiovascular events, metabolic disorders, conditions in which the body's normal processing of energy and nutrients is disrupted, such as type 2 diabetes, cognitive decline, adverse pregnancy outcomes, and premature mortality.

Emerging evidence further indicates that $PM_{2.5}$ exposure can lead to epigenetic modifications, altering gene expression in ways that may increase long-term disease susceptibility across the life course. During pregnancy, inflammatory mediators and fine particles can affect placental function, thereby influencing transplacental effects on foetal development.

Importantly, these mechanisms operate even at relatively low exposure levels, supporting the WHO's conclusion that no safe threshold for particulate matter has been identified.[1] From a policy perspective, this biological coherence across disease categories strengthens the case for ambitious air quality standards and sustained reductions in population exposure.

[1] World Health Organization, 2021, *WHO global air quality guidelines: particulate matter (PM2.5 and PM10), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide*. Available at: https://www.who.int/publications/i/item/9789240034228.

2.1. Health effects on mortality and chronic diseases

KEY FINDINGS

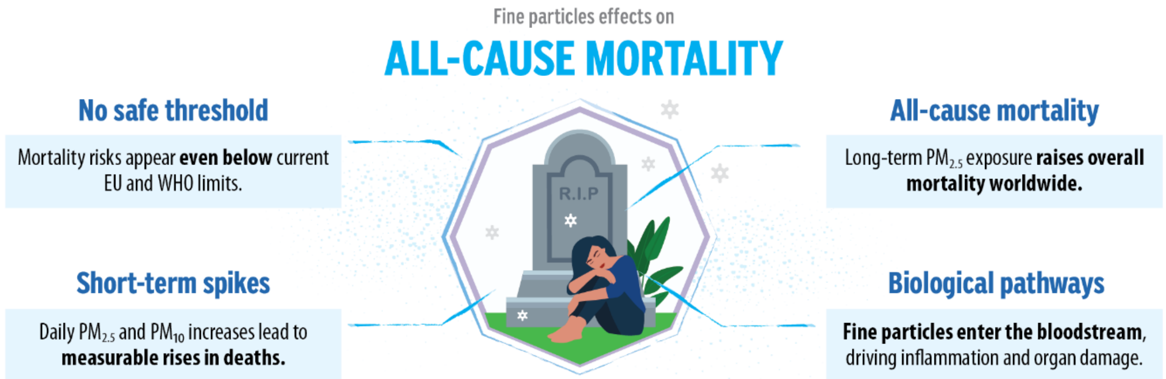
The evidence consistently shows that both short- and long-term exposure to particulate matter increase the risk of premature mortality and contribute to a broad range of chronic diseases. While adverse effects are observed for both $PM_{2.5}$ and PM_{10}, the strongest and most consistent associations are found for the relation between, including its magnitude, long-term exposure to $PM_{2.5}$.

The most robust evidence relates to respiratory and cardiovascular health, with particulate matter linked to conditions such as asthma, COPD, heart attacks, and stroke. Growing evidence also points to important impacts on neurological and mental health, including cognitive decline, dementia, depression, and adverse neurodevelopmental outcomes. In addition, long-term exposure has been associated with an increased risk of lung cancer and several chronic metabolic conditions, including type 2 diabetes and chronic kidney disease.

Evidence further suggests that there is no clear safe threshold below which health effects do not occur, with adverse outcomes reported even at concentrations below current air quality standards. The burden is not shared equally, with children, older adults, individuals with pre-existing health conditions, and socioeconomically disadvantaged populations consistently facing higher risks.

2.1.1. All-cause mortality

Figure 1: All-cause mortality



Source: Authors' own elaboration.

Exposure to fine particulate matter is consistently associated with increased all-cause mortality. Fine particles ($PM_{2.5}$) are small enough to reach the deepest parts of the lungs and pass into the bloodstream, where they can trigger widespread inflammation and oxidative stress, disturb the body's normal immune and nervous system responses, and damage blood vessels and organs. These combined effects place additional strain on the heart, lungs, metabolism, and kidneys, increasing the likelihood of serious health events and contributing to higher all-cause mortality. This relationship has been observed across a wide range of geographic settings, study designs, and exposure levels, with the strongest and most certain evidence observed for long-term $PM_{2.5}$ exposure[2 3 4 5 6]. All-cause mortality is commonly used as an aggregate endpoint in air pollution research, as it captures the net health impact across causes of death and is less sensitive to misclassification than cause-specific mortality.

Evidence from large-scale systematic reviews and meta-analyses, such as the Global Burden of Disease (GBD) 2019 study, shows that long-term exposure to $PM_{2.5}$ is consistently associated with increased all-cause mortality. These analyses synthesised data from a wide range of cohort studies to estimate how changes in exposure levels are associated with changes in mortality risk across different populations and health outcomes. Across studies, the relationship is typically estimated as an approximately 6–8% increase in mortality risk per 10 $\mu g/m^3$ rise in $PM_{2.5}$ concentrations. Importantly, even relatively modest individual risks translate into a substantial population-level burden due to the widespread and chronic nature of exposure, reinforcing air pollution as a major global public health risk factor[7]. Additionally, a group of other large systematic reviews and meta-analyses of studies shows that **long-term $PM_{2.5}$ exposure is associated with an 8-10% increase in all-cause mortality per 10 $\mu g/m^3$ increase in concentration,** with somewhat smaller but still significant effects for PM_{10} [8 9 10]. These findings are consistent across Europe, North America and parts of Asia. Current evidence indicates no established safe threshold within the observed exposure range, with associations reported at concentrations below both previous and current EU and WHO limit values.

Short-term exposure to particulate matter is also associated with increased all-cause mortality. Global meta-analyses indicate that day-to-day increases in $PM_{2.5}$ and PM_{10} are linked to measurable rises in mortality, with estimates showing approximately a **0.4–0.7% increase in risk for every 10 $\mu g/m^3$ rise in concentration**[11 12]. **Although the percentage increases appear smaller than those observed for long-term exposure, short-term effects operate across entire urban populations and therefore translate into substantial numbers of excess deaths.** These short-term effects have been

2 Chen, J., Hoek, G., 2020, *Long-term exposure to PM and all-cause and cause-specific mortality: A systematic review and meta-analysis*, Environment International, Vol. 143. Available at: https://pubmed.ncbi.nlm.nih.gov/32703584/.

3 Rackow, B. et al., 2025, *The interaction between air pollution, weather conditions, and health risks: a systematic review*, Science of the Total Environment, Vol. 996. Available at: https://pubmed.ncbi.nlm.nih.gov/40749248/.

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5 Karanasiou, A. et al., 2021, *Short-term health effects from outdoor exposure to biomass burning emissions: A review*, Science of the Total Environment, Vol. 781. Available at: https://pubmed.ncbi.nlm.nih.gov/33798874/.

6 Karimi, B. and Samadi, S., 2024, *Long-term exposure to air pollution on cardio-respiratory, and lung cancer mortality: a systematic review and meta-analysis*, Journal of Environmental Health Science & Engineering, Vol. 22(1), pp. 75–95. Available at: https://pubmed.ncbi.nlm.nih.gov/38887768/.

7 GBD 2019 Risk Factors Collaborators, 2020, Global burden of 87 risk factors in 204 countries and territories, 1990–2019: a systematic analysis for the Global Burden of Disease Study 2019, The Lancet, Vol. 396(10258), pp. 1223–1249. Available at: https://www.thelancet.com/journals/lancet/article/PIIS0140-6736(20)30752-2/fulltext.

8 Chen, J. and Hoek, G., 2020, *Long-term exposure to PM and all-cause and cause-specific mortality: A systematic review and meta-analysis*, Environment International, Vol. 143, Article 105974. Available at: https://pubmed.ncbi.nlm.nih.gov/32703584/.

9 Orellano, P. et al., 2024, Long-term exposure to particulate matter and mortality: an update of the WHO Global Air Quality Guidelines systematic review and meta-analysis. Available at: https://pubmed.ncbi.nlm.nih.gov/39399882/.

10 Karanasiou, A. et al., 2021, *Short-term health effects from outdoor exposure to biomass burning emissions: A review*, Science of the Total Environment, Vol. 781. Available at: https://pubmed.ncbi.nlm.nih.gov/33798874/. https://pubmed.ncbi.nlm.nih.gov/39399882/.

11 Orellano, P. et al., 2020, Short-term exposure to particulate matter (PM10 and PM2.5), nitrogen dioxide (NO2), and ozone (O3) and all-cause and cause-specific mortality: Systematic review and meta-analysis, Environment International, Vol. 142, Article 105876. Available at: https://pubmed.ncbi.nlm.nih.gov/32590284/.

12 Rackow, B. et al., 2025, *The interaction between air pollution, weather conditions, and health risks: a systematic review*, Science of the Total Environment, Vol. 996. Available at: https://pubmed.ncbi.nlm.nih.gov/40749248/.

observed across diverse climate regions and pollution environments[13]. For example, evidence from specific exposure contexts, such as wildfire smoke and desert dust events, indicates that short-term spikes in particulate matter are associated with increased all-cause mortality, with $PM_{2.5}$ driving impacts during wildfire episodes and PM_{10} playing a more prominent role during dust events[14] [15].

While effect sizes vary by population and exposure context, the **direction of association is consistently positive** across studies. Evidence suggests that certain population groups, including **older adults and individuals with pre-existing health conditions**, experience higher relative risks[16] [17]. In addition, another study finds that while leisure-time physical activity generally reduces all-cause mortality, this protective effect becomes weaker at higher ambient $PM_{2.5}$ concentrations. According to the pooled individual-level analysis, adults meeting recommended activity levels had substantially lower mortality risk under cleaner air conditions, but these benefits diminished once long-term $PM_{2.5}$ levels exceeded 25 µg/m³ and became minimal or non-significant at 35–50 µg/m³ (particularly for cancer mortality). The authors suggest that **prolonged exposure to elevated fine particulate matter may weaken the health gains of physical activity** by contributing to chronic respiratory and systemic inflammation, endothelial dysfunction, and arterial stiffness, factors known to increase cardiovascular and overall mortality risk in a polluted environment[18].

Across the reviewed literature, the **certainty of evidence for the association between $PM_{2.5}$ and PM_{10} and all-cause mortality is rated as high**, including in WHO-commissioned assessments[19] [20] [21] [22]. Although heterogeneity between studies is present, reflecting differences in exposure assessment, population characteristics and regional conditions, the overall evidence base is **consistent**.

13 Orellano, P. et al., 2020, Short-term exposure to particulate matter (PM10 and PM2.5), nitrogen dioxide (NO2), and ozone (O3) and all-cause and cause-specific mortality: Systematic review and meta-analysis, Environment International, Vol. 142, Article 105876. Available at: https://pubmed.ncbi.nlm.nih.gov/32590284/.

14 Wang, Y. et al., 2025, Associations of wildfire-derived particulate matter with hospitalization, emergency department visits and mortality: A systematic review and meta-analysis, Environmental Research, Vol. 273. Available at: https://pubmed.ncbi.nlm.nih.gov/40020860/.

15 Tobías, A. et al., 2025, Short-term exposure to desert dust and sandstorms and all-cause and cause-specific mortality and morbidity: A systematic review and meta-analysis, Environment International, Vol. 196. Available at: https://pubmed.ncbi.nlm.nih.gov/39889591/.

16 Karimi, B. and Samadi, S., 2024, *Long-term exposure to air pollution on cardio-respiratory, and lung cancer mortality: a systematic review and meta-analysis*, Journal of Environmental Health Science & Engineering, Vol. 22(1), pp. 75–95. Available at: https://pubmed.ncbi.nlm.nih.gov/38887768/.

17 Guldan, M. et al., 2025, Association between air pollution and transplant outcomes in kidney transplant recipients: a systematic review and meta-analysis, Clinical Kidney Journal, Vol. 18(8). Available at: https://pubmed.ncbi.nlm.nih.gov/40989710/.

18 Ku, P.W. et al., 2025, Does ambient PM2.5 reduce the protective association of leisure-time physical activity with mortality? A systematic review, meta-analysis, and individual-level pooled analysis of cohort studies involving 1.5 million adults, BMC Medicine, Vol. 23(1). Available at: https://pubmed.ncbi.nlm.nih.gov/41310726/.

19 https://pubmed.ncbi.nlm.nih.gov/32703584/Chen, J. and Hoek, G., 2020, *Long-term exposure to PM and all-cause and cause-specific mortality: A systematic review and meta-analysis*, Environment International, Vol. 143, Article 105974. Available at: https://pubmed.ncbi.nlm.nih.gov/32703584/.

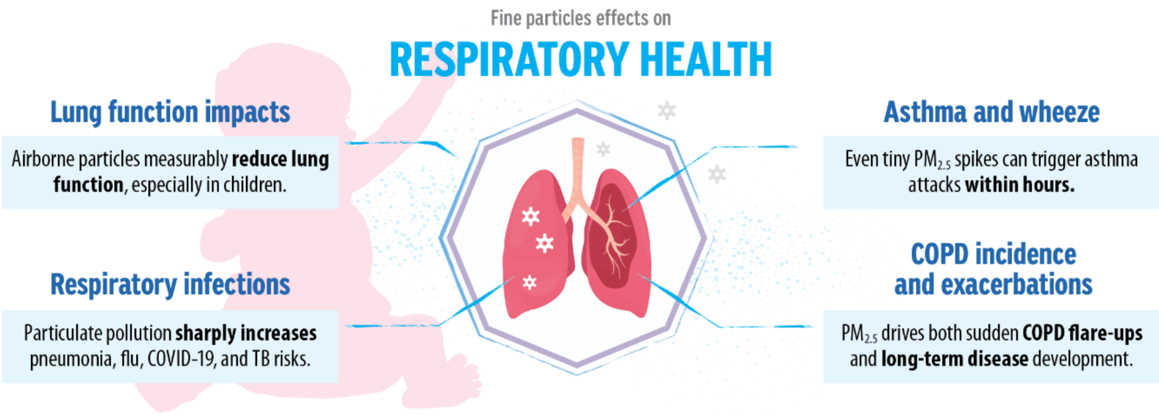
20 Orellano, P. et al., 2020, Short-term exposure to particulate matter (PM10 and PM2.5), nitrogen dioxide (NO2), and ozone (O3) and all-cause and cause-specific mortality: Systematic review and meta-analysis, Environment International, Vol. 142, Article 105876. Available at: https://pubmed.ncbi.nlm.nih.gov/32590284/.

21 Orellano, P. et al., 2024, Long-term exposure to particulate matter and mortality: an update of the WHO Global Air Quality Guidelines systematic review and meta-analysis. Available at: https://pubmed.ncbi.nlm.nih.gov/39399882/.

22 Wang, Y. et al., Associations of wildfire-derived particulate matter with hospitalization, emergency department visits and mortality: A systematic review and meta-analysis, 2025. Available at: https://pubmed.ncbi.nlm.nih.gov/40020860/.

2.1.2. Respiratory health

Figure 2: Respiratory health



Source: Authors' own elaboration.

Adverse respiratory outcomes are directly associated with exposure. These include asthma exacerbations, flare-ups of Chronic Obstructive Pulmonary Disease (COPD), a chronic lung disease that makes breathing difficult; pneumonia, a lung infection in which the air sacs fill with fluid, making it hard to breathe; influenza; and bronchiolitis. Long-term exposure also contributes to the development and progression of chronic conditions such as COPD, tuberculosis (TB), and allergic respiratory diseases. Exposure to both $PM_{2.5}$ and PM_{10} is also associated with an increased risk of lung cancer and other cancers, as discussed in Section 3.1.5. Infectious respiratory diseases, including COVID-19, also show consistent associations with particulate matter exposure. Children, older adults, and individuals with pre-existing respiratory conditions are often the most affected. Effect magnitudes vary due to heterogeneity in exposure metrics, study designs, and background pollution levels, but the overall direction of associations remains positive across the evidence base.

Asthma and wheeze

The evidence linking particulate matter to asthma morbidity is strongest for short-term exposures. A meta-analysis of 26 studies found that each **10 µg/m³ increase in $PM_{2.5}$ was associated with a 4.8% rise in paediatric asthma hospital admissions and emergency department visits**, with effects observed within 0–3 days, particularly pronounced in European settings[23]. A meta-analysis of 22 case-crossover studies similarly reported that $PM_{2.5}$ increased the odds of moderate-to-severe asthma exacerbations in both adults and children; each 10 µg/m³ increase in particulate matter is associated with a 2.8% higher risk. Even small increases in pollution, therefore, lead to measurable rises in population health risk[24]. Across further 84 studies, short-term exposure to both $PM_{2.5}$ and PM_{10} increased same-day and next-day asthma exacerbations, with larger increases for symptom-level outcomes such as wheeze, chest tightness, and medication escalation[25]. Additional evidence shows

[23] Lim, H. et al., 2016, Short-term effect of fine particulate matter on children's hospital admissions and emergency department visits for asthma: A systematic review and meta-analysis, Journal of Preventive Medicine and Public Health, Vol. 49(4), pp. 205–219. Available at: https://pubmed.ncbi.nlm.nih.gov/27499163/.

[24] Orellano, P. et al., 2017, *Effect of outdoor air pollution on asthma exacerbations in children and adults: Systematic review and multilevel meta-analysis*, PLoS One, Vol. 12(3). Available at: https://pubmed.ncbi.nlm.nih.gov/28319180/.

[25] Huang, J. et al., 2022, Outdoor air pollution and the risk of asthma exacerbations in single lag0 and lag1 exposure patterns: a systematic review and meta-analysis, Journal of Asthma, Vol. 59(11), pp. 2322–2339. Available at: https://pubmed.ncbi.nlm.nih.gov/34809505/.

that asthma morbidity can rise within hours of exposure: a sub-daily analysis found increased respiratory risk within 1–12 hours for both $PM_{2.5}$ and PM_{10} [26].

For asthma development, long-term exposure shows mixed results. A review of 41 studies on traffic-related air pollution found significant associations between $PM_{2.5}$ and PM_{10} and childhood asthma development, including robust findings in European cohorts[27]. A large meta-analysis of allergic upper-airway diseases also reported increased asthma risk associated with both particle fractions[28]. In contrast, pooled estimates for adolescent asthma were not statistically significant, despite several individual studies reporting positive associations in high-pollution regions[29], and five European birth cohorts found no association between long-term $PM_{2.5}$ or PM_{10} and childhood asthma prevalence at ages 4 and 8[30]. Overall, **short-term particulate exposure, especially $PM_{2.5}$, consistently worsens asthma control across age groups**, **whereas evidence for long-term effects on asthma development is more heterogeneous and context-dependent**[31] [32] [33].

Chronic Obstructive Pulmonary Disease incidence and exacerbations

Across several large syntheses, both short-term and long-term particulate exposures are associated with COPD morbidity, with the clearest evidence for $PM_{2.5}$. A meta-analysis of 26 studies found that short-term increases in $PM_{2.5}$ raised the **risk of acute COPD exacerbations by 1–2% per 10µg/m³**, with similar patterns for PM_{10} and stronger associations in regions with high ambient pollution, such as China[34]. A review of 19 studies reported that **$PM_{2.5}$ increased COPD hospitalisations by 1.6%, with lagged effects lasting up to three days and risk increases of 3–10% in specific lag windows, particularly in older adults and warmer seasons**[35]. Wider reviews confirm these patterns: short-term $PM_{2.5}$ and PM_{10} increased respiratory admissions by 1.1–1.8% and 0.7–1.3%, respectively, with COPD among the most affected conditions[36].

For long-term exposure, the evidence is strongest for $PM_{2.5}$. Across seven large cohort studies including more than 2.6 million individuals, each 10µg/m³ increase in long-term $PM_{2.5}$ was associated with **an 18% increase in incident COPD, while PM_{10} showed no significant association**[37]. A meta-

[26] Wu, K. et al., 2022, A systematic review and meta-analysis of intraday effects of ambient air pollution and temperature on cardiorespiratory morbidities: First few hours of exposure matters to life, EBioMedicine, Vol. 86. Available at: https://pubmed.ncbi.nlm.nih.gov/36323182/.

[27] Khreis, H. et al., 2017, *Exposure to traffic-related air pollution and risk of development of childhood asthma: A systematic review and meta-analysis*, Environment International, Vol. 100, pp. 1–31. Available at: https://pubmed.ncbi.nlm.nih.gov/27881237/.

[28] Zhang, Z.Q. et al., 2025, *Association between air pollution and allergic upper respiratory diseases: a meta-analysis*, European Respiratory Review, Vol. 34(176). Available at: https://pubmed.ncbi.nlm.nih.gov/40562438/.

[29] Shi, W. et al., 2025, *Outdoor air pollutants and asthma risk in adolescents: evidence from a systematic review and meta-analysis*, Frontiers in Public Health, Vol. 13. Available at: https://pubmed.ncbi.nlm.nih.gov/41450494/.

[30] Fuertes, E. et al., 2020, Associations between air pollution and pediatric eczema, rhinoconjunctivitis and asthma: A meta-analysis of European birth cohorts, Environment International, Vol. 136. Available at: https://pubmed.ncbi.nlm.nih.gov/31962272/.

[31] Lim, H. et al., 2016, Short-term effect of fine particulate matter on children's hospital admissions and emergency department visits for asthma: a systematic review and meta-analysis. Available at: https://pubmed.ncbi.nlm.nih.gov/27499163/.

[32] Orellano, P. et al., 2017, *Effect of outdoor air pollution on asthma exacerbations in children and adults: Systematic review and multilevel meta-analysis*, PLoS One, Vol. 12(3). Available at: https://pubmed.ncbi.nlm.nih.gov/28319180/.

[33] Khreis, H. et al., *Exposure to traffic-related air pollution and risk of development of childhood asthma: A systematic review and meta-analysis*, 2017. Available at: https://pubmed.ncbi.nlm.nih.gov/27881237/.

[34] Li, N. et al., 2022, Association of PM2.5 and PM10 with acute exacerbation of chronic obstructive pulmonary disease at lag0 to lag7: A systematic review and meta-analysis, COPD, Vol. 19(1), pp. 243–254. Available at: https://pubmed.ncbi.nlm.nih.gov/35616887/.

[35] Delavar, M. et al., 2023, Relationship between fine particulate matter (PM2.5) concentration and risk of hospitalization due to chronic obstructive pulmonary disease: a systematic review and meta-analysis, BMC Public Health, Vol. 23(1). Available at: https://pubmed.ncbi.nlm.nih.gov/37953239/.

[36] Ab Manan, N. et al., 2018, *Effect of air pollution and hospital admission: A systematic review*, Annals of Global Health, Vol. 84(4), pp. 670–678. Available at: https://pubmed.ncbi.nlm.nih.gov/30779516/.

[37] Park, J. et al., 2021, Impact of long-term exposure to ambient air pollution on the incidence of chronic obstructive pulmonary disease: A systematic review and meta-analysis, Environmental Research, Vol. 194. Available at: https://pubmed.ncbi.nlm.nih.gov/33417909/.

analysis of studies from China found that higher $PM_{2.5}$ exposure is associated with a substantially increased risk of COPD, with individuals exposed to **higher levels having about a 73% higher risk**, likely due to long-term inflammation and oxidative stress caused by fine particles[38]. Together, these results indicate that particulate matter contributes to both acute COPD worsening and long-term development of COPD, with the most consistent results observed for $PM_{2.5}$ [39] [40] [41].

Respiratory infections

Short-term particulate exposure consistently increases the risk of acute respiratory infections. A meta-analysis of 21 studies across multiple continents reported that each **10 µg/m³ increase in $PM_{2.5}$ raised pneumonia hospitalisations by 1.0% and PM_{10} by 0.4%, with stronger associations in East Asia and during colder months**[42]. For bronchiolitis in infants, a meta-analysis of 23 studies showed that $PM_{2.5}$ and PM_{10} consistently increased hospitalisation risk, particularly at lags of 1–3 days, with overall increases of 2–9% [43]. Additional evidence found mixed short-term PM_{10} results but identified that $PM_{2.5}$ increased bronchiolitis hospitalisation risk in some settings[44] .

Short-term exposure also increases influenza incidence. **A review of 19 studies found that $PM_{2.5}$ increased influenza cases by 2.2% and PM_{10} by 0.7% per 10 µg/m³, with stronger associations in children and in winter**[45]. Wildfire-derived $PM_{2.5}$ further increased acute respiratory infection risk by around 3% and elevated respiratory emergency visits globally[46]. Evidence on SARS-related respiratory outcomes showed consistently positive associations for $PM_{2.5}$ and PM_{10} across 46 studies[47].

Across multiple systematic reviews, $PM_{2.5}$ shows robust associations with infectious disease incidence, severity, and mortality, particularly for COVID-19 and pulmonary tuberculosis. Numerous COVID-19 reviews reported that short- and long-term $PM_{2.5}$ exposure was associated with higher incidence, case counts, and mortality across Europe, North America, and Asia, **with several studies observing 2–3% increases in daily COVID-19** cases per 10 µg/m³ $PM_{2.5}$, and nearly half of mortality analyses reporting significant positive associations. PM_{10} findings were more variable but pointed in

38 Chen, H. et al., 2021, Epidemiological evidence relating risk factors to chronic obstructive pulmonary disease in China: A systematic review and meta-analysis, PLoS One, Vol. 16(12). Available at: https://pubmed.ncbi.nlm.nih.gov/34962941/.

39 Li, N. et al., 2022, Association of PM2.5 and PM10 with acute exacerbation of chronic obstructive pulmonary disease at lag0 to lag7: A systematic review and meta-analysis, COPD, Vol. 19(1), pp. 243–254. Available at: https://pubmed.ncbi.nlm.nih.gov/35616887/.

40 Delavar, M. et al., 2023, Relationship between fine particulate matter (PM2.5) concentration and risk of hospitalization due to chronic obstructive pulmonary disease: a systematic review and meta-analysis, BMC Public Health, Vol. 23(1). Available at: https://pubmed.ncbi.nlm.nih.gov/37953239/.

41 Park, J. et al., 2021, Impact of long-term exposure to ambient air pollution on the incidence of chronic obstructive pulmonary disease: A systematic review and meta-analysis, Environmental Research, Vol. 194. Available at: https://pubmed.ncbi.nlm.nih.gov/33417909/.

42 Yee, J. et al., 2021, *Short-term exposure to air pollution and hospital admission for pneumonia: a systematic review and meta-analysis*, Environmental Health, Vol. 20(1). Available at: https://doi.org/10.1186/s12940-020-00687-7.

43 Comotti, A. et al., 2025, *Air pollution and hospitalization risk in infants with bronchiolitis: a systematic review and meta-analysis*, Pediatric Allergy and Immunology, Vol. 36(5). Available at: https://pubmed.ncbi.nlm.nih.gov/40358039/.

44 King, C. et al., 2018, *The effect of outdoor air pollution on the risk of hospitalisation for bronchiolitis in infants: a systematic review*, PeerJ. Available at: https://pubmed.ncbi.nlm.nih.gov/30186673/.

45 Sun, R. et al., 2024, *Air pollution and influenza: A systematic review and meta-analysis*, Iranian Journal of Public Health, Vol. 53(1), pp. 1–11. Available at: https://pubmed.ncbi.nlm.nih.gov/38694869/.

46 Mahendran, R. et al., 2025, *Wildfire-related air pollution and infectious diseases: A systematic review and meta-analysis*, ACS Environmental Au, Vol. 5(3), pp. 253–266. Available at: https://pubmed.ncbi.nlm.nih.gov/40416841/.

47 Podury, S. et al., 2023, *Severe acute respiratory syndrome and particulate matter exposure: A systematic review*, Life, Vol. 13(2). Available at: https://pubmed.ncbi.nlm.nih.gov/36836898/.

the same direction, especially in high-pollution settings[48] [49] [50]. Evidence for SARS-CoV-1 and combined SARS-CoV-1/2 outcomes was directionally similar, with most studies reporting increased incidence and mortality associated with $PM_{2.5}$ and PM_{10}, albeit with regional variability[53].

For tuberculosis (TB), multiple reviews converge on long-term $PM_{2.5}$ exposure as a risk factor. A meta-analysis of 24 studies found a 12% increase in TB incidence per 10 μg/m³ $PM_{2.5}$, with PM_{10} increasing risk by 6%[51]. A larger synthesis of 25 studies reported similar positive associations for both particle fractions[52], and ecological evidence found a 33% increase in TB incidence associated with $PM_{2.5}$ across 17 countries[53]. Short-term exposures were inconsistent, with one review reporting null single-day effects for both $PM_{2.5}$ and PM_{10} but a small positive cumulative effect for PM_{10}[54].

Overall, these findings show that short-term particulate exposure increases acute respiratory infections, while long-term $PM_{2.5}$ exposure contributes to TB incidence, with PM_{10} showing weaker but directionally similar evidence[55] [56] [57] [58].

Lung function impacts

Across several reviews, particulate matter exposure is consistently associated with reduced lung function, especially in children. A meta-analysis of 11 cohort studies found that short-term exposure to $PM_{2.5}$ was associated with a 1.74 L/min decrease in **peak expiratory flow (PEF), reflecting a small but measurable reduction in lung function,** with larger declines observed in children with asthma and more pronounced effects in certain geographic contexts[59]. A broader review of 16 studies across Europe, North America, and Asia reported consistent reductions in FEV_1 (Forced Expiratory Volume in one second), FVC (Forced Vital Capacity), and PEF associated with both $PM_{2.5}$ and PM_{10}, including delayed effects up to 3-4 days and stronger impacts during outdoor physical activity and among children with asthma[60]. Findings from traffic-related pollution studies support these patterns,

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48 Copat, C. et al., 2020, *The role of air pollution (PM and NO_2) in COVID-19 spread and lethality: A systematic review*, Environmental Research, Vol. 191. Available at: https://pubmed.ncbi.nlm.nih.gov/32853663/.

49 Carballo, I. et al., 2022, The impact of air pollution on COVID-19 incidence, severity, and mortality: A systematic review of studies in Europe and North America, Environmental Research, Vol. 215. Available at: https://pubmed.ncbi.nlm.nih.gov/36030916/.

50 Katoto, P.D.M.C. et al., 2021, Acute and chronic exposure to air pollution in relation with incidence, prevalence, severity and mortality of COVID-19: a rapid systematic review, Environmental Health. Available at: https://pubmed.ncbi.nlm.nih.gov/33838685/.

51 Dimala, C. and Kadia, B., 2022, *A systematic review and meta-analysis on the association between ambient air pollution and pulmonary tuberculosis*, Scientific Reports, Vol. 12(1). Available at: https://pubmed.ncbi.nlm.nih.gov/35788679/.

52 Kumari, N. et al., 2025, Effect of exposure to ambient particulate matter on risk of developing pulmonary tuberculosis: A systematic review and meta-analysis, Lung India, Vol. 42(4), pp. 359–366. Available at: https://pubmed.ncbi.nlm.nih.gov/40569406/.

53 Liyew, A. et al., 2024, *Ecological-level factors associated with tuberculosis incidence and mortality: A systematic review and meta-analysis*, PLOS Global Public Health, Vol. 4(10). Available at: https://pubmed.ncbi.nlm.nih.gov/39405319/.

54 Song, J. et al., 2024, *A systematic review and meta-analysis of the association between air pollutants and the incidence of tuberculosis*, Heliyon, Vol. 10(8). Available at: https://www.sciencedirect.com/science/article/pii/S2405844024048321.

55 Yee, J. et al., 2021, *Short-term exposure to air pollution and hospital admission for pneumonia: a systematic review and meta-analysis*, Environmental Health, Vol. 20(1). Available at: https://pubmed.ncbi.nlm.nih.gov/33413431/.

56 Comotti, A. et al., 2025, *Air pollution and hospitalization risk in infants with bronchiolitis: a systematic review and meta-analysis*, Pediatric Allergy and Immunology, Vol. 36(5). Available at: https://pubmed.ncbi.nlm.nih.gov/40358039/.

57 Sun, R. et al., 2024, *Air pollution and influenza: A systematic review and meta-analysis*, Iranian Journal of Public Health, Vol. 53(1), pp. 1–11. Available at: https://pubmed.ncbi.nlm.nih.gov/38694869/.

58 Dimala, C. and Kadia, B., 2022, *A systematic review and meta-analysis on the association between ambient air pollution and pulmonary tuberculosis*, Scientific Reports, Vol. 12(1). Available at: https://pubmed.ncbi.nlm.nih.gov/35788679/.

59 Zhang, Y. et al., 2023, *Effect of acute PM2.5 exposure on lung function in children: A systematic review and meta-analysis*, Journal of Asthma and Allergy, Vol. 16, pp. 529–540. Available at: https://pubmed.ncbi.nlm.nih.gov/37193111/.

60 Gudziunaite, S. et al., 2025, Global Trends in the Relationship Between Chronic Air Pollution Exposure, Physical Activity and Lung Function in Youth Aged 5–18 Years with and Without Asthma: A Systematic Review, Sports Medicine – Open, Vol. 11(1). Available at: https://pubmed.ncbi.nlm.nih.gov/40399510/.

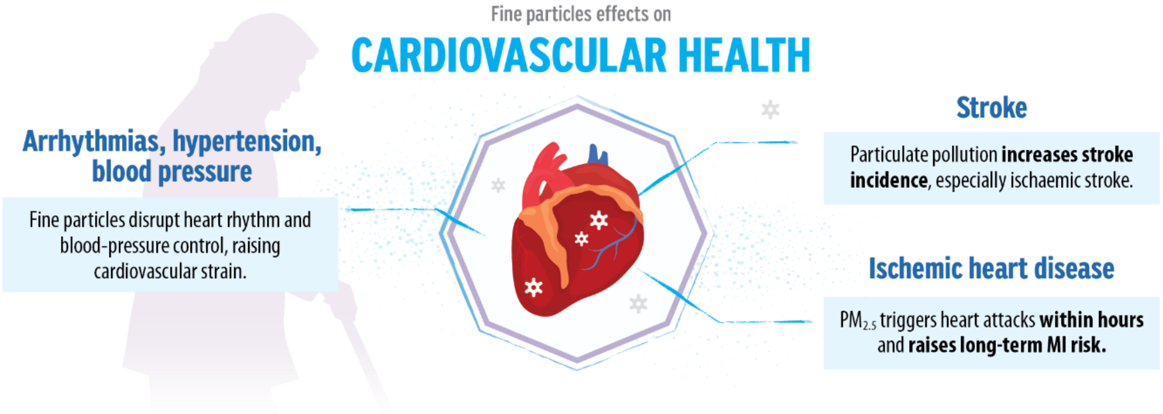
documenting reduced lung function in both children and adults exposed to $PM_{2.5}$ and PM_{10} in urban environments[61].

Together, these results show that particulate matter adversely affects ventilatory performance, with repeated evidence of reduced expiratory flow and lung volume parameters across diverse populations[62] [63] [64].

Across a substantial and diverse body of evidence, exposure to $PM_{2.5}$ and, in many settings, PM_{10}, is consistently associated with increased risks of adverse respiratory outcomes. **Short-term particulate exposure reliably precipitates acute events, including asthma exacerbations, COPD flare-ups, pneumonia, influenza, and bronchiolitis, with effects observed within hours to days. Long-term exposure contributes to the development or progression of chronic respiratory diseases such as COPD, TB, and allergic respiratory conditions, and affects lung function across the life course**. Children, older adults, and individuals with existing respiratory disease consistently emerge as the most vulnerable groups. Although effect sizes vary across studies, the direction of association is overwhelmingly positive, underscoring the significant respiratory health benefits that could be achieved through reductions in population-level particulate matter exposure.

2.1.3. Cardiovascular health

Figure 3: Cardiovascular health



Source: Authors' own elaboration.

Exposure to fine particulate matter is also found to negatively affect cardiovascular health. Through several rapid and longer-term biological responses, fine particles can enter the bloodstream, where they cause inflammation and oxidative stress that damage blood vessels and accelerate atherosclerosis[65]. Particulate matter exposure has also been shown to disrupt normal heart regulation

[61] Debelu, D. et al., 2024, *Global Public Health Implications of Traffic Related Air Pollution: Systematic Review*, Environmental Health Insights, Vol. 18. Available at: https://pubmed.ncbi.nlm.nih.gov/39192968/.

[62] Zhang, Y. et al., 2023, *Effect of acute PM2.5 exposure on lung function in children: A systematic review and meta-analysis*, Journal of Asthma and Allergy, Vol. 16, pp. 529–540. Available at: https://pubmed.ncbi.nlm.nih.gov/37193111/.

[63] Gudziunaite, S. et al., 2025, Global Trends in the Relationship Between Chronic Air Pollution Exposure, Physical Activity and Lung Function in Youth Aged 5–18 Years with and Without Asthma: A Systematic Review, Sports Medicine – Open, Vol. 11(1). Available at: https://pubmed.ncbi.nlm.nih.gov/40399510/.

[64] Debelu, D. et al., 2024, *Global Public Health Implications of Traffic Related Air Pollution: Systematic Review*, Environmental Health Insights, Vol. 18. Available at: https://pubmed.ncbi.nlm.nih.gov/39192968/.

[65] Ndlovu, N. et al., 2024, *Impact of Indoor Air Pollutants on the Cardiovascular Health Outcomes of Older Adults: Systematic Review*, Clinical Interventions in Aging, Vol. 19, pp. 1629–1639. Available at: https://pubmed.ncbi.nlm.nih.gov/39372166/.

by the nervous system, increasing cardiovascular instability[66]. In the short term, pollution peaks can trigger immediate vascular stress and changes in blood clotting, raising the risk of acute cardiovascular events shortly after exposure[67].

Myocardial infarction / ischemic heart disease

The most common increased cardiovascular risks are **myocardial infarction (MI)** and **ischaemic heart disease (IHD)**, which occur when the heart does not receive enough oxygen because fine particles trigger inflammation, narrow the arteries, and make blood more likely to clot. Across systematic reviews and meta-analyses covering a wide range of geographic settings, study designs, and exposure levels, higher PM concentrations are linked to higher rates of acute coronary events, cardiovascular hospital attendance, and cardiovascular mortality categories that include IHD. The evidence indicates that both short-term increases (hours to days) and long-term exposure (months to years) contribute to elevated risk, with $PM_{2.5}$ generally demonstrating stronger and more consistent associations than PM_{10}[68] [69] [70] [71].

Short-term exposure appears to act as a trigger for acute coronary events. A meta-analysis indicates that a 10 µg/m³ rise in $PM_{2.5}$ concentration is associated with approximately **2% increase in MI-risk**, which is consistent across different study designs[72]. Another study similarly reports that $PM_{2.5}$ is positively associated with acute cardiovascular events, including MI and IHD outcomes, with the majority of studies finding statistically significant increases in risk. The pooled analyses in this literature show increased risk for cardiovascular hospitalisations for $PM_{2.5}$, while the associations for PM_{10} are less consistent, reflecting fewer studies and greater heterogeneity[73]. Evidence shows that the triggering of MI can even occur rapidly after short-term exposure. In a sub-daily analysis, MI risk increases within hours following exposure to both $PM_{2.5}$ and PM_{10}, with again a larger pooled excess risk for $PM_{2.5}$[74]. Short-term exposure in these studies generally reflected several consecutive days of elevated urban particulate concentrations with daily or sub-daily $PM_{2.5}$ and PM_{10} levels rising under typical pollution conditions such as traffic emissions, seasonal smog, or meteorological stagnation.

The association with acute MI risk and PM_{10} is typically smaller, but still statistically significant. A dedicated systematic review and metanalysis examining short-term PM_{10} exposure and MI in adults finds a **1% increase in MI risk** per 10 µg/m³ increase in PM_{10}, although the magnitude varied across

[66] Gandhi, T. et al., 2022, *Outdoor Physical Activity in an Air Polluted Environment and Its Effect on the Cardiovascular System – A Systematic Review*, International Journal of Environmental Research and Public Health, Vol. 19. Available at: https://pubmed.ncbi.nlm.nih.gov/36078268/.

[67] Wu, K. et al., 2022, A Systematic Review and Meta-Analysis of Intraday Effects of Ambient Air Pollution and Temperature on Cardiorespiratory Morbidities: First Few Hours of Exposure Matters to Life, EBioMedicine, Vol. 86. Available at: https://pubmed.ncbi.nlm.nih.gov/36323182/.

[68] Orellano, P. et al., 2020, Short-term exposure to particulate matter (PM10 and PM2.5), nitrogen dioxide (NO2), and ozone (O3) and all-cause and cause-specific mortality: Systematic review and meta-analysis, Environment International, Vol. 142, Article 105876. Available at: https://pubmed.ncbi.nlm.nih.gov/32590284/.

[69] Farhadi, Z. et al., 2020, *Association between PM2.5 and Risk of Hospitalization for Myocardial Infarction: A Systematic Review and a Meta-Analysis*, BMC Public Health, Vol. 20(1). Available at: https://pubmed.ncbi.nlm.nih.gov/32164596/.

[70] Zou, L. et al., 2021, *Long-term exposure to ambient air pollution and myocardial infarction: A systematic review and meta-analysis*, Frontiers in Medicine, Vol. 8. Available at: https://pubmed.ncbi.nlm.nih.gov/33816520/.

[71] Islam, F. et al., 2025, Air pollution and cardiovascular disease: a systematic review of the effects of air pollution, including bushfire smoke, on cardiovascular disease, American Heart Journal Plus, Vol. 54. Available at: https://pubmed.ncbi.nlm.nih.gov/40322276/.

[72] Farhadi, Z. et al., 2020, *Association between PM2.5 and Risk of Hospitalization for Myocardial Infarction: A Systematic Review and a Meta-Analysis*, BMC Public Health, Vol. 20(1). Available at: https://pubmed.ncbi.nlm.nih.gov/32164596/.

[73] Mahakalkar, A. et al., 2024, Geospatial analysis of short-term exposure to air pollution and risk of cardiovascular diseases and mortality: A systematic review, Chemosphere, Vol. 353. Available at: https://pubmed.ncbi.nlm.nih.gov/38373448/.

[74] Wu, K. et al., 2022, A Systematic Review and Meta-Analysis of Intraday Effects of Ambient Air Pollution and Temperature on Cardiorespiratory Morbidities: First Few Hours of Exposure Matters to Life, EBioMedicine, Vol. 86. Available at: https://pubmed.ncbi.nlm.nih.gov/36323182/.

study designs and effect metrics[75]. Consistent with this, global evidence shows that short-term PM_{10} exposure is associated with measurable increases in cardiovascular events. Meta-analytic estimates indicate that each 10 µg/m^3 increase in daily PM_{10} concentrations leads to a **0.6% rise in cardiovascular mortality**, with comparable increases reported for MI-related admissions and other acute cardiovascular hospitalisations[76][77].

Long-term exposure is associated with even higher incidence rates of MI. A large cohort-based meta-analysis shows that every 10 µg/m^3 increase in long-term $PM_{2.5}$ exposure is **linked to an 18% higher risk** of MI, whereas the **corresponding increase for PM_{10} is 3%**[78]. A large, separate synthesis of cohort studies on incident cardiovascular disease similarly finds a significant association between $PM_{2.5}$ and higher incident cardiovascular risk (including MI and IHD among the most commonly assessed outcomes), with pooled estimates indicating a modest but consistent increase in risk per 10 µg/m^3 increase. In this review, pooled PM_{10} estimates suggest an insignificant increased risk[79].

The reviewed evidence supports a consistent association between particulate matter exposure and MI and IHD outcomes across multiple settings, exposure windows, and regions, with small short-term triggering effects and larger long-term risk increases for $PM_{2.5}$.

Stroke (ischemic and haemorrhagic)

Particulate matter affects blood vessels, blood pressure regulation, and the body's clotting system, thereby increasing the likelihood of either a blockage or bleeding event, which can result in stroke. **A substantial body of epidemiological evidence indicates that exposure to particulate matter is associated with an increased risk of stroke. Positive associations have been observed across multiple outcomes, including stroke incidence, hospital admissions, mortality, and years of life lost.** The most consistent findings relate to short-term exposure, particularly for ischaemic stroke incidence[80][81][82].

Short-term exposure in the several days leading up to stroke onset is consistently linked to statistically significant increases in ischaemic stroke incidence. A large global meta-analysis of 110 observational studies reports that **each 10 µg/m^3 increase in $PM_{2.5}$ is associated with a 15% increase in ischaemic stroke incidence, while PM_{10} shows a similar increase of 14%.** Although smaller in magnitude, 9% for $PM_{2.5}$ and 2% for PM_{10}, the associations with stroke mortality remain statistically

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75 Strobl, K. et al., 2024, *Association between PM10 exposure and risk of myocardial infarction in adults: A systematic review and meta-analysis*, PLoS One, Vol. 19(5). Available at: https://pubmed.ncbi.nlm.nih.gov/38691568/.

76 Ab Manan, N. et al., 2018, *Effect of air pollution and hospital admission: A systematic review*, Annals of Global Health, Vol. 84(4), pp. 670–678. Available at: https://pubmed.ncbi.nlm.nih.gov/30779516/.

77 Orellano, P. et al., 2020, Short-term exposure to particulate matter (PM10 and PM2.5), nitrogen dioxide (NO2), and ozone (O3) and all-cause and cause-specific mortality: Systematic review and meta-analysis, Environment International, Vol. 142, Article 105876. Available at: https://pubmed.ncbi.nlm.nih.gov/32590284/.

78 Zou, L. et al., 2021, *Long-term exposure to ambient air pollution and myocardial infarction: A systematic review and meta-analysis*, Frontiers in Medicine, Vol. 8. Available at: https://doi.org/10.3389/fmed.2021.616355.

79 Brown, J. et al., 2025, Impact of neighbourhood and environmental factors on the risk of incident cardiovascular disease: a systematic review and meta-analysis, European Journal of Preventive Cardiology, Vol. 32(18), pp. 1903–1912. Available at: https://pubmed.ncbi.nlm.nih.gov/40106665/.

80 Toubasi, A. and Al-Sayegh, T., 2023, *Short-term exposure to air pollution and ischemic stroke: A systematic review and meta-analysis*, Neurology, Vol. 101(19), pp. e1922–e1932. Available at: https://pubmed.ncbi.nlm.nih.gov/37758483/.

81 Niu, Z. et al., 2021, Association between exposure to ambient air pollution and hospital admission, incidence, and mortality of stroke: an updated systematic review and meta-analysis of more than 23 million participants, Environmental Health and Preventive Medicine, Vol. 26(1), Article 15. Available at: https://pubmed.ncbi.nlm.nih.gov/33499804/.

82 Ab Manan, N. et al., 2018, *Effect of air pollution and hospital admission: A systematic review*, Annals of Global Health, Vol. 84(4), pp. 670–678. Available at: https://pubmed.ncbi.nlm.nih.gov/30779516/.

significant[83]. A multi-country meta-analysis of 68 studies involving more than 23 million participants found small but consistent increases in stroke risk with higher particulate matter exposure. For each 10 μg/m^3 increase, $PM_{2.5}$ was associated with a 0.8% rise in hospital admissions, a 5% increase in stroke incidence, and a 0.8% increase in mortality. For PM_{10}, hospital admissions increased by 0.4% and mortality by 0.6%. The strongest and clearest association was observed for stroke incidence with $PM_{2.5}$ [84].

For haemorrhagic stroke, which is caused by the rupture of a blood vessel leading to bleeding within or around the brain, cohort studies indicate a positive association with $PM_{2.5}$ exposure. The combined results show approximately a **10% higher risk among those exposed to higher levels**[85]. However, long-term evidence overall remains more limited and less precise than the findings for ischaemic stroke. Reviews of traffic-related air pollution report positive but statistically imprecise associations for both $PM_{2.5}$ and PM_{10}, and classify the certainty of evidence as low to moderate[86].

Long-term exposure to particulate matter is also associated with an increased risk of stroke, although the evidence base is less extensive than for short-term exposure. Cohort studies indicate that prolonged exposure to $PM_{2.5}$ contributes to vascular dysfunction, including effects on blood pressure regulation, inflammation, and the body's clotting system, thereby increasing the likelihood of both ischaemic and haemorrhagic stroke. In particular, long-term exposure to $PM_{2.5}$ has been associated with an **approximately 10% higher risk of haemorrhagic stroke** among populations exposed to higher concentrations.

Across outcomes, $PM_{2.5}$ generally demonstrates the strongest and most consistent association with stroke risk. PM_{10} also shows positive associations, particularly for short-term stroke incidence, hospital admissions, and mortality, though effect estimates are typically smaller[87] [88].

Arrhythmias, hypertension, and blood pressure

In addition to its effects on stroke-related outcomes, particulate matter influences key cardiovascular regulatory pathways, particularly arrhythmias, hypertension, and blood pressure changes. Evidence from large-scale systematic reviews indicates that exposure to particulate matter ($PM_{2.5}$ and PM_{10}) contributes to cardiovascular conditions involving blood-pressure dysregulation and cardiac electrical instability, including hypertension and arrhythmias. Even though several analyses present combined

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83 Toubasi, A. and Al-Sayegh, T., 2023, *Short-term exposure to air pollution and ischemic stroke: A systematic review and meta-analysis*, Neurology, Vol. 101(19), pp. e1922–e1932. Available at: https://pubmed.ncbi.nlm.nih.gov/37758483/.

84 Niu, Z. et al., 2021, Association between exposure to ambient air pollution and hospital admission, incidence, and mortality of stroke: an updated systematic review and meta-analysis of more than 23 million participants, Environmental Health and Preventive Medicine, Vol. 26(1), Article 15. Available at: https://pubmed.ncbi.nlm.nih.gov/33499804/.

85 Zhao, K. et al., 2021, Ambient fine particulate matter of diameter ≤ 2.5 μm and risk of haemorrhagic stroke: a systematic review and meta-analysis of cohort studies, Environmental Science and Pollution Research International, Vol. 28(17), pp. 20970–20980. Available at: https://pubmed.ncbi.nlm.nih.gov/33694113/.

86 Haddad, P. et al., 2023, *Long-term exposure to traffic-related air pollution and stroke: A systematic review and meta-analysis*, International Journal of Hygiene and Environmental Health, Vol. 247. Available at: https://pubmed.ncbi.nlm.nih.gov/36446272/.

87 Toubasi, A. and Al-Sayegh, T., 2023, *Short-term exposure to air pollution and ischemic stroke: A systematic review and meta-analysis*, Neurology, Vol. 101(19), pp. e1922–e1932. Available at: https://pubmed.ncbi.nlm.nih.gov/37758483/.

88 Niu, Z. et al., 2021, Association between exposure to ambient air pollution and hospital admission, incidence, and mortality of stroke: an updated systematic review and meta-analysis of more than 23 million participants, Environmental Health and Preventive Medicine, Vol. 26(1), Article 15. Available at: https://pubmed.ncbi.nlm.nih.gov/33499804/.

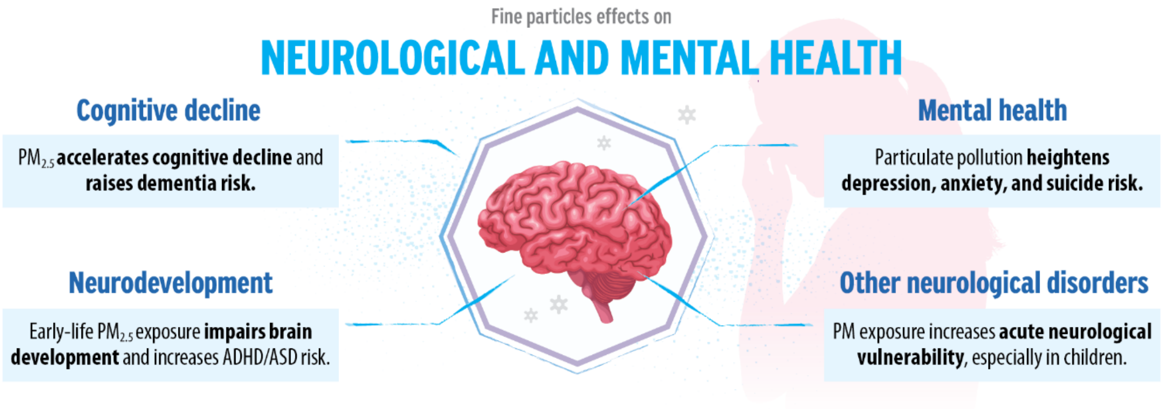
cardiovascular outcomes instead of isolating arrhythmias or hypertension, both conditions are included within the ICD-based cardiovascular categories used for the pooled estimates[89] [90].

Evidence from 80 studies worldwide shows that exposure to $PM_{2.5}$ and PM_{10} air pollution, both in the short and long term, is linked to a higher risk of hospital admissions for heart rhythm disorders (arrhythmias), problems with the heart's electrical signalling system (atrioventricular conduction disorders), and other cardiovascular diseases. Each 10 µg/m³ increase in particulate matter was associated with 0.52% higher cardiovascular mortality and 1.92 additional years of life lost[91]. Similarly, a meta-analysis of 30 short-term studies conducted in China reported statistically significant increases in cardiovascular mortality of 0.68% per 10 µg/m³ rise in $PM_{2.5}$ and 0.39% PM_{10}[92].

Overall, the evidence indicates that particulate matter contributes to cardiovascular deterioration through mechanisms that affect blood pressure control and cardiac electrical regulation. While effect sizes per 10 µg/m³ increase are generally modest, they are consistent.

2.1.4. Neurological and mental health

Figure 4: Neurological and mental health



Source: Authors' own elaboration.

Dementia and cognitive decline

Across numerous systematic reviews and meta-analyses, evidence consistently shows that exposure to particulate matter, especially $PM_{2.5}$, is correlated with cognitive deterioration and an increased risk of dementia. A global meta-analysis of 21 studies found that higher **$PM_{2.5}$ exposure was associated with approximately a 49% higher likelihood of impaired global cognitive function**, **while PM_{10} showed a smaller but still significant increase of around 30%,** and cohort-based estimates for $PM_{2.5}$ remained robust at approximately 35%[93]. A larger synthesis of 54 studies similarly reported

[89] Zhao, L. et al., 2017, *Association between air pollution and cardiovascular mortality in China: a systematic review and meta-analysis*, Oncotarget, Vol. 8(39), pp. 66438–66448. Available at: https://pubmed.ncbi.nlm.nih.gov/29029525/.

[90] Brown, J. et al., 2025, Impact of neighbourhood and environmental factors on the risk of incident cardiovascular disease: a systematic review and meta-analysis, European Journal of Preventive Cardiology, Vol. 32(18), pp. 1903–1912. Available at: https://pubmed.ncbi.nlm.nih.gov/40106665/.

[91] Islam, F. et al., 2025, Air pollution and cardiovascular disease: a systematic review of the effects of air pollution, including bushfire smoke, on cardiovascular disease, American Heart Journal Plus, Vol. 54. Available at: https://pubmed.ncbi.nlm.nih.gov/40322276/.

[92] Islam, F. et al., 2025, Air pollution and cardiovascular disease: a systematic review of the effects of air pollution, including bushfire smoke, on cardiovascular disease, American Heart Journal Plus, Vol. 54. Available at: https://pubmed.ncbi.nlm.nih.gov/40322276/.

[93] Meo, S. et al., 2024, *Effect of air pollutants particulate matter (PM2.5, PM10), Sulfur dioxide (SO_2) and ozone (O_3) on cognitive health*, Scientific Reports, Vol. 14(1). Available at: https://pubmed.ncbi.nlm.nih.gov/39179784/.

dose-dependent declines in cognitive scores for both $PM_{2.5}$ and PM_{10}, noting reductions of -0.79 and -0.48 cognitive units per 1 $\mu g/m^3$, respectively, and emphasised the absence of a safe threshold[94].

A systematic review covering Europe, Asia, and North America also found consistent evidence that both pollutants are linked to poorer global cognition, accelerated decline, increased prevalence of mild cognitive impairment, and higher dementia risk in older adults[95]. A life-course review of 84 studies found similar associations across adulthood and older age. Brain imaging studies further indicate that exposure to these pollutants may be associated with shrinkage of the hippocampus, which plays a key role in memory, and the prefrontal cortex, which is important for attention and decision-making[96].

Evidence for dementia risk is particularly strong and most consistent for $PM_{2.5}$. Two systematic reviews of longitudinal cohort studies found hazard ratios between 1.03 and 1.92 per exposure increment, meaning the risk increased by approximately 3% to 92% with higher exposure. Stronger effects were observed in genetically susceptible groups [97] [98]. **A meta-analysis including 26 million adults found that long-term $PM_{2.5}$ increased incident dementia risk with 8% per 5 $\mu g/m^3$ increase,** whereas the associations for PM_{10} and other particles were not statistically significant[99].

Consistent findings were also reported in another global meta-analysis, which found statistically significant increases in the risk of dementia associated with $PM_{2.5}$, **including all-cause dementia (around 3% higher risk), Alzheimer's disease (around 8%), and vascular dementia (also around 3%).** In contrast, there was not enough consistent evidence to draw firm conclusions for PM_{10}[100]. A combined analysis of two Chinese cohort studies and a meta-analysis of 15 studies found that dementia risk increases with higher pollution levels. **At very high $PM_{2.5}$ concentrations (above 63–64 $\mu g/m^3$), the risk more than doubled, with a clear stepwise increase in risk as exposure levels rose**[101]. Traffic-related air pollution studies similarly found that long-term $PM_{2.5}$ and PM_{10} exposure was associated with cognitive decline and increased dementia incidence. For example, one study reported higher dementia risk among individuals living in areas with the highest levels of traffic-related air pollution, illustrating a pattern observed more broadly across the reviewed literature[102].

Structural neuroimaging studies (brain imaging techniques such as MRI used to assess brain structure) strengthen these epidemiological patterns. A meta-analysis of MRI-based studies found that higher $PM_{2.5}$ exposure is associated with a measurable **reduction in hippocampal volume**

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94 Geto, A. et al., 2025, *The association between air pollution and cognitive impairment: a systematic review and meta-analysis of global studies*, BMC Public Health, Vol. 25(1), Article 3548. Available at: https://pmc.ncbi.nlm.nih.gov/articles/PMC12538874/.

95 Cativiela-Campos, B. et al., 2025, *What are the consequences of PM air pollution exposure on elderly Behavior? A systematic review*, Environmental Pollution, Vol. 375, Article 126279. Available at: https://pubmed.ncbi.nlm.nih.gov/40288634/.

96 Chandra, M. et al., 2022, Air pollution and cognitive impairment across the life course in humans: A systematic review with specific focus on income level of study area, International Journal of Environmental Research and Public Health, Vol. 19(3), Article 1405. Available at: https://pubmed.ncbi.nlm.nih.gov/35162428/.

97 Peters, R. et al., 2019, *Air pollution and dementia: A systematic review*, Journal of Alzheimer's Disease, Vol. 70(S1), pp. S145–S163. Available at: https://pubmed.ncbi.nlm.nih.gov/30775976/.

98 Peters, R. et al., 2021, Putting fine particulate matter and dementia in the wider context of noncommunicable disease: Where are we now and what should we do next: A systematic review, Neuroepidemiology, Vol. 55(4), pp. 253–265. Available at: https://pubmed.ncbi.nlm.nih.gov/34062541/.

99 Rogowski, C. et al., 2025, *Long-term air pollution exposure and incident dementia: a systematic review and meta-analysis*, The Lancet Planetary Health, Vol. 9(7). Available at: https://pubmed.ncbi.nlm.nih.gov/40716448/.

100 Dhiman, V. et al., 2022, *Is air pollution associated with increased risk of dementia? A meta-analysis of epidemiological research*, Neurology India, Vol. 70(3), pp. 1004–1019. Available at: https://pubmed.ncbi.nlm.nih.gov/35864632/.

101 Tang, J. et al., 2023, *Association of air pollution with dementia: a systematic review with meta-analysis including new cohort data from China*, Environmental Research, Vol. 223. Available at: https://pubmed.ncbi.nlm.nih.gov/36529331/.

102 Debelu, D. et al., 2024, *Global Public Health Implications of Traffic Related Air Pollution: Systematic Review*, Environmental Health Insights, Vol. 18. Available at: https://pubmed.ncbi.nlm.nih.gov/39192968/.

(around 7.6 mm^3 per 1 $\mu g/m^3$ increase), while findings for PM_{10} were smaller and not statistically significant[103]. Broader neuroimaging reviews similarly reported consistent associations between $PM_{2.5}$ and reduced total brain volume, particularly in frontotemporal and hippocampal regions relevant to cognitive ageing and dementia[104]. **Additional evidence indicates links between $PM_{2.5}$ and Alzheimer's-related neuropathology, including white-matter loss and amyloid-β accumulation (a build-up of protein in the brain associated with Alzheimer's disease)**[105]. Collectively, these findings indicate that long-term $PM_{2.5}$ exposure is a robust risk factor for cognitive decline and dementia, while PM_{10} associations are more variable and generally weaker[106][107].

Neurodevelopment (ADHD, ASD, IQ loss)

In reviews evaluating early-life exposure, particulate matter, especially $PM_{2.5}$, shows strong and consistent evidence with impaired neurodevelopment. **A meta-analysis of six cohort studies found that each 1 $\mu g/m^3$ increase in $PM_{2.5}$ was associated with reductions of -0.24 to -0.40 IQ points in childhood**, with the largest declines observed for performance IQ and with effects detected across prenatal and early-childhood exposure windows[108]. A broader life-course review also reported frequent associations between both $PM_{2.5}$ and PM_{10} and lower cognitive performance in children, including deficits in memory, reasoning, and general cognitive development[109]. **Evidence from traffic-related air pollution studies further demonstrated that higher exposures to $PM_{2.5}$, PM_{10}, and elemental carbon were associated with reduced memory scores and diminished growth in cognitive development markers during the school years**[110].

A substantial body of evidence links particulate matter to neurodevelopmental disorders. A systematic review of 23 studies found that prenatal **exposure to $PM_{2.5}$ more than doubled the risk of autism spectrum disorder (ASD) (over 130% increase per 10 $\mu g/m^3$) while PM_{10} was linked to a smaller increase of around 7%.** Nearly all included studies indicated elevated ASD risk with higher particulate exposure, particularly during prenatal periods, consistent with heightened vulnerability in early neurodevelopment[111]. Similarly, a meta-analysis of 25 studies found that **both $PM_{2.5}$ and PM_{10} were positively associated with ADHD diagnoses** or symptom severity across cohorts from Asia, Europe, and North America, with mechanistic pathways pointing to neuroinflammation, oxidative

103 Balboni, E. et al., 2022, The association between air pollutants and hippocampal volume from magnetic resonance imaging: A systematic review and meta-analysis, Environmental Research, Vol. 204(Pt A). Available at: https://pubmed.ncbi.nlm.nih.gov/34478724/.

104 Weuve, J. et al., 2021, Exposure to air pollution in relation to risk of dementia and related outcomes: An updated systematic review of the epidemiological literature, Environmental Health Perspectives, Vol. 129(9). Available at: https://pubmed.ncbi.nlm.nih.gov/34558969/.

105 Peters, R. et al., 2019, *Air pollution and dementia: A systematic review*, Journal of Alzheimer's Disease, Vol. 70(S1), pp. S145–S163. Available at: https://pubmed.ncbi.nlm.nih.gov/30775976/.

106 Peters, R. et al., 2021, Putting fine particulate matter and dementia in the wider context of noncommunicable disease: Where are we now and what should we do next: A systematic review, Neuroepidemiology, Vol. 55(4), pp. 253–265. Available at: https://pubmed.ncbi.nlm.nih.gov/34062541/.

107 Rogowski, C. et al., 2025, *Long-term air pollution exposure and incident dementia: a systematic review and meta-analysis*, The Lancet Planetary Health, Vol. 9(7). Available at: https://pubmed.ncbi.nlm.nih.gov/40716448/.

108 Alter, N.C. et al., 2024. *Quantifying the association between PM2.5 air pollution and IQ loss in children: a systematic review and meta-analysis*, Environmental Health. Available at: https://pubmed.ncbi.nlm.nih.gov/39551729/.

109 Chandra, M. et al., 2022, Air pollution and cognitive impairment across the life course in humans: A systematic review with specific focus on income level of study area, International Journal of Environmental Research and Public Health, Vol. 19(3), Article 1405. Available at: https://pubmed.ncbi.nlm.nih.gov/35162428/.

110 Debelu, D. et al., 2024, *Global Public Health Implications of Traffic Related Air Pollution: Systematic Review*, Environmental Health Insights, Vol. 18. Available at: https://pubmed.ncbi.nlm.nih.gov/39192968/.

111 Lam, J. et al., 2016, *A systematic review and meta-analysis of multiple airborne pollutants and autism spectrum disorder*, PLoS One, Vol. 11(9). Available at: https://pubmed.ncbi.nlm.nih.gov/27653281/.

stress, and neurotransmitter disruption.[112] These findings collectively indicate that early-life exposure to particulate matter is associated with impaired cognitive development and increased risk of ASD and ADHD, with the strongest and most consistent evidence observed for $PM_{2.5}$.

Mental health (depression, anxiety, suicide risk)

Although mental health outcomes do not constitute cognitive outcomes per se, a substantial body of evidence links particulate matter exposure to psychiatric symptoms that share underlying neurobiological mechanisms with cognitive decline. A systematic review of 22 studies found that **long-term exposure to $PM_{2.5}$ is associated with around a 10% higher risk of depression per 10 µg/m^3 increase.** Additional links were found between $PM_{2.5}$ and anxiety disorders, and between short-term exposure to PM_{10} and an increased risk of suicide[113]. A meta-analysis of 39 studies similarly found that long-term exposure to $PM_{2.5}$ is associated with about a 7.4% higher risk of depression, while short-term increases in both $PM_{2.5}$ and PM_{10} were linked to smaller increases of around 0.9% in risk per increase[114].

Mechanistic evidence provides further support. A review synthesising 111 human and animal studies reported widespread associations between **both $PM_{2.5}$ and PM_{10} and increased levels of depression and anxiety, as well as changes in brain regions involved in memory, emotions, decision-making, and cognitive function**[115]. Studies suggest that these effects may be driven by neuroinflammation, oxidative stress, disrupted communication between nerve cells, and loss of grey matter in brain regions that regulate emotion and behaviour. Although the evidence on suicide risk is more limited, available studies indicate a small but significant increase in risk following short-term exposure to particulate matter, suggesting broader effects on brain health and mental well-being[116].

Other neurological disorders

Evidence for additional neurological outcomes is more limited but indicates that particulate matter exposure may exacerbate certain neurological conditions. **A multi-city study from China reported that short-term increases in $PM_{2.5}$ and PM_{10} were associated with higher childhood epilepsy hospitalisations, with effect estimates largest at a 1-day lag and stronger in colder seasons**. Preschool-aged children were more sensitive to $PM_{2.5}$ exposure, indicating heightened acute neurological vulnerability in early childhood[117]. Reviews examining pollution–weather interactions also found that combined exposure to NO_2 and high temperatures increased risks of neurological and mental health outcomes, although these analyses did not isolate particulate-specific effects and

[112] Ahmad, S. et al., 2024. Association Between Ambient Air Pollution and Attention-Deficit/Hyperactivity Disorder (ADHD) in Children: A Systematic Review and Meta-Analysis, Cureus. Available at: https://pubmed.ncbi.nlm.nih.gov/39544605/.

[113] Braithwaite, I. et al., 2019, Air Pollution (Particulate Matter) Exposure and Associations with Depression, Anxiety, Bipolar, Psychosis and Suicide Risk: A Systematic Review and Meta-Analysis, Environmental Health Perspectives, Vol. 127(12), Article 126002. Available at: https://pubmed.ncbi.nlm.nih.gov/31850801/.

[114] Borroni, E. et al., 2022, *Air pollution exposure and depression: A comprehensive updated systematic review and meta-analysis*, Environmental Pollution, Vol. 292(Pt A). Available at: https://pubmed.ncbi.nlm.nih.gov/34600062/.

[115] Zundel, C. et al., 2022, *Air pollution, depressive and anxiety disorders, and brain effects: A systematic review*, Neurotoxicology, Vol. 93, pp. 272–300. Available at: https://pubmed.ncbi.nlm.nih.gov/36280190/.

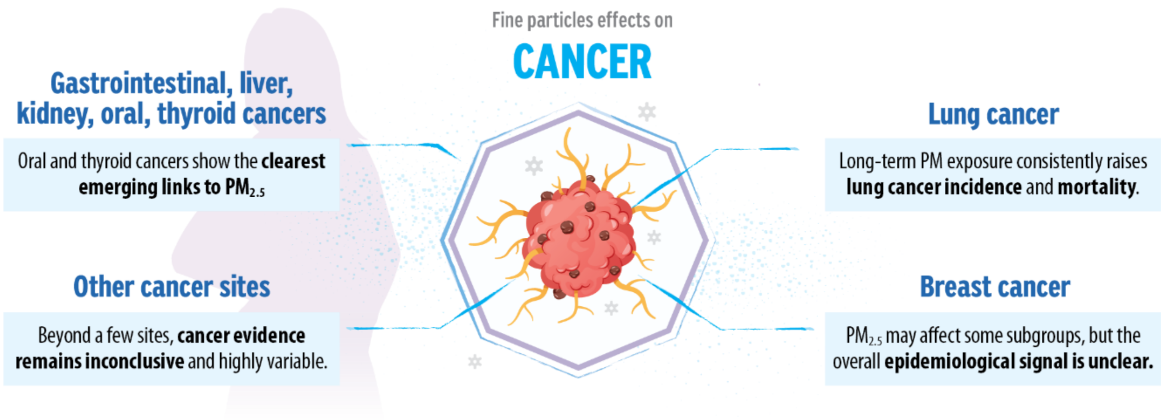
[116] Braithwaite, I. et al., 2019, Air Pollution (Particulate Matter) Exposure and Associations with Depression, Anxiety, Bipolar, Psychosis and Suicide Risk: A Systematic Review and Meta-Analysis, Environmental Health Perspectives, Vol. 127(12), Article 126002. Available at: https://pubmed.ncbi.nlm.nih.gov/31850801/.

[117] Cheng, J. et al., 2022, Short-term effect of air pollution on childhood epilepsy in eastern China: A space-time-stratified case-crossover and pooled analysis, Environment International, Vol. 170. Available at: https://pubmed.ncbi.nlm.nih.gov/36279736/.

therefore provide contextual rather than direct evidence[118]. No studies in the provided evidence set reported associations with Parkinson's disease or other adult-onset neurological conditions.

2.1.5. Cancer

Figure 5: Cancer



Source: Authors' own elaboration.

Fine particulate matter can enter the body through inhalation and, once deposited in the lungs, may pass into the bloodstream and circulate systemically. This ongoing exposure can trigger chronic inflammation and oxidative stress, which damage DNA and weaken the body's natural repair mechanisms. At the same time, fine particles often carry carcinogenic substances, such as polycyclic aromatic hydrocarbons and heavy metals, which can reach sensitive tissues. Over time, these combined effects create conditions that increase the likelihood of malignant cell changes and the development of cancer in multiple organs.

Lung cancer

The lungs are among the organs most directly affected by particulate matter, as they are in continuous contact with inhaled air. Fine particles can penetrate deep into the respiratory system and reach the alveoli, where they may remain in lung tissue. Prolonged exposure can, over time, lead to an increased risk of malignant changes and the development of lung cancer.

Across all reviews, long-term exposure to fine particulate matter shows the clearest and most consistent association with lung cancer, with multiple meta-analyses demonstrating increased incidence and mortality at higher concentrations. Six systematic reviews report a statistically significant increase in lung cancer risk for each **10 µg/m³ rise in $PM_{2.5}$, with effect estimates ranging**

[118] Rackow, B. et al., 2025, *The interaction between air pollution, weather conditions, and health risks: a systematic review*, Science of the Total Environment, Vol. 996. Available at: https://pubmed.ncbi.nlm.nih.gov/40749248/.

from 8% to 17% across global, multi-country, and regional cohorts[119] [120] [121] [122] [123] [124]. Similarly, **PM_{10} exposure is associated with increases of 8–13%** in lung cancer mortality or incidence[125] [126] [127] [128]. These associations have been documented in Europe, North America, Asia, and South America, with several reviews noting that risks persist even at levels below current WHO guideline concentrations[129] [130].

Breast cancer

Evidence for breast cancer is more variable and less conclusive than for lung cancer. Across several large systematic reviews, most pooled estimates for $PM_{2.5}$ and PM_{10} show no statistically significant association with breast cancer incidence or with mortality. **A global synthesis of urban air-pollution studies reported a 17% increase in breast cancer mortality per 10 µg/m³ $PM_{2.5}$**, but incidence findings were inconsistent and generally non-significant, with wide confidence intervals[131]. Similarly, a broad review of air-pollution health impacts concluded that evidence for breast cancer remains insufficient to establish a clear link, in contrast to the well-established evidence for lung cancer[132].

Some individual cohort and case-control studies suggested higher $PM_{2.5}$-related mortality among women with early-stage breast cancer, but subgroup analyses across hormone-receptor status, menopausal state or tumour subtype did not identify consistent patterns[133].

Overall, the available evidence suggests that while $PM_{2.5}$ may contribute to breast cancer mortality in some populations, the overall epidemiological signal remains inconsistent, with substantial heterogeneity across regions and study designs.

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119 Chen, J. and Hoek, G., 2020, *Long-term exposure to PM and all-cause and cause-specific mortality: A systematic review and meta-analysis*, Environment International, Vol. 143, Article 105974. Available at: https://pubmed.ncbi.nlm.nih.gov/32703584/.

120 Peters, R. et al., 2021, Putting fine particulate matter and dementia in the wider context of noncommunicable disease: Where are we now and what should we do next: A systematic review, Neuroepidemiology, Vol. 55(4), pp. 253–265. Available at: https://pubmed.ncbi.nlm.nih.gov/34062541/.

121 Huang, F. et al., 2017, *Relationship between exposure to PM2.5 and lung cancer incidence and mortality: A meta-analysis*, Oncotarget, Vol. 8(26), pp. 43322–43331. Available at: https://pubmed.ncbi.nlm.nih.gov/28487493/.

122 Kim, H. et al., 2018, *Long-term exposure to air pollutants and cancer mortality: A meta-analysis of cohort studies*, International Journal of Environmental Research and Public Health, Vol. 15(11). Available at: https://pubmed.ncbi.nlm.nih.gov/30469439/.

123 Karimi, B. and Samadi, S., 2024, *Long-term exposure to air pollution on cardio-respiratory, and lung cancer mortality: a systematic review and meta-analysis*, Journal of Environmental Health Science and Engineering, Vol. 22(1), pp. 75–95. Available at: https://pubmed.ncbi.nlm.nih.gov/38887768/.

124 Yu, P. et al., 2021, *Cohort studies of long-term exposure to outdoor particulate matter and risks of cancer: A systematic review and meta-analysis*, The Innovation, Vol. 2(3). Available at: https://pubmed.ncbi.nlm.nih.gov/34557780/.

125 Chen, J. and Hoek, G., 2020, *Long-term exposure to PM and all-cause and cause-specific mortality: A systematic review and meta-analysis*, Environment International, Vol. 143, Article 105974. Available at: https://pubmed.ncbi.nlm.nih.gov/32703584/.

126 Kim, H. et al., 2018, *Long-term exposure to air pollutants and cancer mortality: A meta-analysis of cohort studies*, International Journal of Environmental Research and Public Health, Vol. 15(11). Available at: https://pubmed.ncbi.nlm.nih.gov/30469439/.

127 Karimi, B. and Samadi, S., 2024, *Long-term exposure to air pollution on cardio-respiratory, and lung cancer mortality: a systematic review and meta-analysis*, Journal of Environmental Health Science and Engineering, Vol. 22(1), pp. 75–95. Available at: https://pubmed.ncbi.nlm.nih.gov/38887768/.

128 Yu, P. et al., 2021, *Cohort studies of long-term exposure to outdoor particulate matter and risks of cancer: A systematic review and meta-analysis*, The Innovation, Vol. 2(3). Available at: https://pubmed.ncbi.nlm.nih.gov/34557780/.

129 Chen, J. and Hoek, G., 2020, *Long-term exposure to PM and all-cause and cause-specific mortality: A systematic review and meta-analysis*, Environment International, Vol. 143, Article 105974. Available at: https://pubmed.ncbi.nlm.nih.gov/32703584/.

130 Yu, P. et al., 2021, *Cohort studies of long-term exposure to outdoor particulate matter and risks of cancer: A systematic review and meta-analysis*, The Innovation, Vol. 2(3). Available at: https://pubmed.ncbi.nlm.nih.gov/34557780/.

131 Arif, I. et al., 2024, *A meta-analysis of the carcinogenic effects of particulate matter and polycyclic aromatic hydrocarbons*, Environmental Pollution, Vol. 351. Available at: https://pubmed.ncbi.nlm.nih.gov/38614427/.

132 Chen, J. and Hoek, G., 2020, *Long-term exposure to PM and all-cause and cause-specific mortality: A systematic review and meta-analysis*, Environment International, Vol. 143, Article 105974. Available at: https://pubmed.ncbi.nlm.nih.gov/32703584/.

133 Yu, P. et al., 2021, *Cohort studies of long-term exposure to outdoor particulate matter and risks of cancer: A systematic review and meta-analysis*, The Innovation, Vol. 2(3). Available at: https://pubmed.ncbi.nlm.nih.gov/34557780/.

Gastrointestinal, liver, kidney, oral, thyroid cancers

Associations between particulate matter and gastrointestinal cancers also show mixed and inconsistent patterns. Some reviews identify statistically significant associations between $PM_{2.5}$ and colorectal cancer mortality[134], whereas others find no consistent evidence for colorectal or stomach cancer incidence across Europe and North America[135]. Evidence for pancreatic cancer is also mixed: PM_{10} was associated with higher pancreatic cancer mortality in one meta-analysis[136], but this has not been widely replicated across other studies.

The strongest emerging evidence outside lung cancer relates to oral and thyroid cancer. A 2024 systematic review and meta-analysis covering 14 epidemiological studies found a statistically significant **association between $PM_{2.5}$ exposure and oral cancer, with five of seven $PM_{2.5}$ studies showing increased risk of 13% of oral cancer[137]. $PM_{2.5}$ exposure has also been linked to a higher risk of thyroid cancer, with studies reporting increases of approximately 18–23%, as well as a greater occurrence of small growths or lumps in the thyroid gland.** Evidence for PM_{10} is weaker and less consistent[138].

Limited evidence suggests possible associations between $PM_{2.5}$ exposure and liver cancer mortality, with one multi-country meta-analysis reporting a significantly elevated risk of approximately 29%.[139] However, other systematic reviews did not provide liver-specific findings, and results for incidence remain sparse and inconsistent[140]. Thus, liver cancer presents emerging but not yet robust evidence of particulate-related risk.

For kidney cancer, the most recent systematic evidence indicates significant associations with PM_{10} exposure, with a 29% higher risk of kidney cancer incidence and a 38% higher risk of hospitalisation or mortality per 10 µg/m^3 PM_{10}[141]. Another review identified positive associations between $PM_{2.5}$ and kidney cancer mortality,[142] though findings were **less consistent across cohorts**.

Taken together, the evidence suggests a potentially meaningful link, but with a smaller and less certain body of research than for lung cancer.

Other cancer sites

Beyond the major systems described above, evidence for other cancer types remains inconclusive. Some meta-analyses identify associations for bladder cancer, pancreatic cancer, and lymphoid cancers, but findings vary considerably between regions and study methodologies, with several

134 Kim, H. et al., 2018, *Long-term exposure to air pollutants and cancer mortality: A meta-analysis of cohort studies*, International Journal of Environmental Research and Public Health, Vol. 15(11). Available at: https://pubmed.ncbi.nlm.nih.gov/30469439/.

135 Yu, P. et al., 2021, *Cohort studies of long-term exposure to outdoor particulate matter and risks of cancer: A systematic review and meta-analysis*, The Innovation, Vol. 2(3). Available at: https://pubmed.ncbi.nlm.nih.gov/34557780/.

136 Kim, H. et al., 2018, *Long-term exposure to air pollutants and cancer mortality: A meta-analysis of cohort studies*, International Journal of Environmental Research and Public Health, Vol. 15(11). Available at: https://pubmed.ncbi.nlm.nih.gov/30469439/.

137 Zhan, H. et al., 2024, Exposure to mixture particulate contaminants in the air and the risk of oral cancer: An updated systematic review and meta-analysis, Heliyon, Vol. 10(19). Available at: https://pubmed.ncbi.nlm.nih.gov/39391488/.

138 Li, X. et al., 2025, *Mapping the association between environmental pollutants and steatotic liver disease: A systematic review and meta-analysis*, Environmental Research, Vol. 285(Pt 5). Available at: https://pubmed.ncbi.nlm.nih.gov/40840603/.

139 Ibid.

140 Yu, P. et al., 2021, *Cohort studies of long-term exposure to outdoor particulate matter and risks of cancer: A systematic review and meta-analysis*, The Innovation, Vol. 2(3). Available at: https://pubmed.ncbi.nlm.nih.gov/34557780/.

141 Dahman, L. et al., 2024, *Air pollution and kidney cancer risk: a systematic review and meta-analysis*, Journal of Nephrology, Vol. 37(7), pp. 1779–1790. Available at: https://pubmed.ncbi.nlm.nih.gov/38913266/.

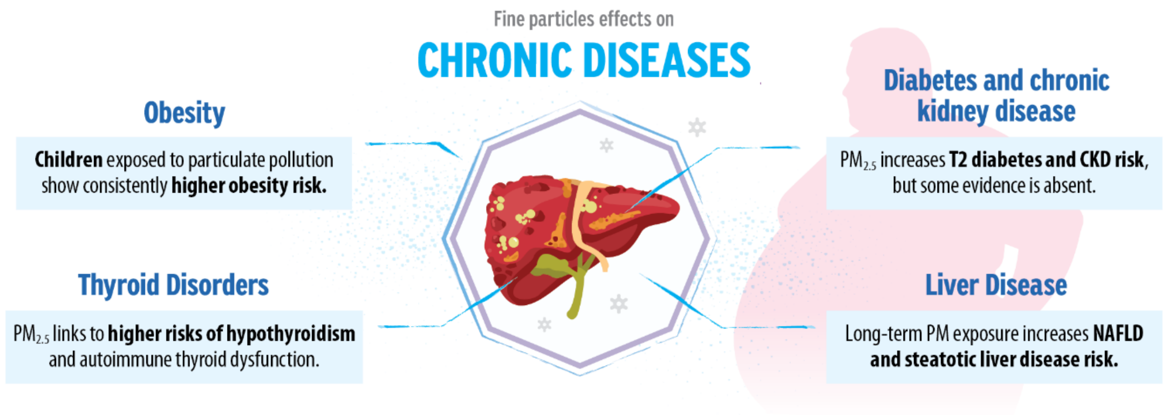
142 Kim, H. et al., 2018, *Long-term exposure to air pollutants and cancer mortality: A meta-analysis of cohort studies*, International Journal of Environmental Research and Public Health, Vol. 15(11). Available at: https://pubmed.ncbi.nlm.nih.gov/30469439/.

cohorts reporting null associations[143] [144]. A large global synthesis reports elevated risks for overall cancer incidence and mortality associated with both $PM_{2.5}$ and PM_{10}, driven primarily by lung cancer, but site-specific relationships beyond lung and, to a lesser extent, kidney and oral cancers remain inconsistent[145].

Taken together, these findings suggest potential links between fine particulate matter and several cancer types, though the evidence remains uneven and considerably less robust than that for lung and oral cancers.

2.1.6. Metabolic, endocrine, and other chronic diseases

Figure 6: Metabolic, endocrine, and other chronic diseases



Source: Authors' own elaboration.

Fine particulate matter triggers systemic biological processes and disruptions in metabolic signalling pathways. These processes can impair glucose regulation, alter lipid metabolism, increase insulin resistance, and affect hormone-producing organs, including the liver, kidneys, and thyroid. Over time, repeated exposure can increase the risk of developing several chronic diseases, including diabetes, obesity, fatty liver disease, and chronic kidney disease, and may also worsen existing conditions.

Diabetes (Type 2, Type 1, gestational) and chronic kidney disease

The strongest and most consistent findings concern Type 2 diabetes and chronic kidney disease (CKD) in relation to long-term exposure to $PM_{2.5}$. A major systematic review of Europe, North America, Asia, and Australia reports a **10% increase in Type 2 diabetes incidence per 10 µg/m³ $PM_{2.5}$**[146].

In relation to chronic kidney disease, the same review identified two eligible cohort studies from North America and Asia, both reporting elevated CKD incidence with long-term $PM_{2.5}$ exposure. **Effect estimates indicated a 6% to 27% higher risk of chronic kidney disease per 10 µg/m³ $PM_{2.5}$,**

143 Yu, P. et al., 2021, *Cohort studies of long-term exposure to outdoor particulate matter and risks of cancer: A systematic review and meta-analysis*, The Innovation, Vol. 2(3). Available at: https://pubmed.ncbi.nlm.nih.gov/34557780/.

144 Arif, I. et al., 2024, *A meta-analysis of the carcinogenic effects of particulate matter and polycyclic aromatic hydrocarbons*, Environmental Pollution, Vol. 351. Available at: https://pubmed.ncbi.nlm.nih.gov/38614427/.

145 Ibid.

146 Peters, R. et al., 2021, Putting fine particulate matter and dementia in the wider context of noncommunicable disease: Where are we now and what should we do next: A systematic review, Neuroepidemiology, Vol. 55(4), pp. 253–265. Available at: https://pubmed.ncbi.nlm.nih.gov/34062541/.

indicating a directionally consistent association despite the limited number of studies[147]. No evidence was available on how particulate pollution influences the progression of CKD or on the effects of short-term exposure on this process.

A separate review of hospital attendance among adults with multiple chronic conditions found that both short- and long-term exposure to $PM_{2.5}$ and PM_{10} were associated with higher hospital use, particularly among patients who had metabolic diseases alongside cardiovascular or respiratory conditions. These associations reflected increased vulnerability among people already living with chronic illnesses, rather than new disease onset[148] .

Overall, the evidence base indicates that long-term $PM_{2.5}$ exposure is associated with increased risk of Type 2 diabetes and CKD, while short-term and long-term particulate exposure increases health service utilisation among adults with diabetes as part of multimorbidity clusters. No evidence was identified for Type 1 diabetes, gestational diabetes, or diabetes-related progression beyond these outcomes.

Obesity

Evidence on particulate pollution and childhood obesity is more extensive than for adult metabolic outcomes. A review of epidemiological studies found consistent positive associations between long-term exposure to $PM_{2.5}$ and PM_{10} and multiple indicators of body fat levels in children and adolescents, including higher BMI z-scores, increased waist circumference, and greater prevalence of general or central obesity[149]. Several studies documented concentration-response relationships, for example, adolescent **obesity odds doubled per 10 µg/m^3 $PM_{2.5}$ in Mexico, and large Chinese cohorts reported higher overweight/obesity risk per 10 µg/m^3 increase in either $PM_{2.5}$ or PM_{10}.**

Prenatal and early-life exposure also showed associations with accelerated infant weight gain, including elevated weight-for-length and BMI z-scores at age one. A minority of studies in lower-pollution European settings reported null findings, suggesting context-specific variability[150].

A complementary meta-analysis found that **every 10 µg/m^3 increase in particulate matter was associated with a 12% higher obesity risk for PM_{10} and a 28% higher risk for $PM_{2.5}$**[151]. Increases in BMI were small, around 0.03–0.11 kg/m^2 per 10 µg/m^3, with stronger associations observed in higher-pollution settings.

Taken together, the available evidence indicates a consistent association between long-term particulate exposure and increased obesity risk in children, with dose-response patterns and stronger effects in high-pollution environments.

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147 Ibid.

148 Hassan, N. et al., 2026, *The impact of poor air quality on hospital attendance of multimorbid patients*, Frontiers in Medicine, Vol. 12. Available at: https://pubmed.ncbi.nlm.nih.gov/41574384/.

149 Siewert, B. et al., 2024, *Examining the link between air quality (PM, SO_2, NO_2, PAHs) and childhood obesity: A systematic review*, Journal of Clinical Medicine, Vol. 13(18). Available at: https://pubmed.ncbi.nlm.nih.gov/39337093/.

150 Ibid.

151 Huang, C. et al., 2022, *The association between childhood exposure to ambient air pollution and obesity: A systematic review and meta-analysis*, International Journal of Environmental Research and Public Health, Vol. 19(8). Available at: https://pubmed.ncbi.nlm.nih.gov/35457358/.

Liver Disease (NAFLD, cirrhosis, steatotic liver disease)

Two systematic reviews provide consistent evidence that long-term particulate matter exposure increases the risk of non-alcoholic fatty liver disease (NAFLD) and related chronic liver outcomes.

The first review, covering more than 4.3 million participants, found that long-term exposure to particulate matter was associated with a higher risk of fatty liver disease and liver cirrhosis, a condition in which scarring impairs normal liver function. For a 10 µg/m³ increase in concentration, **$PM_{2.5}$ was associated with a 33% higher risk and PM_{10} with a 27% higher risk**[152]. Associations were stronger in developing countries, with approximately a 41% higher risk than in lower-exposure groups, whereas effects were smaller in high-income settings. All included studies assessed long-term exposure, and no evidence on short-term effects was reported.

A second meta-analysis of 34 observational studies reported similar findings for steatotic liver disease (SLD). For **each 10 µg/m³ increase in $PM_{2.5}$ the study reported a 23% higher risk of SLD**. **For PM_{10} there is a much lower risk of 7%**[153]. Across both reviews, the evidence consistently indicates that long-term exposure to particulate matter, particularly $PM_{2.5}$, is associated with an increased risk of non-alcoholic fatty liver disease (NAFLD) and steatotic liver disease, with stronger associations observed in higher-pollution settings and no evidence for short-term effects.

Thyroid Disorders

The strongest associations were observed between long-term $PM_{2.5}$ exposure and thyroid health problems, particularly hypothyroidism (an underactive thyroid, where the gland produces too little thyroid hormone). A large systematic review reported that each 10 µg/m³ increase in **$PM_{2.5}$ was associated with a 5% higher risk of hypothyroidism, a 2% higher risk of subclinical hypothyroidism, and a 2% higher risk of thyroid autoantibody positivity**[154]. Additionally, the cohort evidence indicated that long-term exposure to $PM_{2.5}$ and PM_{10} was associated with increased risk of thyroid eye disease, with hazard ratios ranging from 49% to 74% per standard deviation increase in exposure[155].

These findings support a positive association between particulate matter and autoimmune or inflammatory thyroid conditions. The evidence suggests that long-term exposure to $PM_{2.5}$ and to a lesser extent PM_{10}, is associated with increased risk of thyroid dysfunction, particularly autoimmune-related disorders. However, some individual studies reported no statistically significant associations, indicating heterogeneity in the evidence.

[152] He, X. et al., 2025, Air pollution exposure and prevalence of non-alcoholic fatty liver disease and related cirrhosis: A systematic review and meta-analysis, Ecotoxicology and Environmental Safety, Vol. 289. Available at: https://pubmed.ncbi.nlm.nih.gov/39657383/.

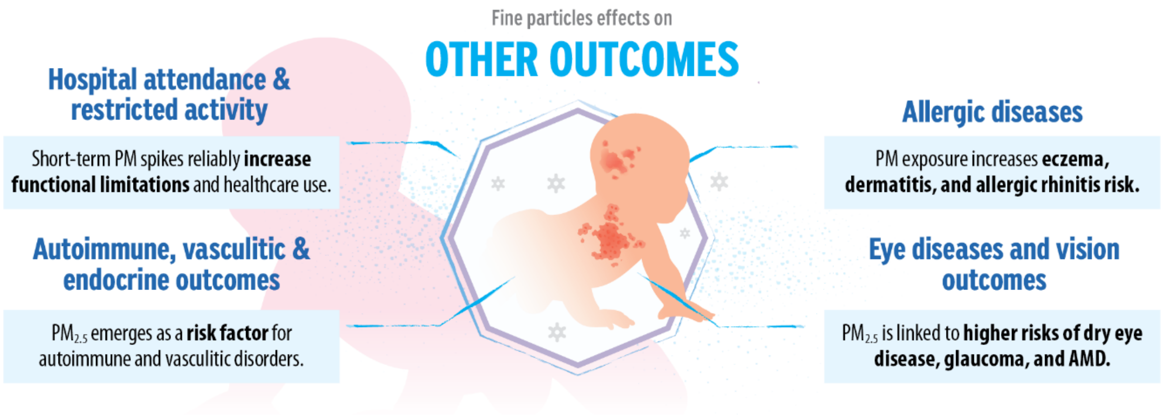
[153] Li, X. et al., 2025, *Mapping the association between environmental pollutants and steatotic liver disease: A systematic review and meta-analysis*, Environmental Research, Vol. 285(Pt 5). Available at: https://pubmed.ncbi.nlm.nih.gov/40840603/.

[154] Wang, J. et al., 2025, *Epidemiological and experimental evidence of environmental factor-related autoimmune thyroid disease: A systematic review*, Ecotoxicology and Environmental Safety, Vol. 305. Available at: https://pubmed.ncbi.nlm.nih.gov/41130066/.

[155] Ibid.

2.1.7. Other outcomes

Figure 7: Other outcomes



Source: Authors' own elaboration.

Allergic diseases

Across studies, particulate matter, especially $PM_{2.5}$, is linked to small but consistent increases in allergic and inflammatory conditions. **A meta-analysis of 55 studies found that long-term exposure to PM_{10} was associated with a higher risk of eczema, with an increase of around 58%.** Smaller short-term increases were also observed for both $PM_{2.5}$ and PM_{10}. In addition, long-term exposure to $PM_{2.5}$ was linked to a modest increase in hay fever, of around 6%[156]. Another review of 13 studies reported similar patterns, with $PM_{2.5}$ associated with eczema and atopic dermatitis, especially in children, and short-term exposures to **both pollutants showing statistically significant 1-1.6% increases per 10 µg/m³**[157]. Evidence from upper respiratory tract microbiome studies consistently showed PM-associated microbial dysbiosis, supporting biological pathways for allergic disease, although clinical outcomes were not quantified[158].

Overall, findings consistently indicate increased risks of eczema and dermatitis with $PM_{2.5}$ and PM_{10} associated eczema in long-term models.

Eye diseases and vision outcomes

Evidence linking particulate matter to eye health problems is strong for dry eye disease (DED) and glaucoma, which can lead to gradual vision loss, and emerging for age-related macular degeneration (AMD), a condition that causes blurred or lost central vision. A broad review found consistent associations between long-term $PM_{2.5}$ and PM_{10} and higher DED prevalence and severity, with large studies in China and India reporting substantial increases, including a 65% higher symptom burden at high $PM_{2.5}$ concentrations[159]. A meta-analysis on age-related eye diseases found that exposure to long-term $PM_{2.5}$ is associated with an 18% higher risk of glaucoma. In contrast, findings for cataracts

156 Wang, H. et al., 2022, *Ambient air pollutants increase the risk of immunoglobulin E-mediated allergic diseases: a systematic review and meta-analysis*, Environmental Science and Pollution Research International, Vol. 29(33), pp. 49534–49552. Available at: https://pubmed.ncbi.nlm.nih.gov/35595897/.

157 Ngoc, L. et al., 2017, *Systematic review and meta-analysis of human skin diseases due to particulate matter*, International Journal of Environmental Research and Public Health, Vol. 14(12). Available at: https://pubmed.ncbi.nlm.nih.gov/29186837/.

158 Arca-Lafuente, S. et al., 2025, *Effects of urban airborne particulate matter exposure on the human upper respiratory tract microbiome: a systematic review*, Respiratory Research, Vol. 26(1). Available at: https://pubmed.ncbi.nlm.nih.gov/40156019/.

159 Onyeze, N. and Jacob, J., 2025, *Climate change and its impact on ocular health: A systematic review*, Cureus, Vol. 17(9). Available at: https://pubmed.ncbi.nlm.nih.gov/41050032/.

were mostly inconclusive, and results for AMD were mixed across studies[160]. **Another review reported a 10% higher risk of overall vision disorder per 10 µg/m³ $PM_{2.5}$ with stronger associations for glaucoma and AMD, and higher susceptibility in children and adolescents**[161]. Evidence for pink eye was weaker: pooled estimates for both $PM_{2.5}$ and PM_{10} were non-significant, although several city-specific analyses found short-term PM_{10}-related increases in visits[162].

Overall, reviews consistently indicate $PM_{2.5}$-related increases in DED, glaucoma and AMD, while PM_{10} evidence is weaker and more inconsistent.

Hospital attendance and restricted activity days

Evidence across continents indicates that short-term PM exposure contributes to reduced functional capacity and increased healthcare utilisation. **A WHO-commissioned review found 1.7% and 1.9% increases in restricted activity days per 10 µg/m³ of $PM_{2.5}$ and PM_{10}, respectively, including work and school absences, with findings robust in sensitivity analyses.** The evidence also showed increased hospital visits linked to short-term $PM_{2.5}$ and PM_{10} exposure across multiple patient groups, although estimates varied by condition and population[163]. Overall, the evidence indicates that short-term PM exposure reliably increases day-to-day functional limitations and hospital visits.

Immune-mediated, autoimmune, and endocrine outcomes

Several conditions outside the major outcome domains also show PM-associated risks. Meta-analytic evidence indicates that exposure to $PM_{2.5}$ is associated with an increased risk of systemic lupus erythematosus (SLE). This is a chronic autoimmune disease in which the immune system mistakenly attacks healthy tissue throughout the body. The risk increase associated with $PM_{2.5}$ is around 16%, while findings for PM_{10} were smaller and not statistically significant[164]. A smaller review noted that short-term $PM_{2.5}$ elevations were associated with increased flare markers and higher odds of active disease in some cohorts[165].

Two reviews found that particulate matter exposure increases the risk of Kawasaki disease, a childhood condition that causes inflammation of the blood vessels throughout the body. Short-term $PM_{2.5}$ and PM_{10} exposures produced small but significant increases, while long-term exposure to $PM_{2.5}$ was linked to a substantially higher risk of around 42%[166] [167].

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[160] Grant, A. et al., 2022, *Ambient air pollution and age-related eye disease: A systematic review and meta-analysis*, Investigative Ophthalmology & Visual Science, Vol. 63(9). Available at: https://pubmed.ncbi.nlm.nih.gov/35960515/.

[161] Han, Z. et al., 2024, *Ambient air pollution and vision disorder: A systematic review and meta-analysis*, Toxics, Vol. 12(3). Available at: https://pubmed.ncbi.nlm.nih.gov/38535942/.

[162] Chen, R. et al., 2019, *Global associations of air pollution and conjunctivitis diseases: A systematic review and meta-analysis*, International Journal of Environmental Research and Public Health, Vol. 16(19). Available at: https://pubmed.ncbi.nlm.nih.gov/31569424/.

[163] Orellano, P., Reynoso, J. and Quaranta, N., 2023, *Effects of air pollution on restricted activity days: systematic review and meta-analysis*, Environmental Health, Vol. 22(1), Article 31. Available at: https://pubmed.ncbi.nlm.nih.gov/36991377/.

[164] Xu, Y. et al., 2025, *Air pollution, emerging chemical exposures, and systemic lupus erythematosus: A meta-epidemiology study*, Frontiers in Immunology, Vol. 16. Available at: https://pubmed.ncbi.nlm.nih.gov/41181096/.

[165] Gilcrease, G. et al., 2020, Is air pollution affecting the disease activity in patients with systemic lupus erythematosus? State of the art and a systematic literature review, European Journal of Rheumatology, Vol. 7(1), pp. 31–34. Available at: https://pubmed.ncbi.nlm.nih.gov/32023206/.

[166] Yang, P. et al., 2025, *Prenatal and postnatal ambient air pollution and Kawasaki disease: A systematic review and meta-analysis*, JACC: Advances, Vol. 4(4). Available at: https://pubmed.ncbi.nlm.nih.gov/40088736/.

[167] Moncur, C. et al., 2025, *Early life exposure to ambient particulate matter and Kawasaki disease: A systematic review and meta-analysis*, Frontiers in Cardiovascular Medicine, Vol. 12. Available at: https://pubmed.ncbi.nlm.nih.gov/40860365/.

Across these diverse conditions, the evidence most consistently identifies $PM_{2.5}$ as an environmental risk factor for autoimmune, vasculitic and endocrine disorders.

KEY FINDINGS

The evidence shows that particulate matter can affect health across the entire life course, from before conception through to older age. However, vulnerability is not evenly distributed. The strongest and most consistent evidence relates to pregnancy and early childhood, which emerge as particularly sensitive periods of exposure.

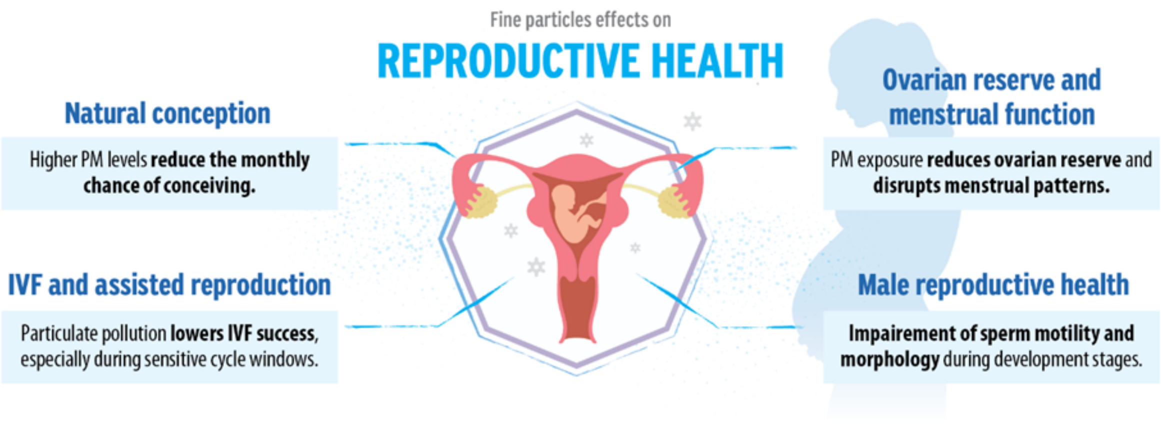
Exposure to particulate matter has been linked to a wide range of adverse outcomes, including reduced fertility, complications during pregnancy, adverse birth outcomes, and impacts on child health and development. Evidence also suggests associations with increased risks of pregnancy loss and certain congenital anomalies. While both $PM_{2.5}$ and PM_{10} are linked to these outcomes, $PM_{2.5}$ generally shows the strongest and most consistent associations.

Across life stages, the direction of effects is remarkably consistent, although the magnitude of risk varies depending on the pollutant, timing of exposure, and health outcome considered. Overall, the findings suggest that exposure to particulate matter can influence health from the earliest stages of life, with consequences that may extend into later childhood and adulthood.

Health impacts in vulnerable and high-risk populations Exposure to particulate matter is linked to a wide range of adverse health outcomes across the life course, affecting individuals from preconception and early development through to older age. The evidence shows that susceptibility varies across different life stages, with certain periods, such as **pregnancy, early childhood, and older age, representing windows of increased vulnerability**. Health impacts span multiple systems, including reproductive, cardiovascular, respiratory, neurological, and metabolic health. The following sections present evidence across key life stages, highlighting both the strength and consistency of associations and important differences in risk across populations.

2.1.8. Reproductive health

Figure 8: Reproductive health



Source: Authors' own elaboration.

Across reviews, exposure to fine particulate matter ($PM_{2.5}$ and PM_{10}) is consistently linked with a **lower chance of becoming pregnant and reduced success in fertility treatment**, with the most consistent signals observed for $PM_{2.5}$ and additional risks from PM_{10} during sensitive periods of the menstrual cycle[168] [169] [170]. A global review covering 49 studies reported that each 10µg/m³ increase in $PM_{2.5}$ was associated with an **estimated 22% reduction in the monthly likelihood of conceiving**. In addition, it found **lower IVF success rates at higher particulate concentrations, particularly in regions with** severe air pollution or wildfire smoke[171].

Evidence suggests that long-term exposure to $PM_{2.5}$ may adversely affect female reproductive health. Studies have reported lower levels of anti-Müllerian hormone (AMH) and a reduced antral follicle count (AFC), two widely used indicators of ovarian reserve. Together, these findings suggest that air pollution may accelerate the natural decline in fertility. For example, several studies found reductions in AMH of approximately 2.1% for every 10 µg/m³ increase in $PM_{2.5}$, and reductions in AFC of between 6.2–7.2% for every 2 µg/m³ increase in $PM_{2.5}$. Higher exposure levels were associated with a greater likelihood of diminished ovarian reserve, with women in the highest exposure groups showing around a 45–55% higher likelihood compared to those with lower exposure. PM_{10} exposure was also linked to lower AMH levels, with around a 1.9% reduction per 10 µg/m³ increase, and higher exposure among women with diminished ovarian reserve[172].

A larger synthesis of 40 cohort reports also found consistent associations between both $PM_{2.5}$ and PM_{10} and reductions in AMH and AFC, including one study in which the effect of $PM_{2.5}$ on ovarian reserve was estimated to be comparable to approximately two years of reproductive ageing. This review noted particularly pronounced effects of PM_{10} among women with infertility, and rated the overall evidence as high quality for $PM_{2.5}$ and lower quality for PM_{10} due to heterogeneity and several null findings[173]. Complementing these findings, a global systematic review and meta-analysis concluded that exposure to both $PM_{2.5}$ and PM_{10} is associated with **reduced ovarian reserve and menstrual irregularities**, consistent with the observed reductions in natural conception rates and lower success in assisted reproduction across diverse geographical settings[174] [175] [176].

Evidence also indicates that exposure to fine particulate matter can **adversely affect male reproductive health, particularly aspects of semen quality**. A global review of 17 epidemiological studies found that while results were mixed for sperm count and sperm swimming ability, the most consistent finding was an **increase in the proportion of abnormally shaped sperm** associated with

168 Papadiochou, A. et al., 2024, *Impact of Climate Change on Reproductive Health and Pregnancy Outcomes: A Systematic Review*, Cureus, Vol. 16. Available at: https://pubmed.ncbi.nlm.nih.gov/39347228/.

169 Carré, J. et al., 2017, *Does air pollution play a role in infertility? a systematic review*, Environmental Health, Vol. 16. Available at: https://pubmed.ncbi.nlm.nih.gov/28754128/.

170 Coppeta, L. et al., 2025, *Systematic literature review and meta-analysis on the reproductive effects of micro-pollutants in humans and animals*, Frontiers in Toxicology, Vol. 7. Available at: https://pubmed.ncbi.nlm.nih.gov/41347044/.

171 Papadiochou, A. et al., 2024, *Impact of Climate Change on Reproductive Health and Pregnancy Outcomes: A Systematic Review*, Cureus, Vol. 16. Available at: https://pubmed.ncbi.nlm.nih.gov/39347228/.

172 Zupo, R. et al., 2024, *Air pollutants and ovarian reserve: a systematic review of the evidence*, Frontiers in Public Health, Vol. 12. Available at: https://pubmed.ncbi.nlm.nih.gov/39376999/.

173 An, L. et al., 2025, *Assessment of ovarian dysfunction induced by environmental toxins: a systematic review*, Frontiers in Public Health, Vol. 13. Available at: https://pubmed.ncbi.nlm.nih.gov/40809751/.

174 Coppeta, L. et al., 2025, *Systematic literature review and meta-analysis on the reproductive effects of micro-pollutants in humans and animals*, Frontiers in Toxicology, Vol. 7. Available at: https://pubmed.ncbi.nlm.nih.gov/41347044/.

175 Papadiochou, A. et al., 2024, *Impact of Climate Change on Reproductive Health and Pregnancy Outcomes: A Systematic Review*, Cureus, Vol. 16. Available at: https://pubmed.ncbi.nlm.nih.gov/39347228/.

176 Carré, J. et al., 2017, *Does air pollution play a role in infertility? a systematic review*, Environmental Health, Vol. 16. Available at: https://pubmed.ncbi.nlm.nih.gov/28754128/.

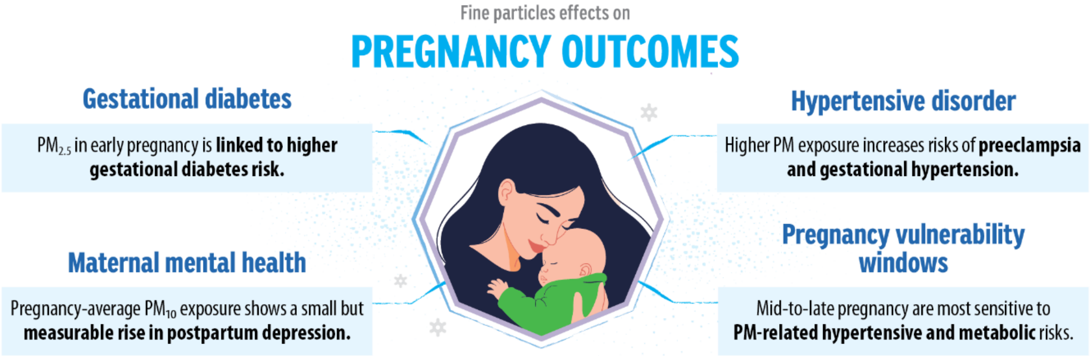
higher levels of $PM_{2.5}$ and PM_{10} alongside suggestive links with **greater DNA damage**, although differences in study design and exposure assessment limited firm causal conclusions[177].

More detailed evidence from a large meta-analysis of nearly 94,000 men in China showed that higher short-term exposure to both $PM_{2.5}$ and PM_{10} during the 90-day period in which sperm develop was associated with **reductions in total sperm motility**, including at particularly sensitive points in the development cycle, and with **lower total sperm number** during several of these windows, while sperm concentration showed little consistent association[178]. Findings from multi-country reviews support this pattern, reporting associations between higher particulate exposure and reduced motility, increased abnormalities in sperm shape, and greater chromosomal irregularities in sperm cells, although the magnitude of these effects varied across settings and exposure metrics[179].

Taken together, these studies suggest that particulate air pollution can impair key aspects of semen quality, most consistently motility and morphology, and that exposure during critical stages of sperm development may be particularly relevant[180] [181] [182] [183].

2.1.9. Pregnancy outcomes

Figure 9: Pregnancy outcomes



Source: Authors' own elaboration.

Evidence suggests that exposure to particulate matter during pregnancy increases the risk of pregnancy-related high blood pressure disorders, particularly preeclampsia. The strongest and most consistent evidence has been found for $PM_{2.5}$ exposure. A meta-analysis of nine cohort studies, covering almost 600,000 pregnancies, found that each **10 µg/m³ increase in $PM_{2.5}$ during pregnancy was associated with a 32% increase in the risk of preeclampsia**, with indications that the third

[177] Lafuente, R. et al., 2016, *Outdoor air pollution and sperm quality*, Fertility and Sterility, Vol. 106. Available at: https://pubmed.ncbi.nlm.nih.gov/27565259/.

[178] Liu, J. et al., 2023, *Does air pollution exposure affect semen quality? Evidence from a systematic review and meta-analysis of 93,996 Chinese men*, Frontiers in Public Health, Vol. 11. Available at: https://pubmed.ncbi.nlm.nih.gov/37601219/.

[179] Carré, J. et al., 2017, *Does air pollution play a role in infertility? a systematic review*, Environmental Health, Vol. 16. Available at: https://pubmed.ncbi.nlm.nih.gov/28754128/.

[180] Lafuente, R. et al., 2016, *Outdoor air pollution and sperm quality*, Fertility and Sterility, Vol. 106. Available at: https://pubmed.ncbi.nlm.nih.gov/27565259/.

[181] Liu, J. et al., 2023, *Does air pollution exposure affect semen quality? Evidence from a systematic review and meta-analysis of 93,996 Chinese men*, Frontiers in Public Health, Vol. 11. Available at: https://pubmed.ncbi.nlm.nih.gov/37601219/.

[182] Carré, J. et al., 2017, *Does air pollution play a role in infertility? a systematic review*, Environmental Health, Vol. 16. Available at: https://pubmed.ncbi.nlm.nih.gov/28754128/.

[183] Papadiochou, A. et al., 2024, *Impact of Climate Change on Reproductive Health and Pregnancy Outcomes: A Systematic Review*, Cureus, Vol. 16. Available at: https://pubmed.ncbi.nlm.nih.gov/39347228/.

trimester may be a particularly sensitive period[184]. A broader review of 27 studies similarly reported that most research found positive associations between both $PM_{2.5}$ and PM_{10} and hypertensive disorders, including gestational hypertension and increases in systolic and diastolic blood pressure, though the size of the effect varied across studies due to differences in exposure metrics and baseline pollution levels. This review also noted that the second trimester was most frequently identified as a critical window for developing these conditions[185].

A larger meta-analysis of 26 studies, covering more than 2 million pregnancies, found small but consistent increases in the risk of preeclampsia associated with both pollutants. Women exposed to **higher levels of $PM_{2.5}$ had approximately a 10% higher likelihood of preeclampsia, while exposure to PM_{10} was associated with an approximately 8% higher likelihood,** with slightly stronger associations observed during the second trimester. However, the authors noted substantial variation across studies, and the causal nature of the relationship remains uncertain, suggesting that some of the observed associations may be influenced by unmeasured factors[186].

Another global meta-analysis focusing on $PM_{2.5}$ reported a small but significant increase in the risk of preeclampsia, with a 10 $\mu g/m^3$ increase in exposure associated with an approximately 11% higher likelihood. Higher exposure levels were consistently associated with greater risk, whereas the evidence for gestational hypertension was weaker and often not statistically significant[187]. Overall, while the magnitude of the association varies between studies, the direction of the evidence is largely consistent: higher exposure to $PM_{2.5}$, and to a lesser extent PM_{10}, is associated with increased risks of preeclampsia and other hypertensive disorders during pregnancy, with several studies pointing to mid-to-late pregnancy as a period of heightened vulnerability[188] [189] [190] [191].

Evidence on the relationship between particulate matter and gestational diabetes shows a broadly consistent pattern for $PM_{2.5}$, although results vary in strength across reviews. A large meta-analysis including more than 3.1 million participants found that long-term exposure to $PM_{2.5}$ was clearly associated with a higher risk of type 2 diabetes in the general population, but **evidence for gestational diabetes within the four pregnancy-specific studies was limited and inconsistent**, with the highest risk estimates observed for exposure averaged across the whole pregnancy, though these did not reach statistical significance[192]. In contrast, a broader systematic review of 27 studies reported that most studies identified positive associations between both $PM_{2.5}$ and PM_{10} and gestational diabetes, though the size of the effect differed substantially between studies due to variations in

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184 Yu, H. et al., 2020, *The impact of particulate matter 2.5 on the risk of preeclampsia: an updated systematic review and meta-analysis*, Environmental Science and Pollution Research, Vol. 28. Available at: https://pubmed.ncbi.nlm.nih.gov/32740838/.

185 Alvarado-Jiménez, D. et al., 2023, A systematic review on the association between exposure to air particulate matter during pregnancy and the development of hypertensive disorders of pregnancy and gestational diabetes mellitus, Reviews on Environmental Health, Vol. 39. Available at: https://pubmed.ncbi.nlm.nih.gov/37141623/.

186 Ma, R. et al., 2025, Gestational exposure to particulate matter and preeclampsia risk: evidence from a meta-analysis and Mendelian randomization study, Journal of Clinical Hypertension, Vol. 27. Available at: https://pubmed.ncbi.nlm.nih.gov/40662997/.

187 Gao, S. et al., 2025, *Prenatal PM2.5 exposure and hypertensive disorders of pregnancy: a systematic review and meta-analysis*, Frontiers in Public Health, Vol. 13. Available at: https://pubmed.ncbi.nlm.nih.gov/41246102/.

188 Yu, H. et al., 2020, *The impact of particulate matter 2.5 on the risk of preeclampsia: an updated systematic review and meta-analysis*, Environmental Science and Pollution Research, Vol. 28. Available at: https://pubmed.ncbi.nlm.nih.gov/32740838/.

189 Alvarado-Jiménez, D. et al., 2023, A systematic review on the association between exposure to air particulate matter during pregnancy and the development of hypertensive disorders of pregnancy and gestational diabetes mellitus, Reviews on Environmental Health, Vol. 39. Available at: https://pubmed.ncbi.nlm.nih.gov/37141623/.

190 Ma, R. et al., 2025, Gestational exposure to particulate matter and preeclampsia risk: evidence from a meta-analysis and Mendelian randomization study, Journal of Clinical Hypertension, Vol. 27. Available at: https://pubmed.ncbi.nlm.nih.gov/40662997.

191 Song, J. et al., 2024*, A systematic review and meta-analysis of the association between air pollutants and the incidence of tuberculosis*, Heliyon. Available at: https://www.sciencedirect.com/science/article/pii/S2405844024048321.

192 He, D. et al., 2017, *Association between particulate matter 2.5 and diabetes mellitus: a meta-analysis of cohort studies*, Journal of Diabetes Investigation. Available at: https://pubmed.ncbi.nlm.nih.gov/28122165/.

exposure measurement and background pollution levels. This review also noted that early pregnancy, particularly the first and second trimesters, was most often identified as a sensitive window[193].

The strongest and most consistent evidence comes from a global meta-analysis of 26 studies, which found that $PM_{2.5}$ exposure is associated with a higher risk of gestational diabetes. **This corresponds to around a 10% higher likelihood with exposure in the first trimester and about a 7% higher likelihood in the second trimester**, with consistent results across studies. Additional evidence also suggests that exposure before pregnancy may play a role[194]. Taken together, the evidence suggests that $PM_{2.5}$ exposure, particularly in early pregnancy, is associated with an increased risk of gestational diabetes, while the picture for PM_{10} is less consistent and supported mainly by qualitative findings rather than pooled estimates[195] [196] [197].

Furthermore, one large European analysis suggests a **possible link between particulate matter and postpartum depression**. In an individual-participant meta-analysis pooling 12 cohorts from several European countries, higher pregnancy-average PM_{10} exposure was associated with a slightly increased risk of PPD, while $PM_{2.5}$ showed no clear association[198]. Although the observed effect for PM_{10} was modest, the findings suggest that particulate pollution during pregnancy may affect maternal mental health, warranting further investigation.

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193 Alvarado-Jiménez, D. et al., 2023, A systematic review on the association between exposure to air particulate matter during pregnancy and the development of hypertensive disorders of pregnancy and gestational diabetes mellitus, Reviews on Environmental Health. Available at: https://pubmed.ncbi.nlm.nih.gov/37141623/.

194 Georgaki, M.N. et al., 2025, *Assessment of environmental risk factors for gestational diabetes mellitus: a ten-year systematic review and meta-analysis*, Journal of Clinical Medicine. Available at: https://pubmed.ncbi.nlm.nih.gov/40095587/.

195 He, D. et al., 2017, *Association between particulate matter 2.5 and diabetes mellitus: a meta-analysis of cohort studies*, Journal of Diabetes Investigation. Available at: https://pubmed.ncbi.nlm.nih.gov/28122165/.

196 Alvarado-Jiménez, D. et al., 2023, A systematic review on the association between exposure to air particulate matter during pregnancy and the development of hypertensive disorders of pregnancy and gestational diabetes mellitus, Reviews on Environmental Health. Available at: https://pubmed.ncbi.nlm.nih.gov/37141623/.

197 Georgaki, M.N. et al., 2025, *Assessment of environmental risk factors for gestational diabetes mellitus: a ten-year systematic review and meta-analysis*, Journal of Clinical Medicine. Available at: https://pubmed.ncbi.nlm.nih.gov/40095587/.

198 Cadman, T. et al., 2024, Urban environment in pregnancy and postpartum depression: An individual participant data meta-analysis of 12 European birth cohorts, Environment International. Available at: https://pubmed.ncbi.nlm.nih.gov/38368715/.

2.1.10. Foetal outcomes

Across reviews, higher maternal exposure to $PM_{2.5}$ and, in several contexts, PM_{10} is associated with a **small but consistent increase in preterm birth risk**, with signals observed across multiple regions[199] [200] [201] [202] [203] [204] [205] [206] [207] [208]. A global meta regression **estimated a 12% higher risk per 10 µg/m^3 pregnancy long-term $PM_{2.5}$** and attributed a substantial share of the worldwide preterm birth burden in 2019 to $PM_{2.5}$, highlighting the population-level significance of even modest individual risks[209]. By timing of exposure, $PM_{2.5}$ exposure during mid-to-late pregnancy showed the clearest associations in Chinese studies, with a risk increase of 3-7%.

A global synthesis also reported increased risks at lower average exposure levels and during the first trimester, corresponding to around a 4–5% higher likelihood. In European studies, results for long-term exposure were mixed, although small, short-term increases in risk were observed for specific days of exposure[210] [211] [212] [213] [214] [215]. For PM_{10}, studies report varying results: East Asian research shows **modest increases of around 2–6% per 10 µg/m^3 increase in exposure**, while comparisons between higher and lower exposure levels over the whole pregnancy show much larger differences,

[199] Ghosh, R. et al., 2021, Ambient and household PM2.5 pollution and adverse perinatal outcomes: a meta-regression and analysis of attributable global burden for 204 countries and territories, PLOS Medicine. Available at: https://pubmed.ncbi.nlm.nih.gov/34582444/.

[200] Guo, B., Jiang, X., 2025, *Association between atmospheric particulate matter pollution during pregnancy and premature birth in China: a meta-analysis*, Frontiers in Public Health. Available at: https://pubmed.ncbi.nlm.nih.gov/39916718/.

[201] Desye, B. et al., 2024, Exposure to ambient air pollutions and its association with adverse birth outcomes: a systematic review and meta-analysis of epidemiological studies, Frontiers in Public Health. Available at: https://pubmed.ncbi.nlm.nih.gov/39606063/.

[202] Simoncic, V. et al., 2020, *Adverse birth outcomes related to NO_2 and PM exposure: European systematic review and meta-analysis*, International Journal of Environmental Research and Public Health. Available at: https://pubmed.ncbi.nlm.nih.gov/33153181/.

[203] Jacobs, M. et al., 2017, *The association between ambient air pollution and selected adverse pregnancy outcomes in China: a systematic review*, Science of the Total Environment. Available at: https://pubmed.ncbi.nlm.nih.gov/27913015/.

[204] Ghosh, R. et al., 2021, Ambient and household PM2.5 pollution and adverse perinatal outcomes: a meta-regression and analysis of attributable global burden for 204 countries and territories, PLOS Medicine. Available at: https://pubmed.ncbi.nlm.nih.gov/34582444/.

[205] Guo, B. and Jiang, X., 2025, *Association between atmospheric particulate matter pollution during pregnancy and premature birth in China: a meta-analysis*, Frontiers in Public Health. Available at: https://pubmed.ncbi.nlm.nih.gov/39916718/.

[206] Desye, B. et al., 2024, Exposure to ambient air pollutions and its association with adverse birth outcomes: a systematic review and meta-analysis of epidemiological studies, Frontiers in Public Health. Available at: https://pubmed.ncbi.nlm.nih.gov/39606063/.

[207] Simoncic, V. et al., 2020, Adverse birth outcomes related to NO_2 and PM exposure: European systematic review and meta-analysis, International Journal of Environmental Research and Public Health. Available at: https://pubmed.ncbi.nlm.nih.gov/33153181/.

[208] Jacobs, M. et al., 2017, *The association between ambient air pollution and selected adverse pregnancy outcomes in China: a systematic review*, Science of the Total Environment. Available at: https://pubmed.ncbi.nlm.nih.gov/27913015/.

[209] Ghosh, R. et al., 2021, Ambient and household PM2.5 pollution and adverse perinatal outcomes: a meta-regression and analysis of attributable global burden for 204 countries and territories, PLOS Medicine. Available at: https://pubmed.ncbi.nlm.nih.gov/34582444/.

[210] Guo, B. and Jiang, X., 2025, *Association between atmospheric particulate matter pollution during pregnancy and premature birth in China: a meta-analysis*, Frontiers in Public Health. Available at: https://pubmed.ncbi.nlm.nih.gov/39916718/.

[211] Desye, B. et al., 2024, Exposure to ambient air pollutions and its association with adverse birth outcomes: a systematic review and meta-analysis of epidemiological studies, Frontiers in Public Health. Available at: https://pubmed.ncbi.nlm.nih.gov/39606063/.

[212] Simoncic, V. et al., 2020, *Adverse birth outcomes related to NO_2 and PM exposure: European systematic review and meta-analysis*, International Journal of Environmental Research and Public Health. Available at: https://pubmed.ncbi.nlm.nih.gov/33153181/.

[213] Guo, B. and Jiang, X., 2025, *Association between atmospheric particulate matter pollution during pregnancy and premature birth in China: a meta-analysis*, Frontiers in Public Health. Available at: https://pubmed.ncbi.nlm.nih.gov/39916718/.

[214] Desye, B. et al., 2024, *Exposure to ambient air pollutions and its association with adverse birth outcomes: a systematic review and meta-analysis of epidemiological studies*, Frontiers in Public Health. Available at: https://pubmed.ncbi.nlm.nih.gov/39606063/.

[215] Simoncic, V. et al., 2020, *Adverse birth outcomes related to NO_2 and PM exposure: European systematic review and meta-analysis*, International Journal of Environmental Research and Public Health. Available at: https://pubmed.ncbi.nlm.nih.gov/33153181/.

with around a 49% higher risk at higher exposure levels. This suggests that the estimated risk depends strongly on how exposure is measured and compared[216] [217] [218] [219].

Premature rupture of membranes, a common pathway to preterm birth, has been associated with exposure to both $PM_{2.5}$ and PM_{10}. Exposure during the second trimester was linked to a higher likelihood of this outcome, with increases of around 15% for $PM_{2.5}$ and 17% for $PM_{2.5}$. Smaller short-term effects of $PM_{2.5}$ were also observed, suggesting that both long-term and short-term particulate exposure may contribute to pathways leading to preterm birth[220]. Context also matters, as syntheses note higher risks during smoke events and at higher air quality index levels, and greater impacts in lower-income or disaster-affected settings[221]. At the same time, heterogeneity in exposure assessment, baseline concentrations, and study design, as well as potential confounding, means effect sizes vary and some analyses, particularly in Europe, are mixed; nonetheless, the overall direction remains positive for $PM_{2.5}$ and, in several contexts, PM_{10}[222] [223] [224] [225] [226] [227] [228] [229].

Across syntheses, **higher long-term prenatal exposure to $PM_{2.5}$ and PM_{10} is associated with lower birth weight and a higher risk of low birth weight** (LBW), including at term (TLBW), with consistent signals for both particle sizes and modest per unit effects that gain public health importance at the

216 Jacobs, M. et al., 2017, *The association between ambient air pollution and selected adverse pregnancy outcomes in China: a systematic review*, Science of the Total Environment. Available at: https://pubmed.ncbi.nlm.nih.gov/27913015/.

217 Guo, B. and Jiang, X., 2025, *Association between atmospheric particulate matter pollution during pregnancy and premature birth in China: a meta-analysis*, Frontiers in Public Health. Available at: https://pubmed.ncbi.nlm.nih.gov/39916718/.

218 Jacobs, M. et al., 2017, *The association between ambient air pollution and selected adverse pregnancy outcomes in China: a systematic review*, Science of the Total Environment. Available at: https://pubmed.ncbi.nlm.nih.gov/27913015/.

219 Desye, B. et al., 2024, Exposure to ambient air pollutions and its association with adverse birth outcomes: a systematic review and meta-analysis of epidemiological studies, Frontiers in Public Health. Available at: https://pubmed.ncbi.nlm.nih.gov/39606063/.

220 Liang, Y. et al., 2024, The relationship between maternal exposure to ambient air pollutants and premature ruptue of membranes: a systematic review and meta-analysis, Environmental Pollution. Available at: https://pubmed.ncbi.nlm.nih.gov/38417606/.

221 Papadiochou, A. et al., 2024, *Impact of climate change on reproductive health and pregnancy outcomes: a systematic review*, Cureus. Available at: https://pubmed.ncbi.nlm.nih.gov/39347228/.

222 Guo, B. and Jiang, X., 2025, *Association between atmospheric particulate matter pollution during pregnancy and premature birth in China: a meta-analysis*, Frontiers in Public Health. Available at: https://pubmed.ncbi.nlm.nih.gov/39916718/.

223 Simoncic, V. et al., 2020, *Adverse birth outcomes related to NO_2 and PM exposure: European systematic review and meta-analysis*, International Journal of Environmental Research and Public Health. Available at: https://pubmed.ncbi.nlm.nih.gov/33153181/.

224 Ibid.

225 Papadiochou, A. et al., 2024, *Impact of climate change on reproductive health and pregnancy outcomes: a systematic review*, Cureus. Available at: https://pubmed.ncbi.nlm.nih.gov/39347228/.

226 Guo, B. and Jiang, X., 2025, *Association between atmospheric particulate matter pollution during pregnancy and premature birth in China: a meta-analysis*, Frontiers in Public Health. Available at: https://pubmed.ncbi.nlm.nih.gov/39916718/.

227 Simoncic, V. et al., 2020, *Adverse birth outcomes related to NO_2 and PM exposure: European systematic review and meta-analysis*, International Journal of Environmental Research and Public Health. Available at: https://pubmed.ncbi.nlm.nih.gov/33153181/.

228 Desye, B. et al., 2024, Exposure to ambient air pollutions and its association with adverse birth outcomes: a systematic review and meta-analysis of epidemiological studies, Frontiers in Public Health. Available at: https://pubmed.ncbi.nlm.nih.gov/39606063/.

229 Papadiochou, A. et al., 2024*, Impact of climate change on reproductive health and pregnancy outcomes: a systematic review*, Cureus. Available at: https://pubmed.ncbi.nlm.nih.gov/39347228/.

population level[230] [231] [232] [233] [234] [235] [236] [237] [238] [239] [240] [241] [242] [243]. For $PM_{2.5}$, studies commonly show small decreases in average birth weight and a higher likelihood of low birth weight. For example, a global meta-regression found a reduction of around 22 grams in birth weight and an approximately 11% higher likelihood of low birth weight per 10 µg/m³ increase in exposure, with substantial health impacts at population-level[244] [245]. A meta-analysis of 32 studies covering more than 15 million births reported a reduction of around 15.9 grams and an approximately 9% higher likelihood of low birth weight, with stronger effects observed during the second and third trimesters and indications of harmful effects from specific $PM_{2.5}$ components[246] [247]. In addition, a meta-analysis of 13 studies (6.64 million births) found a small but consistent increase in the likelihood of low birth weight, particularly for exposures during the first and second trimesters[248].

For PM_{10}, multiple reviews report lower birth weight and a higher likelihood of term low birth weight, with effect sizes broadly similar to $PM_{2.5}$. These typically correspond to around a 2–3% higher likelihood per 10 µg/m³ increase or comparable exposure range. Some evidence also suggests slightly

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230 Ghosh, R. et al., 2021, Ambient and household PM2.5 pollution and adverse perinatal outcomes: a meta-regression and analysis of attributable global burden for 204 countries and territories, PLOS Medicine. Available at: https://pubmed.ncbi.nlm.nih.gov/34582444/.

231 Sun, X. et al., 2016, The associations between birth weight and exposure to fine particulate matter (PM2.5) and its chemical constituents during pregnancy: a meta-analysis, Environmental Pollution. Available at: https://pubmed.ncbi.nlm.nih.gov/26736054/.

232 Liu, J. et al., 2023, *Prenatal exposure to particulate matter and term low birth weight: systematic review and meta-analysis*, Environmental Science and Pollution Research International. Available at: https://pubmed.ncbi.nlm.nih.gov/37059952/.

233 Uwak, I. et al., 2021, Application of the navigation guide systematic review methodology to evaluate prenatal exposure to particulate matter air pollution and infant birth weight, Environment International. Available at: https://pubmed.ncbi.nlm.nih.gov/33508708/.

234 Desye, B. et al., 2024, Exposure to ambient air pollutions and its association with adverse birth outcomes: a systematic review and meta-analysis of epidemiological studies, Frontiers in Public Health. Available at: https://pubmed.ncbi.nlm.nih.gov/39606063/.

235 Jacobs, M. et al., 2017, *The association between ambient air pollution and selected adverse pregnancy outcomes in China: a systematic review*, Science of the Total Environment. Available at: https://pubmed.ncbi.nlm.nih.gov/27913015/.

236 Nyadanu, S.D. et al., 2022, Prenatal exposure to ambient air pollution and adverse birth outcomes: an umbrella review of 36 systematic reviews and meta-analyses, Environmental Pollution. Available at: https://pubmed.ncbi.nlm.nih.gov/35569625/.

237 Ibid.

238 Dzekem, B.S. et al., 2023, *Air pollution and racial disparities in pregnancy outcomes in the United States: a systematic review*, Journal of Racial and Ethnic Health Disparities. Available at: https://pubmed.ncbi.nlm.nih.gov/36897527/.

239 Bosetti, C. et al., 2010*, Ambient particulate matter and preterm birth or birth weight: a review of the literature*, Archives of Toxicology. Available at: https://pubmed.ncbi.nlm.nih.gov/20140425/.

240 Desye, B. et al., 2024, Exposure to ambient air pollutions and its association with adverse birth outcomes: a systematic review and meta-analysis of epidemiological studies, Frontiers in Public Health. Available at: https://pubmed.ncbi.nlm.nih.gov/39606063/.

241 Papadiochou, A. et al., 2024, *Impact of climate change on reproductive health and pregnancy outcomes: a systematic review*, Cureus. Available at: https://pubmed.ncbi.nlm.nih.gov/39347228/.

242 Simoncic, V. et al., 2020, *Adverse birth outcomes related to NO_2 and PM exposure: European systematic review and meta-analysis*, International Journal of Environmental Research and Public Health. Available at: https://pubmed.ncbi.nlm.nih.gov/33153181/.

243 Liang, Y. et al., 2024, *The relationship between maternal exposure to ambient air pollutants and premature rupture of membranes: a systematic review and meta-analysis*, Environmental Pollution. Available at: https://pubmed.ncbi.nlm.nih.gov/38417606/.

244 Ghosh, R. et al., 2021, Ambient and household PM2.5 pollution and adverse perinatal outcomes: a meta-regression and analysis of attributable global burden for 204 countries and territories, PLOS Medicine. Available at: https://pubmed.ncbi.nlm.nih.gov/34582444/.

245 Nyadanu, S.D. et al., 2022, Prenatal exposure to ambient air pollution and adverse birth outcomes: an umbrella review of 36 systematic reviews and meta-analyses, Environmental Pollution. Available at: https://pubmed.ncbi.nlm.nih.gov/35569625/.

246 Sun, X. et al., 2016, The associations between birth weight and exposure to fine particulate matter (PM2.5) and its chemical constituents during pregnancy: a meta-analysis, Environmental Pollution. Available at: https://pubmed.ncbi.nlm.nih.gov/26736054/.

247 Liu, J. et al., 2023, *Does air pollution exposure affect semen quality? Evidence from a systematic review and meta-analysis of 93,996 Chinese men*, Frontiers in Public Health, Vol. 11. Available at: https://pubmed.ncbi.nlm.nih.gov/37601219/.

248 Liang, Y. et al., 2024, The relationship between maternal exposure to ambient air pollutants and premature ruptue of membranes: a systematic review and meta-analysis, Environmental Pollution. Available at: https://pubmed.ncbi.nlm.nih.gov/38417606/.

stronger effects during the second trimester[249] [250] [251]. **A European synthesis found a higher likelihood of term low birth weight with increased exposure to both $PM_{2.5}$ and PM_{10}, corresponding to around an 18% higher likelihood for $PM_{2.5}$ and a 16% higher likelihood for PM_{10} per 10 µg/m^3 increase**. These associations were most pronounced for exposure during late pregnancy or throughout the entire pregnancy[252].

Region-specific reviews from China and Taiwan also report PM_{10}-related weight reductions in birth in early pregnancy and mixed findings for $PM_{2.5}$, underscoring regional heterogeneity[253]. In categorical comparisons across many countries covering around 21 million pregnancies, the likelihood of low birth weight increased with higher $PM_{2.5}$ exposure across pregnancy (≥10 µg/m^3 compared to lower levels) and with higher PM_{10} exposure over the whole pregnancy period, aligning with the overall pattern of lower birth weight at higher exposure levels[254]. Complementary qualitative evidence from diverse settings also indicates that both $PM_{2.5}$ and PM_{10} contribute to lower birth weight and a higher likelihood of low birth weight, with stronger effects observed in low-socioeconomic status populations or in areas affected by disasters[255].

While the direction of effects is generally consistent, the magnitude of findings varies depending on how exposure is measured, background pollution levels, and study design. The strength of evidence also differs by pollutant and exposure window. For example, several reviews concluded that associations between PM_{10} and continuous reductions in birth weight are more consistent, particularly for exposure during the third trimester or across the whole pregnancy, whereas findings for $PM_{2.5}$ show greater variation across studies[256] [257]. **One large global review of 74 cohort studies reported substantially higher estimates than other syntheses, with around a 140% higher likelihood of low birth weight associated with $PM_{2.5}$ exposure and around a 46% higher likelihood for PM_{10} per 10 µg/m^3 increase**. The same review also found an average reduction in birth weight of around 10.7 grams per 10 µg/m^3 increase in $PM_{2.5}$, with stronger effects observed among women aged 30 years and older. Given its size and scope, these higher estimates should be considered alongside the

[249] Liu, J. et al., 2023, *Does air pollution exposure affect semen quality? Evidence from a systematic review and meta-analysis of 93,996 Chinese men*, Frontiers in Public Health, Vol. 11. Available at: https://pubmed.ncbi.nlm.nih.gov/37601219/.

[250] Dzekem, B.S. et al., 2023, *Air pollution and racial disparities in pregnancy outcomes in the United States: a systematic review*, Journal of Racial and Ethnic Health Disparities. Available at: https://pubmed.ncbi.nlm.nih.gov/36897527/.

[251] Bosetti, C. et al., 2010*, Ambient particulate matter and preterm birth or birth weight: a review of the literature*, Archives of Toxicology. Available at: https://pubmed.ncbi.nlm.nih.gov/20140425/.

[252] Simoncic, V. et al., 2020, *Adverse birth outcomes related to NO_2 and PM exposure: European systematic review and meta-analysis*, International Journal of Environmental Research and Public Health. Available at: https://pubmed.ncbi.nlm.nih.gov/33153181/.

[253] Jacobs, M. et al., 2017, *The association between ambient air pollution and selected adverse pregnancy outcomes in China: A systematic review*, Science of the Total Environment. Available at: https://pubmed.ncbi.nlm.nih.gov/27913015/.

[254] Desye, B. et al., 2024, Exposure to ambient air pollutions and its association with adverse birth outcomes: a systematic review and meta-analysis of epidemiological studies, Frontiers in Public Health. Available at: https://pubmed.ncbi.nlm.nih.gov/39606063/.

[255] Papadiochou, A. et al., 2024, *Impact of climate change on reproductive health and pregnancy outcomes: a systematic review*, Cureus. Available at: https://pubmed.ncbi.nlm.nih.gov/39347228/.

[256] Bosetti, C. et al., 2010*, Ambient particulate matter and preterm birth or birth weight: a review of the literature*, Archives of Toxicology. Available at: https://pubmed.ncbi.nlm.nih.gov/20140425/.

[257] Dzekem, B.S. et al., 2023, *Air pollution and racial disparities in pregnancy outcomes in the United States: a systematic review*, Journal of Racial and Ethnic Health Disparities. Available at: https://pubmed.ncbi.nlm.nih.gov/36897527/.

smaller, more consistent effects reported in other large reviews when interpreting the overall evidence [258] [259] [260] [261] [262] [263].

Evidence from a systematic review of 22 cohort studies (around 3.48 million participants) indicates that higher $PM_{2.5}$ exposure during pregnancy is associated with a small increase in the likelihood of foetal overgrowth (LGA/macrosomia), generally in the low single-digit percentage range per 10 µg/m³ increase. These associations were often stronger for exposure during mid- to late pregnancy. Findings for PM_{10} were more limited and less consistent[264].

Across reviews, evidence linking particulate matter to **pregnancy loss** points to increased risks in specific contexts and windows, with PM_{10} most consistently associated with **very early losses** around the time conception occurs and $PM_{2.5}$ is associated with early miscarriage, where the pregnancy stops developing in the first trimester, particularly at higher exposure levels. Evidence for stillbirth remains more limited and inconsistent across studies [265] [266] [267]. Short-term rises in PM_{10} during the days leading up to ovulation were associated with higher odds of early miscarriage, including in IVF patients (for example, higher-exposure categories showing markedly elevated risks), highlighting the relevance of timing close to conception for PM_{10} particles[268].

Qualitative multi-country evidence indicates that first-trimester $PM_{2.5}$, particularly at high concentrations (including disaster smoke or very poor air-quality days), was associated with **missed abortion**, suggesting sensitivity early in embryonic development[269]. For stillbirth, a large global synthesis using categorical exposure contrasts reported increased risks of adverse birth outcomes overall but provided more granular pooled estimates for preterm birth and low birth weight than for stillbirth, reflecting study heterogeneity and fewer consistent estimates for loss later in gestation[270].

Overall, while effect sizes vary and methods differ across studies, the balance of evidence suggests that PM_{10} is linked to early pregnancy loss near conception and that high first-trimester $PM_{2.5}$ may

[258] Sun, X. et al., 2016, The associations between birth weight and exposure to fine particulate matter (PM2.5) and its chemical constituents during pregnancy: a meta-analysis, Environmental Pollution. Available at: https://pubmed.ncbi.nlm.nih.gov/26736054/.

[259] Ji, Y. et al., 2017, Association between exposure to particulate matter during pregnancy and birthweight: a systematic review and a meta-analysis of birth cohort studies, Journal of Biomedical Research. Available at: https://pubmed.ncbi.nlm.nih.gov/29089474/.

[260] Nyadanu, S.D. et al., 2022, Prenatal exposure to ambient air pollution and adverse birth outcomes: an umbrella review of 36 systematic reviews and meta-analyses, Environmental Pollution. Available at: https://pubmed.ncbi.nlm.nih.gov/35569625/.

[261] Liu, J. et al., 2023, *Prenatal exposure to particulate matter and term low birth weight: systematic review and meta-analysis*, Environmental Science and Pollution Research International. Available at: https://pubmed.ncbi.nlm.nih.gov/37059952/.

[262] Dzekem, B.S. et al., 2023, *Air pollution and racial disparities in pregnancy outcomes in the United States: a systematic review*, Journal of Racial and Ethnic Health Disparities. Available at: https://pubmed.ncbi.nlm.nih.gov/36897527/.

[263] Liang, Y. et al., 2024, The relationship between maternal exposure to ambient air pollutants and premature rupture of membranes: a systematic review and meta-analysis, Environmental Pollution. Available at: https://pubmed.ncbi.nlm.nih.gov/38417606/.

[264] Rahnemaei, F.A. et al., 2024, *Prenatal exposure to ambient air pollution and risk of fetal overgrowth: Systematic review of cohort studies*, Ecotoxicology and Environmental Safety. Available at: https://pubmed.ncbi.nlm.nih.gov/38823346/.

[265] Carré, J. et al., 2017. *Does air pollution play a role in infertility?: a systematic review*, Environmental Health. Available at: https://pubmed.ncbi.nlm.nih.gov/28754128/.

[266] Papadiochou, A. et al., 2024, *Impact of climate change on reproductive health and pregnancy outcomes: a systematic review*, Cureus. Available at: https://pubmed.ncbi.nlm.nih.gov/39347228/.

[267] Desye, B. et al., 2024, Exposure to ambient air pollutions and its association with adverse birth outcomes: a systematic review and meta-analysis of epidemiological studies, Frontiers in Public Health. Available at: https://pubmed.ncbi.nlm.nih.gov/39606063/.

[268] Carré, J. et al., 2017. *Does air pollution play a role in infertility?: a systematic review*, Environmental Health. Available at: https://pubmed.ncbi.nlm.nih.gov/28754128/.

[269] Papadiochou, A. et al., 2024, *Impact of climate change on reproductive health and pregnancy outcomes: a systematic review*, Cureus. Available at: https://pubmed.ncbi.nlm.nih.gov/39347228/.

[270] Desye, B. et al., 2024, Exposure to ambient air pollutions and its association with adverse birth outcomes: a systematic review and meta-analysis of epidemiological studies, Frontiers in Public Health. Available at: https://pubmed.ncbi.nlm.nih.gov/39606063/.

increase risk of missed abortion, whereas stillbirth findings are less consistent and warrant further standardised investigation[271 272 273].

The evidence suggests that maternal exposure to particulate matter is associated with an increased risk of certain congenital anomalies or physical abnormalities that develop during pregnancy and are present at birth. Early pregnancy, particularly between 5 and 10 weeks of gestation, appears to be a sensitive period for facial development. Some studies have also identified potential risks associated with exposure before conception[274]. A large study that combined results from many studies found that women exposed to higher levels of $PM_{2.5}$ air pollution during the early stages of pregnancy were about 27–29% more likely to have a baby born with a cleft lip or cleft palate. A smaller increase in risk was also observed for PM_{10} in relation to cleft lip. However, another meta-analysis focusing on PM_{10} exposure during early pregnancy found no overall association with cleft lip (with or without cleft palate) or cleft palate. The authors were unable to assess $PM_{2.5}$ due to inconsistent reporting across studies. These findings highlight the variability of results across different studies and settings[275].

Beyond orofacial outcomes, regional evidence from China and Taiwan indicates consistent associations between PM_{10} exposure and congenital heart defects, with a 35% higher likelihood, particularly stronger for specific conditions such as septal defects, great artery abnormalities, and patent ductus arteriosus. In contrast, findings for birth weight outcomes in the same settings were more mixed[276]. A qualitative multi-country review also reported that high first-trimester $PM_{2.5}$, including during wildfire smoke or very poor air-quality days, was associated with birth defects, highlighting that episodes of high exposure may be particularly relevant[277]. Looking earlier in time, a synthesis of preconception exposure found that PM_{10} in the three months before conception was associated with a 6% higher risk of birth defects, whereas the pooled estimate for $PM_{2.5}$ was not statistically significant, again reflecting variability by pollutant fraction and exposure window[278].

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[271] Carré, J. et al., 2017, *Does air pollution play a role in infertility? a systematic review*, Environmental Health, Vol. 16. Available at: https://pubmed.ncbi.nlm.nih.gov/28754128/.

[272] Papadiochou, A. et al., 2024, *Impact of climate change on reproductive health and pregnancy outcomes: a systematic review*, Cureus. Available at: https://pubmed.ncbi.nlm.nih.gov/39347228/.

[273] Desye, B. et al., 2024, Exposure to ambient air pollutions and its association with adverse birth outcomes: a systematic review and meta-analysis of epidemiological studies, Frontiers in Public Health. Available at: https://pubmed.ncbi.nlm.nih.gov/39606063/.

[274] Huang, Z. et al., 2023, *Association between gestational exposure and risk of orofacial clefts: a systematic review and meta-analysis*, BMC Pregnancy and Childbirth. Available at: https://pubmed.ncbi.nlm.nih.gov/38041018/.

[275] Rao, A., et al., 2016, The correlation between maternal exposure to air pollution and the risk of orofacial clefts in infants: a systematic review and meta-analysis, Journal of Oral and Maxillofacial Research. Available at: https://pmc.ncbi.nlm.nih.gov/articles/PMC4837606/.

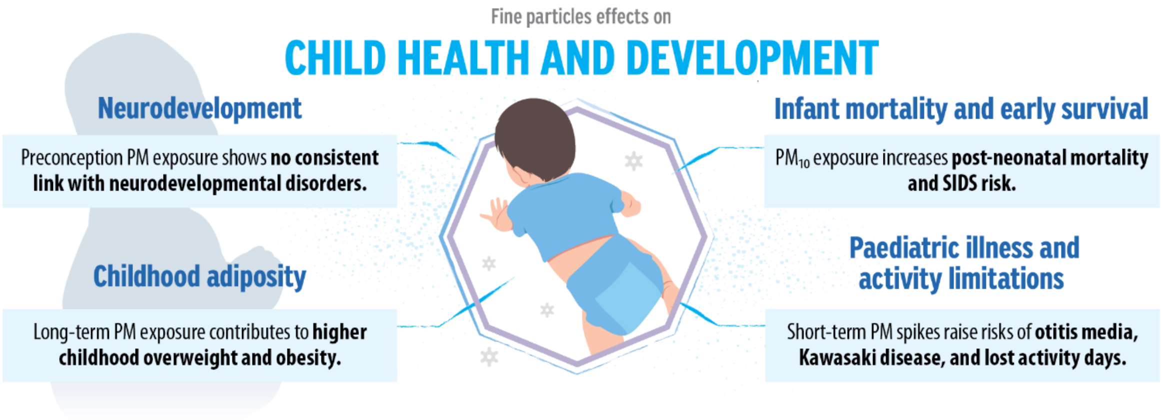
[276] Hwang, B.F. and Jaakkola, J.J.K., 2008, Air pollution and risk of cardiac defects: a population-based case-control study, Taiwanese newborns 2001–2007, Medicine (Baltimore). Available at: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4915884/.

[277] Papadiochou, A. et al., 2024, *Impact of climate change on reproductive health and pregnancy outcomes: a systematic review*, Cureus. Available at: https://pubmed.ncbi.nlm.nih.gov/39347228/.

[278] Blanc, N. et al., 2023, *A systematic review of evidence for maternal preconception exposure to outdoor air pollution on children's health*, Environmental Pollution. Available at: https://doi.org/10.1016/j.envpol.2022.120850.

2.1.11. Child health and development

Figure 10: Child health and development



Source: Authors' own elaboration.

Particulate matter exposure is linked to several adverse outcomes for child health and development, with the strongest and most consistent signals for PM_{10} in infant mortality, positive associations for both $PM_{2.5}$ and PM_{10} in childhood adiposity. Short-term increases in particulate matter exposure were also linked to small increases in selected paediatric conditions and activity limitations. In contrast, evidence on neurodevelopmental outcomes related to preconception exposure is generally non-significant in pooled analyses[279] [280] [281] [282] [283] [284] [285].

A global meta-analysis found that **short-term PM_{10} exposure was associated with higher post-neonatal all-cause mortality** (per 10µg/m^3), and that long-term PM_{10} exposure was linked to respiratory post-neonatal mortality and sudden infant death syndrome (SIDS), whereas pooled estimates for $PM_{2.5}$ (e.g., respiratory mortality, SIDS) were not statistically significant, reflecting heterogeneity in exposure windows and designs[286]. Region-specific evidence from China and Taiwan on perinatal mortality is limited and mixed, though one cohort reported higher peri-neonate death with late-pregnancy PM_{10} exposure[287].

[279] Kihal-Talantikite, W. et al., 2020, *Infant mortality related to NO_2 and PM exposure: systematic review and meta-analysis*, International Journal of Environmental Research and Public Health. Available at: https://pubmed.ncbi.nlm.nih.gov/32290393/.

[280] Qiao, J.-C. et al., 2025, Association between ambient air pollution exposure and pregnancy outcomes in women treated with assisted reproductive technology: an updated systematic review and meta-analysis, BMC Public Health. Available at: https://pmc.ncbi.nlm.nih.gov/articles/PMC12046897/.

[281] Fu, L. et al., 2019, The associations of air pollution exposure during pregnancy with fetal growth and anthropometric measurements at birth: a systematic review and meta-analysis, Environmental Science and Pollution Research. Available at: https://pubmed.ncbi.nlm.nih.gov/31111384/.

[282] Latifi, A.M. et al., 2026, Association between long-term and short-term exposure to outdoor air pollution and stillbirth: a systematic review and meta-analysis, BMC Pregnancy and Childbirth. Available at: https://link.springer.com/article/10.1186/s12884-026-09032-1.

[283] Fussell, J.C. et al., 2023, *Ambient air pollution and adverse birth outcomes: A review of underlying mechanisms*, BJOG: An International Journal of Obstetrics and Gynaecology. Available at: https://pubmed.ncbi.nlm.nih.gov/38037459/.

[284] Latifi, A.M. et al., 2026, Association between long-term and short-term exposure to outdoor air pollution and stillbirth: a systematic review and meta-analysis, BMC Pregnancy and Childbirth. Available at: https://link.springer.com/article/10.1186/s12884-026-09032-1.

[285] Blanc, N. et al., 2023, *A systematic review of evidence for maternal preconception exposure to outdoor air pollution on children's health*, Environmental Pollution. Available at: https://doi.org/10.1016/j.envpol.2022.120850.

[286] Kihal-Talantikite, W. et al., 2020, *Infant mortality related to NO_2 and PM exposure: systematic review and meta-analysis*, International Journal of Environmental Research and Public Health. Available at: https://pubmed.ncbi.nlm.nih.gov/32290393/.

[287] Hwang, B.F. and Jaakkola, J.J.K., 2008, Air pollution and risk of cardiac defects: a population-based case-control study, Taiwanese newborns 2001–2007, Medicine (Baltimore). Available at: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4915884/.

For preconception exposure, a bi-national systematic review and meta-analysis reported that **pooled associations with autism spectrum disorder (ASD) were generally non-significant**, despite small positive signals in some individual $PM_{2.5}$ studies, indicating the need for improved exposure assessment and time-window resolution[288].

Two meta-analyses reported a higher likelihood of childhood overweight and obesity associated with exposure to both $PM_{2.5}$ and PM_{10}. **One analysis of 15 studies found relatively larger effects, corresponding to around a 28% higher likelihood of $PM_{2.5}$ and around a 12% higher likelihood for PM_{10} per 10µg/m³ increase**. A second analysis of eight studies reported more modest increases of around 6–7% for both pollutants. These findings were accompanied by small increases in BMI per 10µg/m³, although results showed substantial variation between studies, particularly for PM_{10}. Overall, this suggests that long-term particulate matter exposure contributes to higher childhood adiposity, while the magnitude of effects varies depending on the context and study design[289][290].

$PM_{2.5}$ and PM_{10} are also linked with other child-related outcomes. Short-term rises in both PM's were associated with **more restricted activity days** (e.g., school loss days), indicating a modest but consistent burden on daily functioning in children and the wider population[291]. For **otitis media, an ear infection most commonly experienced by young children**, pooled analyses showed that **short-term increases in $PM_{2.5}$ and PM_{10} shortly before onset were associated with higher incidence**, with the strongest association in children aged 0–2 years for $PM_{2.5}$, while absolute background levels were less informative than day-to-day increases[292]. For **Kawasaki disease**, risk increased with short-term postnatal exposure to $PM_{2.5}$ and PM_{10} and was substantially higher with long-term $PM_{2.5}$ exposure, whereas evidence for prenatal exposure was too limited for pooling, and individual studies were often positive but nonsignificant[293].

[288] Blanc, N. et al., 2023, *A systematic review of evidence for maternal preconception exposure to outdoor air pollution on children's health*, Environmental Pollution. Available at: https://doi.org/10.1016/j.envpol.2022.120850.

[289] Qiao, J.-C. et al., 2025, Association between ambient air pollution exposure and pregnancy outcomes in women treated with assisted reproductive technology: an updated systematic review and meta-analysis, BMC Public Health. Available at: https://pmc.ncbi.nlm.nih.gov/articles/PMC12046897/.

[290] Fu, L. et al., 2019, The associations of air pollution exposure during pregnancy with fetal growth and anthropometric measurements at birth: a systematic review and meta-analysis, Environmental Science and Pollution Research. Available at: https://pubmed.ncbi.nlm.nih.gov/31111384/.

[291] Latifi, A.M. et al., 2026, Association between long-term and short-term exposure to outdoor air pollution and stillbirth: a systematic review and meta-analysis, BMC Pregnancy and Childbirth. Available at: https://link.springer.com/article/10.1186/s12884-026-09032-1.

[292] Fussell, J.C. et al., 2023, *Ambient air pollution and adverse birth outcomes: A review of underlying mechanisms*, BJOG: An International Journal of Obstetrics and Gynaecology. Available at: https://pubmed.ncbi.nlm.nih.gov/38037459/.

[293] Latifi, A.M. et al., 2026, Association between long-term and short-term exposure to outdoor air pollution and stillbirth: a systematic review and meta-analysis, BMC Pregnancy and Childbirth. Available at: https://link.springer.com/article/10.1186/s12884-026-09032-1.

2.2. Impacts on vulnerable and high-risk populations

KEY FINDINGS

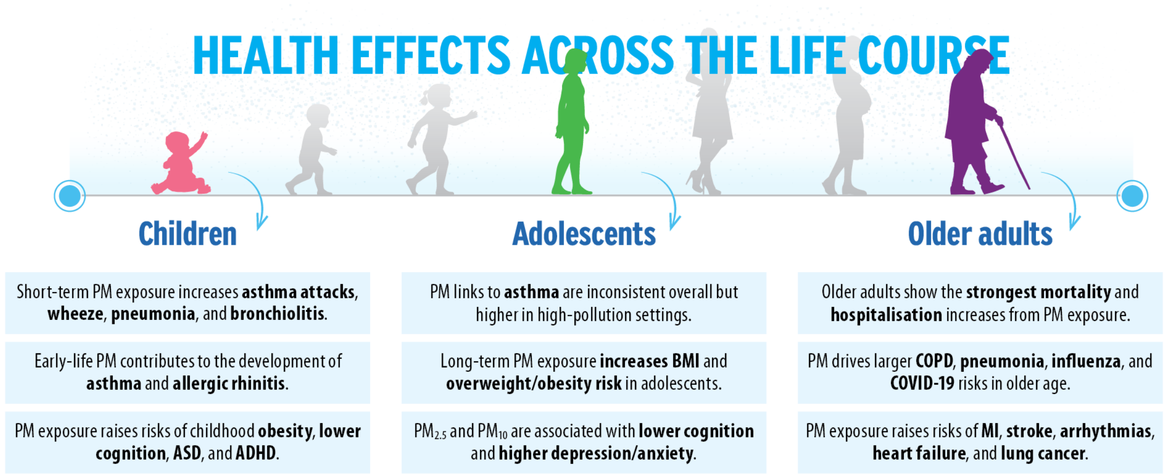
The health impacts of particulate matter are not evenly distributed across the population. Evidence consistently shows that children, older adults, individuals with pre-existing health conditions, and socioeconomically disadvantaged groups are more vulnerable to its effects. This increased susceptibility reflects a combination of biological factors, underlying health status, and, in some cases, higher levels of exposure.

Children are among the most sensitive groups, with evidence linking particulate matter exposure to respiratory illnesses, impaired lung development, and adverse effects on cognitive and neurological development. Older adults face elevated risks of hospitalisation, disease progression, and premature mortality, particularly from cardiovascular and respiratory conditions. Individuals with existing health conditions are also more likely to experience acute health events and worsening disease following exposure.

Socioeconomically disadvantaged populations often face a double burden of greater exposure and increased vulnerability, although the extent of these effects varies across locations and contexts. Across all groups, the evidence points in the same direction: exposure to particulate matter is associated with adverse health outcomes, with $PM_{2.5}$ generally showing stronger and more consistent effects than PM_{10}.

2.2.1. Health effects across the life course

Figure 11: Health effects across the life course



Source: Authors' own elaboration.

Across the reviewed literature, susceptibility to the adverse health effects of particulate matter varies across the life course. **Children, adolescents, and older adults consistently emerge as populations with elevated vulnerability** due to physiological, developmental, and clinical factors that influence how the body absorbs, processes, and responds to particulate matter. These groups not only experience higher pollutant dose per body weight but may also have underlying biological or clinical characteristics that heighten the impact of $PM_{2.5}$ and PM_{10} on key organ systems.

Children

Children are repeatedly identified as one of the most sensitive groups to particulate pollution across multiple health domains. Within the respiratory literature, **short-term $PM_{2.5}$ and PM_{10} exposures lead to higher risks of asthma exacerbations, wheeze, pneumonia, influenza, and bronchiolitis hospitalisations, with effects typically larger in magnitude than in adults**[294] [295] [296] [297] [298]. Children with underlying asthma show particularly pronounced reductions in lung function in response to particulate exposure, including measurable decreases in peak expiratory flow, forced expiratory volume in one second (FEV_1), and forced vital capacity (FVC)[299] [300].

Early-life exposure also influences disease development. **Evidence from traffic-related air pollution shows that long-term $PM_{2.5}$ and PM_{10} exposure contributes to the onset of childhood asthma[301]**, and early-life PM exposure is associated with increased risk of allergic rhinitis in several settings[302]. Among infants, particulate matter contributes to vulnerability to acute viral lower-respiratory infections, including bronchiolitis, where both $PM_{2.5}$ and PM_{10} increase the likelihood of hospitalisation[303] [304].

Beyond respiratory outcomes, broader reviews indicate that childhood exposure to particulate matter is associated with increased adiposity and obesity risk, based on pooled evidence from large international cohorts[305] [306]. Neurodevelopmental outcomes likewise point to heightened sensitivity during prenatal and early-life windows, with consistent associations between early $PM_{2.5}$ exposure,

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294 Sun, R. et al., 2024, *Air pollution and influenza: a systematic review and meta-analysis*, Iranian Journal of Public Health, Vol. 53(1), pp. 1–11. Available at: https://pubmed.ncbi.nlm.nih.gov/38694869/.

295 Comotti, A. et al., 2025, *Air pollution and hospitalization risk in infants with bronchiolitis: a systematic review and meta-analysis*, Pediatric Allergy and Immunology, Vol. 36(5). Available at: https://pubmed.ncbi.nlm.nih.gov/40358039/.

296 J Huang, J., Yang, X., Fan, F., Hu, Y., Wang, X., Zhu, S., Ren, G., Wang, G., 2022. *Outdoor air pollution and the risk of asthma exacerbations in single lag0 and lag1 exposure patterns: a systematic review and meta-analysis*, Journal of Asthma. Available at: https://pubmed.ncbi.nlm.nih.gov/34809505/.

297 Lim, H. et al., 2016, Short-term effect of fine particulate matter on children's hospital admissions and emergency department visits for asthma: a systematic review and meta-analysis. Available at: https://pubmed.ncbi.nlm.nih.gov/27499163/.

298 Yee, J. et al., 2021, *Short-term exposure to air pollution and hospital admission for pneumonia: a systematic review and meta-analysis*, Environmental Health, Vol. 20(1). Available at: https://pubmed.ncbi.nlm.nih.gov/33413431/.

299 Zhang, Y., Guo, Z., Zhang, W., Li, Q., Zhao, Y., Wang, Z., Luo, Z., 2023. *Effect of acute PM2.5 exposure on lung function in children: a systematic review and meta-analysis*, Journal of Asthma and Allergy. Available at: https://pubmed.ncbi.nlm.nih.gov/37193111/.

300 Gudziunaite, S., Mackintosh, K.A., Davies, G.A., Jordan, K.A., Lewis, P.D., Griffiths, C.J., Swain, T.A., McNarry, M.A., 2025. *Global Trends in the Relationship Between Chronic Air Pollution Exposure, Physical Activity and Lung Function in Youth Aged 5–18 Years With and Without Asthma: A Systematic Review*, Sports Medicine – Open. Available at: https://pubmed.ncbi.nlm.nih.gov/40399510/.

301 Khreis, H., Kelly, C., Tate, J., Parslow, R., Lucas, K., Nieuwenhuijsen, M., 2017, *Exposure to traffic-related air pollution and risk of development of childhood asthma: a systematic review and meta-analysis*, Environment International. Available at: https://pubmed.ncbi.nlm.nih.gov/27881237/.

302 Liu, L., Ma, J., Peng, S., Xie, L., 2023, Prenatal and early-life exposure to traffic-related air pollution and allergic rhinitis in children: A systematic literature review, PLOS ONE. Available at: https://pubmed.ncbi.nlm.nih.gov/37079576/.

303 Comotti, A. et al., 2025, *Air pollution and hospitalization risk in infants with bronchiolitis: a systematic review and meta-analysis*, Pediatric Allergy and Immunology, Vol. 36(5). Available at: https://pubmed.ncbi.nlm.nih.gov/40358039/.

304 King, C. et al., 2018, *The effect of outdoor air pollution on the risk of hospitalisation for bronchiolitis in infants: a systematic review*, PeerJ. Available at: https://pubmed.ncbi.nlm.nih.gov/30186673/.

305 Huang, C. et al., 2022, *The association between childhood exposure to ambient air pollution and obesity: a systematic review and meta-analysis*, International Journal of Environmental Research and Public Health. Available at: https://pubmed.ncbi.nlm.nih.gov/35457358/.

306 Parasin, N. et al., 2021, *Effect of Air Pollution on Obesity in Children: A Systematic Review and Meta-Analysis*, Children (Basel). Available at: https://pubmed.ncbi.nlm.nih.gov/33922616/.

lower cognitive performance, and increased risk of neurodevelopmental conditions such as autism spectrum disorder (ASD) and attention-deficit/hyperactivity disorder (ADHD)[307] [308] [309].

Together, these findings show that particulate pollution affects multiple child health domains, with both acute and chronic consequences influenced by rapid growth, higher inhalation rates, and developing organ systems.

Adolescents

The evidence base for adolescents is smaller than for children or older adults but indicates age-specific patterns of susceptibility. **For asthma, pooled evidence suggests that long-term $PM_{2.5}$ and PM_{10} exposure is not consistently associated with asthma prevalence in adolescents**, although several individual studies report elevated risks in high-pollution settings[310]. By contrast, evidence for adiposity and metabolic outcomes appears more consistent. Long-term particulate matter exposure is associated with higher BMI and a greater likelihood of overweight and obesity in adolescents, with increases of around 6–28% per 10µg/m^3 [311] [312].

Neurodevelopmental findings also suggest vulnerability during adolescence, with reviews identifying lower cognitive performance, memory impairment, and structural changes in brain regions critical for learning and emotional regulation in relation to $PM_{2.5}$ and PM_{10} exposure[313]. Some evidence further indicates **heightened risk of mental-health outcomes, including depression and anxiety, linked to long-term $PM_{2.5}$ exposure** in older adolescents[314] [315].

Although the overall evidence is less extensive than for younger children, the studies available indicate that adolescence represents a period of ongoing neurobiological and physiological development during which $PM_{2.5}$ and PM_{10} may exert adverse effects, particularly on mental health, cognitive function, and metabolic outcomes.

Older adults

Older adults consistently rank among the most affected population groups across nearly all health domains. Age-related declines in cardiovascular, respiratory, metabolic, and neurological function

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[307] Alter, N.C. et al., 2024, *Quantifying the association between PM2.5 air pollution and IQ loss in children: a systematic review and meta-analysis*, Environmental Health. Available at: https://pubmed.ncbi.nlm.nih.gov/39551729/.

[308] Lam, J. et al., 2016, *A Systematic Review and Meta-Analysis of Multiple Airborne Pollutants and Autism Spectrum Disorder*, PLOS ONE. Available at: https://pubmed.ncbi.nlm.nih.gov/27653281/.

[309] Ahmad, S. et al., 2024, Association Between Ambient Air Pollution and Attention-Deficit/Hyperactivity Disorder (ADHD) in Children: A Systematic Review and Meta-Analysis, Cureus. Available at: https://pubmed.ncbi.nlm.nih.gov/39544605/.

[310] Shi, W. et al., 2025, *Outdoor air pollutants and asthma risk in adolescents: evidence from a systematic review and meta-analysis*, Frontiers in Public Health. Available at: https://pmc.ncbi.nlm.nih.gov/articles/PMC12727952/.

[311] Qiao, J.-C. et al., 2025, Association between ambient air pollution exposure and pregnancy outcomes in women treated with assisted reproductive technology: an updated systematic review and meta-analysis, BMC Public Health. Available at: https://pmc.ncbi.nlm.nih.gov/articles/PMC12046897/.

[312] Siewert, B. et al., 2024, *Examining the link between air quality (PM, SO_2, NO_2, PAHs) and childhood obesity: A systematic review*, Journal of Clinical Medicine, Vol. 13(18). Available at: https://pubmed.ncbi.nlm.nih.gov/39337093/.

[313] Chandra, M. et al., 2022, Air pollution and cognitive impairment across the life course in humans: A systematic review with specific focus on income level of study area, International Journal of Environmental Research and Public Health, Vol. 19(3), Article 1405. Available at: https://pubmed.ncbi.nlm.nih.gov/35162428/.

[314] Braithwaite, I. et al., 2019, Air Pollution (Particulate Matter) Exposure and Associations with Depression, Anxiety, Bipolar, Psychosis and Suicide Risk: A Systematic Review and Meta-Analysis, Environmental Health Perspectives, Vol. 127(12), Article 126002. Available at: https://pubmed.ncbi.nlm.nih.gov/31850801/.

[315] Borroni, E. et al., 2022, *Air pollution exposure and depression: a comprehensive updated systematic review and meta-analysis*, Environmental Pollution, Vol. 292(Pt A). Available at: https://pubmed.ncbi.nlm.nih.gov/34600062/.

appear to amplify the effects of particulate exposure, contributing to higher relative risks of hospitalisation, mortality, and exacerbation of chronic disease.

Evidence from all-cause mortality studies shows stronger associations in older adults compared with younger populations, with elevated risks even at low or moderate $PM_{2.5}$ concentrations. Large analyses from China indicate that day-to-day increases in particulate levels contribute to measurable rises in mortality, with older adults showing particularly heightened susceptibility[316]. Short-term $PM_{2.5}$ and PM_{10} exposure also increases health-service utilisation among adults with multiple chronic conditions: multimorbidity reviews report elevated rates of stroke-related hospital attendance among hypertensive adults with diabetes and increased hospital visits among those with respiratory or cardiovascular multimorbidity[317].

Respiratory evidence similarly identifies older adults as a high-risk group. **Studies of COPD exacerbations show the largest PM-related increases in hospitalisations among those aged 65 and above**[318], and pneumonia and influenza reviews consistently document larger effect sizes in older adults compared with younger populations[319] [320]. For infectious diseases such as COVID-19, where $PM_{2.5}$ exposure increases incidence, severity, and mortality, older age is repeatedly identified as a key modifier of risk[321] [322] [323] [324].

Across cardiovascular outcomes, including myocardial infarction, stroke, arrhythmias, and heart failure, older adults again show higher vulnerability, with reviews consistently reporting larger relative risks in older age groups[325] [326] [327].

Taken together, the evidence demonstrates that older adults experience greater absolute and relative health impacts from particulate matter exposure. Age-related physiological changes, the higher prevalence of multimorbidity, and cumulative lifetime exposure are likely to contribute to this increased vulnerability across multiple health systems.

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316 Zhao, L. et al., 2017, *Association between air pollution and cardiovascular mortality in China: a systematic review and meta-analysis*, Oncotarget. Available at: https://pubmed.ncbi.nlm.nih.gov/29029525/.

317 Hassan, N., Mohamed, L., Wilson, S., Tolley, C., Ahmed, A., Baxter, C., Slight, R., Namdeo, A., Slight, S.P., 2025. *The impact of poor air quality on hospital attendance of multimorbid patients*, Frontiers in Medicine. Available at: https://pubmed.ncbi.nlm.nih.gov/41574384/.

318 Delavar, M. et al., 2023, Relationship between fine particulate matter (PM2.5) concentration and risk of hospitalization due to chronic obstructive pulmonary disease: a systematic review and meta-analysis, BMC Public Health, Vol. 23(1). Available at: https://pubmed.ncbi.nlm.nih.gov/37953239/.

319 Yee, J. et al., 2021, *Short-term exposure to air pollution and hospital admission for pneumonia: a systematic review and meta-analysis*, Environmental Health, Vol. 20(1). Available at: https://pubmed.ncbi.nlm.nih.gov/33413431/.

320 Sun, R. et al., 2024, *Air pollution and influenza: a systematic review and meta-analysis*, Iranian Journal of Public Health, Vol. 53(1), pp. 1–11. Available at: https://pubmed.ncbi.nlm.nih.gov/38694869/.

321 Katoto, P.D.M.C. et al., 2021, Acute and chronic exposure to air pollution in relation with incidence, prevalence, severity and mortality of COVID-19: a rapid systematic review, Environmental Health. Available at: https://pubmed.ncbi.nlm.nih.gov/33838685/.

322 Hernandez Carballo, I. et al., 2022, The impact of air pollution on COVID-19 incidence, severity, and mortality: a systematic review of studies in Europe and North America, Environmental Research, Vol. 215. Available at: https://pubmed.ncbi.nlm.nih.gov/36030916/.

323 Katoto, P.D.M.C. et al., 2021, Acute and chronic exposure to air pollution in relation with incidence, prevalence, severity and mortality of COVID-19: a rapid systematic review, Environmental Health. Available at: https://pubmed.ncbi.nlm.nih.gov/33838685/.

324 Podury, S. et al., 2023, *Severe Acute Respiratory Syndrome and Particulate Matter Exposure: A Systematic Review*, Life (Basel). Available at: https://pubmed.ncbi.nlm.nih.gov/36836898/.

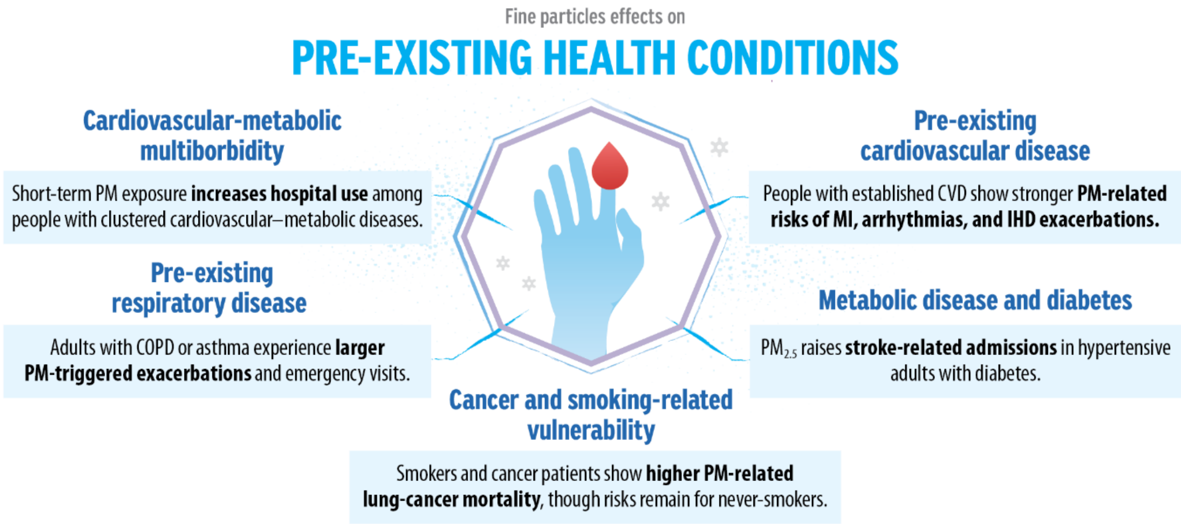
325 Toubasi, A. and Al-Sayegh, T., 2023, *Short-term exposure to air pollution and ischemic stroke: A systematic review and meta-analysis*, Neurology, Vol. 101(19), pp. e1922–e1932. Available at: https://pubmed.ncbi.nlm.nih.gov/37758483/.

326 Ab Manan, N. et al., 2018, *Effect of air pollution and hospital admission: A systematic review*, Annals of Global Health, Vol. 84(4), pp. 670–678. Available at: https://pubmed.ncbi.nlm.nih.gov/30779516/.

327 Zhao, K. et al., 2021, Ambient fine particulate matter of diameter ≤ 2.5 µm and risk of hemorrhagic stroke: a systemic review and meta-analysis of cohort studies, Environmental Science and Pollution Research International. Available at: https://pubmed.ncbi.nlm.nih.gov/33694113/.

2.2.2. People with pre-existing health conditions

Figure 12: People with pre-existing health conditions



Source: Authors' own elaboration.

Across the evidence base, **individuals with pre-existing health conditions consistently exhibit higher susceptibility to the adverse effects of particulate matter**. This increased vulnerability reflects pre-existing impairments in cardiovascular, respiratory, metabolic, and neurological systems, which are further stressed by both short- and long-term exposure to $PM_{2.5}$ and PM_{10}. Evidence from multimorbidity analyses, disease-specific reviews, and age-stratified meta-analyses indicates that people living with chronic cardiometabolic, respiratory, and other systemic conditions experience greater relative and absolute health impacts from particulate matter than healthier populations.

Cardiovascular and metabolic multimorbidity

Across multiple large reviews, individuals with multimorbidity, particularly combinations of cardiovascular and metabolic diseases, show pronounced vulnerability to particulate pollution. Evidence from 19 retrospective studies indicates that short-term exposure to $PM_{2.5}$ and PM_{10} is consistently associated with increased hospital attendance among adults with multiple chronic diseases, including those with ischaemic heart disease (IHD), heart failure, hypertension, and diabetes[328]. **Among multimorbid adults, a 10µg/m³ rise in $PM_{2.5}$ increased hospital attendance by 2.5%** for patients with concurrent IHD and heart failure, and short-term particulate exposure was also linked with emergency visits for arrhythmias and blood-pressure instability. **These effects were stronger among older adults, women, and those with multiple chronic conditions, underscoring the compounding impact of disease clustering**[329].

Long-term exposure contributes to disease onset in high-risk groups. A meta-analysis of 39 cohort studies found that **each 10µg/m³ increase in $PM_{2.5}$ was associated with a 16% higher risk** of incident cardiovascular disease, including hypertension and atrial fibrillation, while PM_{10} showed a positive but

[328] Hassan, N. et al., 2026, *The impact of poor air quality on hospital attendance of multimorbid patients*, Frontiers in Medicine, Vol. 12. Available at: https://pubmed.ncbi.nlm.nih.gov/41574384/.

[329] Ibid.

statistically non-significant trend[330]. Stronger effects were observed among adults aged >65 years and during colder temperatures, suggesting that individuals with pre-existing blood-pressure or cardiac rhythm disorders are particularly vulnerable to both the direct and indirect consequences of particulate exposure[331].

Susceptibility may also reflect interactions between air pollution and beneficial lifestyle behaviours. **Evidence indicates that higher $PM_{2.5}$ concentrations can attenuate the cardiovascular benefits of outdoor physical activity, meaning that individuals with underlying cardiovascular or metabolic conditions may experience reduced protective effects from exercise in polluted environments**[332]. This does not negate the benefits of physical activity but highlights the need for lower pollution levels to maximise health gains in these populations.

Pre-existing cardiovascular disease

Across reviews, individuals with established cardiovascular conditions, including ischaemic heart disease, heart failure, stroke history, and arrhythmias, experience stronger associations between particulate matter and acute cardiac outcomes than the general population. **Evidence consistently shows that older adults and individuals with CVD exhibit higher relative risks of MI and IHD exacerbations following short-term $PM_{2.5}$ and PM_{10} exposure**, with several reviews identifying $PM_{2.5}$ as the pollutant most consistently associated with MI outcomes[333].

Short-term exposure acts as a physiological trigger. Among multimorbid adults, short-term elevations in $PM_{2.5}$ and PM_{10} were linked with increased hospital attendance for acute MI and IHD, with risks amplified in those with combinations of cardiovascular and metabolic conditions[334]. These findings align with broader evidence that particulate exposure disrupts autonomic control, induces vascular stress, and increases coagulability, contributing to both arrhythmic and ischaemic events. Stronger associations among older adults and during colder temperatures further support temperature-pollution interactions affecting people with existing cardiovascular fragility[335]. Long-term exposures also accelerate disease progression. **Chronic $PM_{2.5}$ exposure contributes to the development of early-stage** cardiovascular conditions, hypertension, atrial fibrillation, and other arrhythmias, which may subsequently heighten sensitivity to short-term pollution episodes[336].

Therefore, the evidence demonstrates that individuals with established cardiovascular disease exhibit both greater susceptibility to acute particulate-triggered events and increased longer-term disease progression risks.

[330] Brown, J. et al., 2025, Impact of neighbourhood and environmental factors on the risk of incident cardiovascular disease: a systematic review and meta-analysis, European Journal of Preventive Cardiology, Vol. 32(18), pp. 1903–1912. Available at: https://pubmed.ncbi.nlm.nih.gov/40106665/.

[331] Zhao, L. et al., 2017, *Association between air pollution and cardiovascular mortality in China: a systematic review and meta-analysis*, Oncotarget, Vol. 8(39), pp. 66438–66448. Available at: https://pubmed.ncbi.nlm.nih.gov/29029525/.

[332] Gandhi, T. et al., 2022, *Outdoor Physical Activity in an Air Polluted Environment and Its Effect on the Cardiovascular System – A Systematic Review*, International Journal of Environmental Research and Public Health, Vol. 19(17). Available at: https://pubmed.ncbi.nlm.nih.gov/36078268/.

[333] Ndlovu, N. and Nkeh-Chungag, B., 2024, *Impact of Indoor Air Pollutants on the Cardiovascular Health Outcomes of Older Adults: Systematic Review*, Clinical Interventions in Aging, Vol. 19, pp. 1629–1639. Available at: https://pubmed.ncbi.nlm.nih.gov/39372166/.

[334] Hassan, N. et al., 2026, *The impact of poor air quality on hospital attendance of multimorbid patients*, Frontiers in Medicine, Vol. 12. Available at: https://pubmed.ncbi.nlm.nih.gov/41574384/.

[335] Zhao, L. et al., 2017, *Association between air pollution and cardiovascular mortality in China: a systematic review and meta-analysis*, Oncotarget, Vol. 8(39), pp. 66438–66448. Available at: https://pubmed.ncbi.nlm.nih.gov/29029525/.

[336] Brown, J. et al., 2025, Impact of neighbourhood and environmental factors on the risk of incident cardiovascular disease: a systematic review and meta-analysis, European Journal of Preventive Cardiology, Vol. 32(18), pp. 1903–1912. Available at: https://pubmed.ncbi.nlm.nih.gov/40106665/.

Pre-existing respiratory disease

People with chronic respiratory conditions, including asthma, COPD, and bronchiectasis, consistently show higher susceptibility to particulate pollution. **Short-term $PM_{2.5}$ exposure increases emergency attendance and disease severity in individuals with COPD and chronic respiratory multimorbidity, often at higher magnitudes than population-wide pooled estimates**[337 338].

For asthma, while children show the largest effect sizes, adults with pre-existing asthma also experience higher risks of acute exacerbation, often within hours of exposure to $PM_{2.5}$ or PM_{10} [339 340]. In addition, as stated earlier, those with underlying asthma show pronounced reductions in lung function in response to particulate exposure, such as measurable decreases in peak expiratory flow, FEV_1, FVC[341 342].

Pre-existing metabolic disease and diabetes

Adults with diabetes or cardiometabolic multimorbidity demonstrate heightened risk during short-term pollution episodes. **Evidence shows that short-term $PM_{2.5}$ exposure increases stroke-related admissions among hypertensive adults with diabetes by 0.14–0.72% in the following two days**, reflecting reduced vascular resilience in this group. Multimorbidity analyses consistently identify higher hospital attendance among adults with combined cardiovascular and metabolic diagnoses, including diabetes with heart failure, hypertension, or arrhythmias[343].

These combined findings suggest that particulate matter contributes to both the development of metabolic disease and the acute destabilisation of metabolic–cardiovascular systems among individuals already living with chronic conditions.

Cancer patients and people with smoking histories

Several reviews highlight heightened particulate-related risks among individuals with prior smoking exposure or existing cancer pathology. Studies examining $PM_{2.5}$ and lung cancer outcomes indicate that older adults, men, and current or past smokers experience larger PM-related increases in lung cancer mortality, although positive associations remain present among never-smokers, suggesting an independent pollution effect[344 345].

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[337] Li, N. et al., 2022, Association of PM2.5 and PM10 with acute exacerbation of chronic obstructive pulmonary disease at lag0 to lag7: A systematic review and meta-analysis, COPD, Vol. 19(1), pp. 243–254. Available at: https://pubmed.ncbi.nlm.nih.gov/35616887/.

[338] Ab Manan, N. et al., 2018, *Effect of air pollution and hospital admission: A systematic review*, Annals of Global Health, Vol. 84(4), pp. 670–678. Available at: https://pubmed.ncbi.nlm.nih.gov/30779516/.

[339] Orellano, P. et al., 2017, *Effect of outdoor air pollution on asthma exacerbations in children and adults: Systematic review and multilevel meta-analysis*, PLoS One, Vol. 12(3), Article e0174050. Available at: https://pubmed.ncbi.nlm.nih.gov/28319180/.

[340] Wu, K. et al., 2022, A Systematic Review and Meta-Analysis of Intraday Effects of Ambient Air Pollution and Temperature on Cardiorespiratory Morbidities: First Few Hours of Exposure Matters to Life, EBioMedicine, Vol. 86. Available at: https://pubmed.ncbi.nlm.nih.gov/36323182/.

[341] Zhang, Y., Guo, Z., Zhang, W., Li, Q., Zhao, Y., Wang, Z., Luo, Z., 2023. *Effect of acute PM2.5 exposure on lung function in children: a systematic review and meta-analysis*, Journal of Asthma and Allergy. Available at: https://pubmed.ncbi.nlm.nih.gov/37193111/.

[342] Gudziunaite, S., Mackintosh, K.A., Davies, G.A., Jordan, K.A., Lewis, P.D., Griffiths, C.J., Swain, T.A., McNarry, M.A., 2025. *Global Trends in the Relationship Between Chronic Air Pollution Exposure, Physical Activity and Lung Function in Youth Aged 5–18 Years With and Without Asthma: A Systematic Review*, Sports Medicine – Open. Available at: https://pubmed.ncbi.nlm.nih.gov/40399510/.

[343] Hassan, N. et al., 2026, *The impact of poor air quality on hospital attendance of multimorbid patients*, Frontiers in Medicine, Vol. 12. Available at: https://pubmed.ncbi.nlm.nih.gov/41574384/.

[344] Huang, F. et al., 2017, *Relationship between exposure to PM2.5 and lung cancer incidence and mortality: A meta-analysis*, Oncotarget, Vol. 8(26), pp. 43322–43331. Available at: https://pubmed.ncbi.nlm.nih.gov/28487493/.

[345] Karimi, B. and Samadi, S., 2024, *Long-term exposure to air pollution on cardio-respiratory, and lung cancer mortality: a systematic review and meta-analysis*, Journal of Environmental Health Science and Engineering, Vol. 22(1), pp. 75–95. Available at: https://pubmed.ncbi.nlm.nih.gov/38887768/.

2.2.3. Socially or economically disadvantaged groups

Concerning air pollution, 'socially or economically disadvantaged groups' refers to populations living in less favourable environmental conditions, which often results in higher exposure to pollutants such as $PM_{2.5}$ and PM_{10} compared with more affluent groups[346]. The literature reviewed primarily identified adverse health effects among children living in socioeconomically disadvantaged circumstances, suggesting that higher exposure in these populations may contribute to a greater risk of negative health outcomes.

A systematic review of 33 studies found that **children living in socioeconomically disadvantaged settings were more likely to be exposed to higher concentrations of $PM_{2.5}$, PM_{10} and other air pollutants** and experience stronger pollution-related health effects, including increased obesity risk. Multiple studies reported that **children in high pollution, low-income regions showed consistently positive associations** between long-term exposure to $PM_{2.5}$ and PM_{10} and higher BMI z scores, greater waist circumference, and increased prevalence of both general and central obesity. By contrast, studies conducted in wealthier European settings with **lower background pollution levels** often reported weak or null associations, suggesting socioeconomic and environmental disparities amplify health risks. This review highlights that **urbanisation, limited access to healthy food, reduced availability of safe outdoor spaces, and lower health awareness** disproportionately affect lower socioeconomic groups and increase both pollution exposure and vulnerability to obesity related effects. No findings were reported for other health outcomes beyond childhood obesity[347].

However, if exposure is higher, it could be stated that this will increase the risk of experiencing health problems. Economically **disadvantaged settings were more likely to be exposed to higher concentrations of PM**-related health effects, including increased obesity risk. Multiple studies reported that **pollution and low-income regions showed consistently positive associations with long term exposure to PM-scores, greater waist circumference, and increased prevalence of both general and central obesity**. However, the strength of these associations may vary depending on the underlying concentration-response relationship and may also be influenced by factors such as healthcare access, the built environment, and other socioeconomic determinants. Economic and environmental disparities may therefore amplify health risks. The review highlights that economic groups experience both increased exposure to pollution and greater vulnerability to obesity-related effects. No findings were reported for other health outcomes beyond childhood obesity.

Overall, the evidence indicates that **socially and economically disadvantaged children face a dual risk of higher particulate-matter exposure and stronger associated health impacts**, reinforcing inequalities in environmental and metabolic health[348].

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[346] Fairburn, J. et al., 2019, *Social Inequalities in Exposure to Ambient Air Pollution: A Systematic Review in the WHO European Region*, International Journal of Environmental Research and Public Health, Vol. 16(17), Article 3127. Available at: https://pubmed.ncbi.nlm.nih.gov/31480294/.

[347] Siewert, B. et al., 2024, *Examining the link between air quality (PM, SO_2, NO_2, PAHs) and childhood obesity: A systematic review*, Journal of Clinical Medicine, Vol. 13(18). Available at: https://pubmed.ncbi.nlm.nih.gov/39337093/.

[348] Ibid.

3. TRENDS ACROSS THE EU

KEY FINDINGS

PM exposure has declined across the EU, but progress is uneven. Annual mean $PM_{2.5}$ decreased in all Member States between 2013 and 2023, with larger reductions in Northern and Western Europe (40–50%) and more limited progress in parts of Southern Europe (10–22%). PM_{10} shows a similar pattern, with Spain as the only Member State recording an increase.

Regional hotspots persist despite overall improvements. In 2023, a large majority of NUTS 2 regions still exceeded the WHO $PM_{2.5}$ guideline, with a smaller but significant share also above the 2030 EU limit, indicating that exposure remains geographically concentrated.

Health outcomes broadly follow exposure trends, but recent progress has diverged from them. While $PM_{2.5}$-attributable mortality declined in most Member States over the past decade, recent data (2021–2023) show stagnation or increases in several Southern European countries, in contrast to continued improvements in Northern and Baltic Member States.

The health burden is dominated by cardiovascular disease, but varies by country. Ischaemic heart disease and stroke account for the majority of $PM_{2.5}$-attributable burden, with country-specific patterns influenced by conditions such as diabetes, COPD, and childhood asthma.

Inequalities between and within Member States remain pronounced and, in some cases, are widening. Differences in health burden across countries, regions, age groups, and income levels persist, with higher exposure and mortality risks observed in disadvantaged populations and regions.

This chapter analyses trends in $PM_{2.5}$ and PM_{10} concentrations and the associated health impacts across EU Member States. It first sets out long-term developments in exposure levels (section 3.1), then mirrors these with trends in attributable deaths and burden of disease (section 3.2) and finally examines age-based and socioeconomic disparities (section 3.3). Throughout, results are benchmarked against the limit values under the revised Ambient Air Quality Directive (Directive (EU) 2024/2881) applicable from 1 January 2030 and the WHO 2021 health-based guidelines.

3.1. Trends in $PM_{2.5}$ and PM_{10} concentrations across Member States

KEY FINDINGS

$PM_{2.5}$ fell in every Member State between 2013 and 2023, while PM_{10} fell in every Member State except Spain. The pace of progress diverges sharply between Northern and Western Europe (40–50% reductions) and Mediterranean Europe (10–22%).

There are regional PM hotspots. In 2023, 90% of NUTS 2 regions exceeded the WHO $PM_{2.5}$ guideline of 5 µg/m³ and 25% exceed the 2030 AAQD limit value of 10 µg/m³. The Po Valley, the Silesian basin and the Balkans/South-Eastern area concentrate the EU's residual exposure problem.

Distance to the 2030 AAQD limit values is unequally distributed. Northern and Western Member States are at or close to compliance; Bulgaria, Poland, Italy, Greece, Cyprus and Malta face substantial remaining gaps.

Where PM_{10} progress is slowest (Spain, Malta, Greece, Italy, Romania), source mixes (resuspension, mineral dust, biomass) and dispersion conditions differ from those that govern $PM_{2.5}$, and require different policy levers.

Although EU policies have reduced particulate matter emissions, the remaining $PM_{2.5}$ and PM_{10} burden is increasingly driven by secondary formation, natural sources, and climate-related interactions, making further reductions dependent on integrated, location-specific approaches rather than emission controls alone.

This section assesses how exposure to $PM_{2.5}$ and PM_{10} has evolved across the EU. It combines **(i) national annual means for 2013–2023**, with **(ii) a snapshot for 2023 at NUTS 2 level**[349]. The indicators **are not population-weighted** and, therefore, highlight geographic patterns rather than population exposure. Both indicators are benchmarked against two reference levels: the binding 2030 limit values under the revised AAQD (10 µg/m³ for $PM_{2.5}$ and 20 µg/m³ for PM_{10}), and the WHO 2021 Air Quality Guidelines (5 µg/m³ for $PM_{2.5}$ and 15 µg/m³ for PM_{10}).

3.1.1. Long-term trends across Member States (2013–2023)

The national time series in **Figure 13** show a clear long-term decline in $PM_{2.5}$ concentrations across all Member States between 2013 and 2023, with the exception of a minor decline in exposure in Malta. The same pattern is visible for PM_{10} across 26 of 27 Member States, with the exception of Spain. Progress is therefore broad-based, but it is not uniform in either pace or starting point.

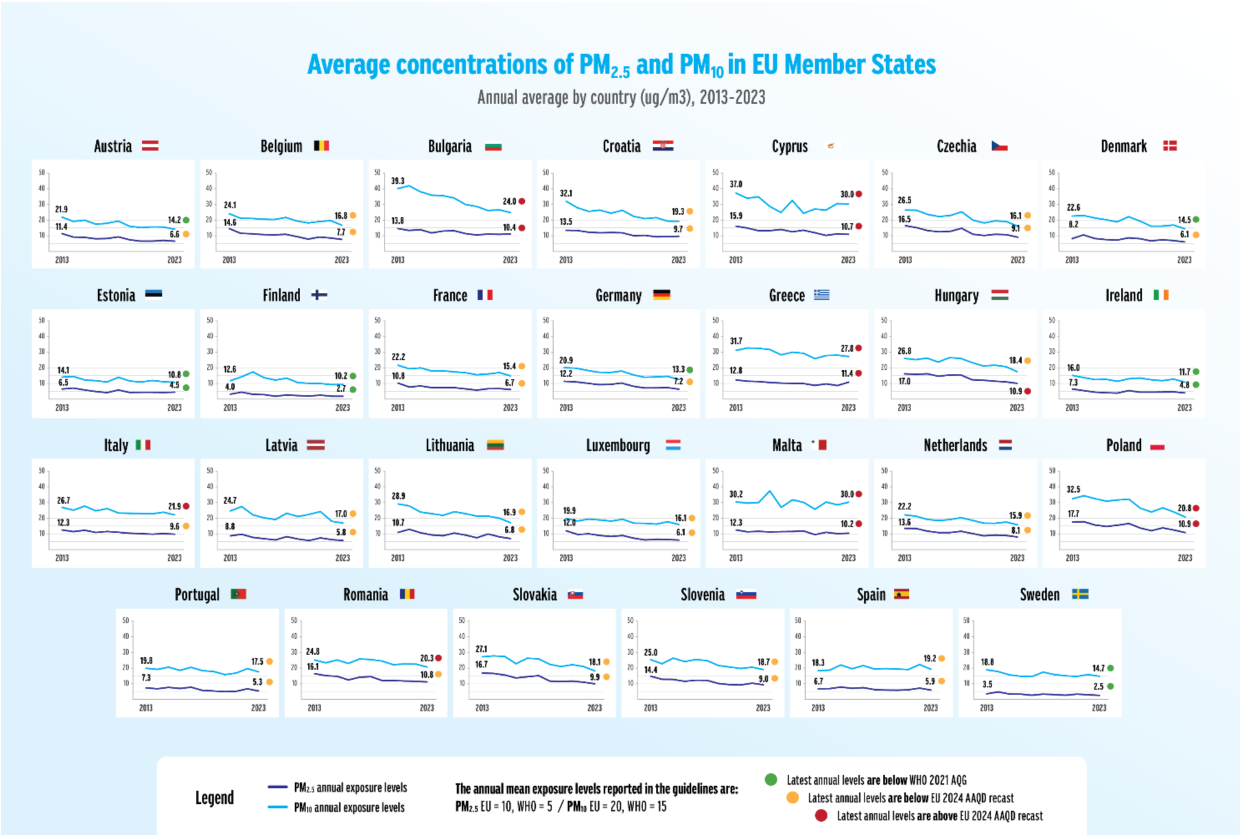
For $PM_{2.5}$, the largest reductions over the decade are recorded in Luxembourg (–49%), Belgium (–47%), Czechia (–45%), Austria (–42%), Germany (–41%) and Slovakia (–41%). These countries have approximately halved their average residential exposure over the past 10 years, a substantial reduction. By contrast, several Mediterranean Member States have seen far slower progress: Greece (–11%), Spain (–12%), Malta (–17%) and Italy (–22%).

PM_{10} trends are directionally similar. The largest reductions are recorded in Lithuania (–42%), Croatia (–40%), Czechia (–39%), Bulgaria (–39%), Germany (–37%) and Poland (–36%). Progress is again more limited in Southern Europe: Greece (–12%), Portugal (–12%), Italy (–18%) and Romania (–18%). Two

[349] NUTS 2 regions are basic territorial units within the EU's Nomenclature of Territorial Units for Statistics, primarily used for the design and implementation of regional policies.

countries stand out at the bottom of the distribution: Malta is essentially flat (–1%), and Spain is the only Member State to record an increase in PM_{10} (+5%).

Figure 13: Annual average concentrations of $PM_{2.5}$ and PM_{10} in EU Member States[350,351]



Comparing the 2023 levels with the EU and WHO policy benchmarks places Member States in three broad groups:

- **Lower exposure groups: The Nordic Member States and Ireland** record the lowest concentrations in the EU. For $PM_{2.5}$ they sit closest to the WHO guideline of 5 µg/m³, although several remain above it. For PM_{10} they typically sit in the range 10–15 µg/m³, which is around or just below the WHO guideline. Distance to the 2030 AAQD limit values is minimal in this group: $PM_{2.5}$ is comfortably below 10 µg/m³ and PM_{10} is comfortably below 20 µg/m³.
- **Mid-range group: Large parts of Western Europe**, including Germany, France, Belgium and the Netherlands, sit in a middle band. $PM_{2.5}$ reductions have been substantial, but levels remain well above the WHO guideline. For PM_{10}, the band is approximately 14–18 µg/m³ in 2023 (Germany 13.3 µg/m³, Denmark 14.5 µg/m³, France 15.4 µg/m³, Netherlands 15.9 µg/m³, Belgium 16.8 µg/m³): countries that look on track for $PM_{2.5}$ still hover at or above the WHO PM_{10} guideline. These countries are on track to meet the 2030 AAQD limit values on current trajectories.

[350] European Environment Agency, *Burden of disease of air pollution (Countries & NUTS), Baseline from WHO 2005 (HRAPIE 2013) and WHO 2021 AQG*. Available at: https://discomap.eea.europa.eu/App/AQViewer/index.html?fqn=Airquality_Dissem.ebd.countries_and_nuts&ScenarioDescription=Baseline%20from%20WHO%202021%20AQG&UrbanisationDegree=All%20Areas%20(incl.unclassified)&Year=2022&Sex=Total.

[351] European Environment Agency, AQ e-reporting Country dashboard, PM10. Available at: https://tableau-public.discomap.eea.europa.eu/views/AQeRep_for_public_for_portal/Countrydashboard?%3Aembed=y&%3AisGuestRedirectFromVizportal=y.

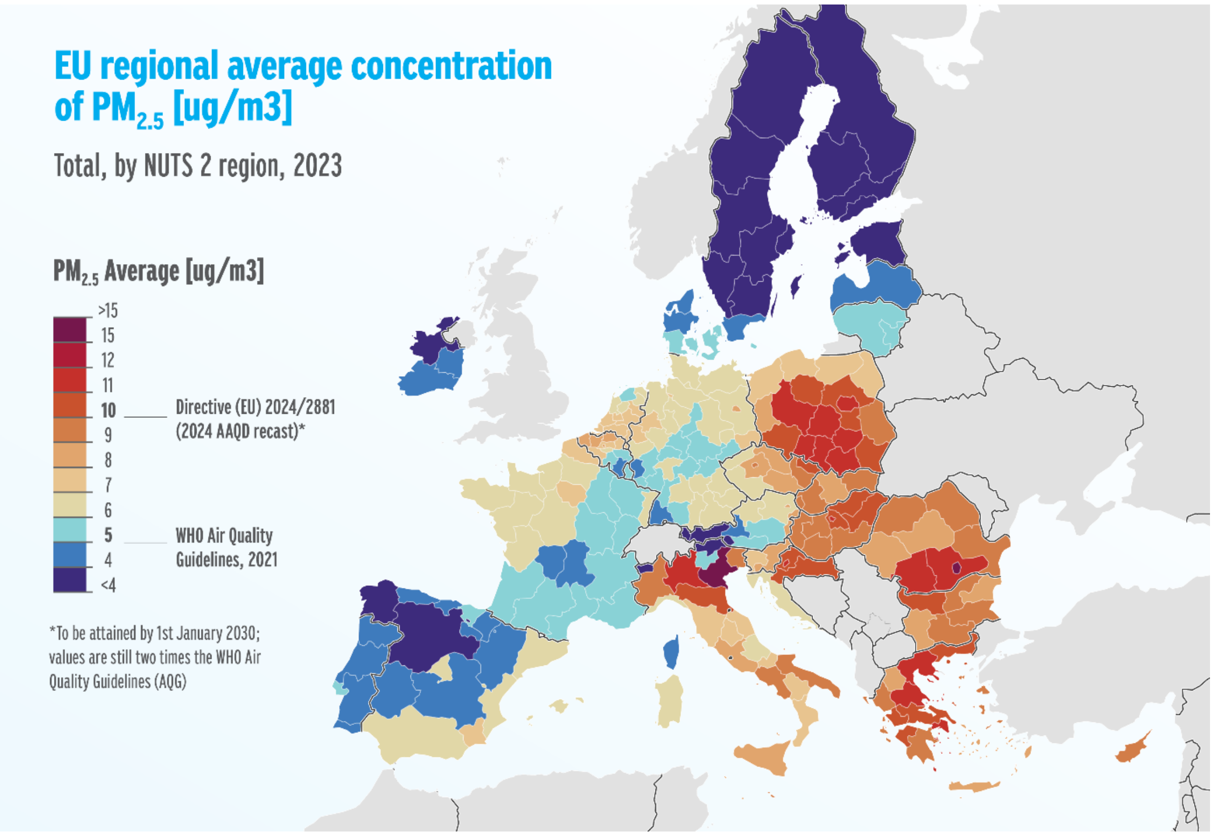
- **Higher exposure groups: Several Member States in Central, Eastern and Southern Europe**, including Malta, Bulgaria, Cyprus, Poland, Italy and Greece, remained above 10 µg/m³ for $PM_{2.5}$ in 2023. This group sits furthest from the WHO guideline and faces the largest gap to the 2030 AAQD limit value. For PM_{10}, 2023 levels in this group are typically in the 20–30 µg/m³ range (Poland 20.8 µg/m³; Italy 21.9 µg/m³; Bulgaria 24.0 µg/m³; Greece 27.8 µg/m³; around 30 µg/m³ in Cyprus and Malta). Long-term declines are visible in many of these Member States, but progress is uneven.

Regional patterns and hotspots in 2023

Figure 14 maps regional $PM_{2.5}$ concentrations (µg/m³) at NUTS 2 level for 2023. Two findings stand out. First, within-country variation is quite noticeable. Italy is the clearest example, where Northern industrial regions sit in the higher-exposure group while Southern regions are closer to the mid-range. Second, hotspots are concentrated in a small number of regions. The highest-value regions in 2023 are București-Ilfov (Romania, 16.2 µg/m³), Veneto (Italy, 15.0 µg/m³), Śląskie (Poland, 14.3 µg/m³), Grad Zagreb (Croatia, 14.2 µg/m³) and Attica (Greece, 13.8 µg/m³). The lowest regional averages are observed in Övre Norrland and Mellersta Norrland (Sweden, 1.7 and 1.8 µg/m³) and Pohjois- ja Itä-Suomi (Finland, 2.3 µg/m³).

The geographic pattern locates the EU's exposure problem in three macro-areas: the Po Valley and surrounding Northern Italian regions, the Silesian and southern Polish basin, and a Balkans/South-Eastern area running from Bucharest through Sofia to Athens. Each of these areas combines emission-intensive sectors (residential solid-fuel heating, industry, road transport), marine traffic, and/or built environment characteristics such as densely built cities with topographic conditions (basins, valleys) that limit dispersion.

Figure 14: Annual average concentrations of $PM_{2.5}$ in EU Member States at NUTS 2 level[352]



Comparison with counterfactuals

Set against the WHO $PM_{2.5}$ guideline, almost the entire EU territory remains out of compliance. **210 of 234 NUTS 2 regions (about 90%) exceed 5 µg/m³ in 2023**, and the EEA's indicator confirms that 94% of the EU urban population remains exposed to $PM_{2.5}$ levels above the WHO guideline[353]. Set against the 2030 AAQD limit value, **56 of 234 regions (about 25%) exceed 10 µg/m³**.

These exceedances are concentrated in a small number of Member States. Poland accounts for the largest number of regions above 10 µg/m³ of $PM_{2.5}$ (12), followed by Greece (10), Hungary (8), Romania (6) and Italy (6). Hungary is the only Member State in the dataset where every NUTS 2 region exceeds 10 µg/m³. Several Member States have no NUTS 2 regions above 10 µg/m³ in 2023: the Netherlands, Belgium, Germany, Austria, France, Spain, Denmark, Portugal, Ireland and Sweden.

3.1.2. Sources of $PM_{2.5}$ and PM_{10}

The EU-wide decline in particulate matter concentrations over the period 2013–2023 reflects a combination of structural and regulatory changes. These include the decarbonisation of electricity generation and large combustion plants under the Industrial Emissions Directive (IED), increasingly stringent vehicle emission standards (Euro 5/6 and Euro VI for heavy-duty vehicles), the gradual

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352 Annual average concentrations of $PM_{2.5}$ in EU Member States at NUTS 2 level in 2023, unweighted for population. European Environment Agency, *Burden of disease of air pollution (Countries & NUTS), Baseline from WHO 2005 (HRAPIE 2013) and WHO 2021 AQG*. Available at: https://discomap.eea.europa.eu/App/AQViewer/index.html?fqn=Airquality_Dissem.ebd.countries_and_nuts&ScenarioDescription=Baseline%20from%20WHO%202021%20AQG&UrbanisationDegree=All%20Areas%20(incl.unclassified)&Year=2022&Sex=Total.

353 European Environment Agency, 2025, *Air quality status report 2025*. Available at: https://www.eea.europa.eu/en/analysis/publications/air-quality-status-report-2025.

phase-out of coal in the residential heating mix of several Member States, and, in some cases, a decline in industrial output. Together, these measures have led to substantial reductions in primary emissions across much of Europe.

The slower progress observed in parts of Southern Europe can be partially explained by factors such as the higher baseline contribution from natural sources, such as dust and wildfires, a slower transition away from solid-fuel residential heating in rural and mountainous areas, persistent road transport emissions in dense Mediterranean urban regions, and slower fleet turnover. None of these factors is easily addressed by short-term abatement measures. In addition, short-term variability linked to climate conditions, including the post-COVID rebound, heatwaves, and the severe wildfire seasons of 2022 and 2023, has introduced fluctuations in observed trends, particularly in countries such as Greece, Spain, Portugal, and Italy[354].

As overall concentrations decline, further reductions increasingly depend on a better understanding of the **origin and formation of particulate matter**, especially the remaining, more persistent fraction. Particulate matter consists of both **primary and secondary components**. Primary PM is directly emitted from sources such as transport, industry, and residential combustion, as well as natural sources, including dust and wildfires. By contrast, a substantial share of $PM_{2.5}$ is formed secondarily in the atmosphere from precursor emissions such as ammonia (e.g. from agriculture), nitrogen oxides, and sulphur dioxide. This means that particulate matter levels are shaped not only by direct emissions but also by **interactions between multiple pollutants and sectors**, including agriculture and non-combustion sources[355]. As a result, the remaining burden of particulate matter is increasingly influenced by **location-specific conditions**, including the relative importance of natural sources, local emission profiles, and meteorological factors. This helps explain why local context can be a stronger determinant of exposure levels than individual emission sources alone.

More broadly, air pollution should be understood as part of the **exposome**, reflecting the totality of environmental exposures individuals experience over their lifetime. Particulate matter does not act in isolation but interacts with other environmental stressors, such as temperature, noise, and socio-economic conditions. These combined exposures can amplify health risks and contribute to differences in observed effects across populations and regions[356].

This interaction is particularly relevant in the context of **climate change**, and in particular rising temperatures and more frequent heatwaves. Evidence from a large multi-country study across 482 cities shows that heat is associated with increased cardiovascular and respiratory mortality, and that these effects are **substantially amplified by higher levels of air pollution**. For example, increases in **summer temperature were associated with a rise in respiratory mortality of around 7.7% at low $PM_{2.5}$ levels, increasing to over 14% at high $PM_{2.5}$ levels**, demonstrating a clear interaction between heat and pollution[357] [358].

This means that climate change not only acts as an independent health risk but also **modifies and intensifies the impacts of air pollution**. Several mechanisms underpin this interaction. Higher temperatures can increase pollutant concentrations through photochemical reactions (e.g. formation

[354] More information in the fiches.

[355] More information in the fiches.

[356] Gao, P., 2026, *The human airborne exposome*, Nature Health. Available at: https://www.nature.com/articles/s44360-025-00026-5.pdf.

[357] Stafoggia, M. et al., 2023, *Joint effect of heat and air pollution on mortality in 620 cities of 36 countries,* Environment International, Vol. 181, Article 108258. Available at: https://www.sciencedirect.com/science/article/pii/S0160412023005317?via%3Dihub.

[358] Rai, M. et al., 2023, *Heat-related cardiorespiratory mortality: Effect modification by air pollution across 482 cities from 24 countries*, Environment International, Vol. 174, Article 107825. Available at: https://doi.org/10.1016/j.envint.2023.107825.

of ozone) and stagnant atmospheric conditions, while also increasing human exposure through behavioural changes (e.g. more time spent outdoors) and physiological responses such as higher ventilation rates. At the same time, heat stress can reduce the body's capacity to respond to environmental toxins, further amplifying health effects.

Together, this evidence highlights that PM should be addressed not only through emission reduction strategies, but within an integrated framework that considers **climate change, environmental co-exposures, and local geographic conditions**, as these factors jointly determine both exposure levels and health impacts[359]. The findings in this chapter should therefore always be interpreted in the broader context of all factors contributing to $PM_{2.5}$ and PM_{10} concentrations.

3.2. Disparities in health burden

KEY FINDINGS

Health benefits are large but spatially concentrated. Attributable deaths from $PM_{2.5}$ in the EU-27 have fallen by approximately 57% since 2005, meeting the Zero Pollution Action Plan's interim 2030 target ahead of schedule. Reductions of 30–50% over 2013–2023 are observed in most Member States, but Italy, Cyprus and Spain show only modest progress, and Greece has not improved.

However, between 2021 and 2023, five Member States recorded increases in the rate of $PM_{2.5}$-attributable DALYs (Portugal, Italy, Greece, Slovenia, Spain). Climate variability and post-COVID conditions explain part of this, but the Mediterranean cluster of stalled progress is now also visible in the burden-of-disease data.

Cardiovascular diseases account for the majority of the health burden, but the picture varies across countries. IHD and stroke together account for 50–75% of the $PM_{2.5}$-attributable burden across the EU. Diabetes accounts for a third of the burden in Croatia and Cyprus. COPD accounts for around a fifth in Belgium, Denmark, Germany and the Netherlands. Childhood asthma accounts for 11–12% in Luxembourg and Poland.

This section translates the exposure trends set out in section 3.1 into health outcomes. The analysis uses two complementary indicators. **Attributable deaths**, premature deaths attributable to $PM_{2.5}$ exposure above the WHO air quality guideline level of 5µg/m3 to capture the mortality dimension. **Disability-adjusted life years (DALYs)**[360] combine years of life lost from premature mortality with years lived with disability, and so additionally capture chronic morbidity in people affected. Both indicators are taken from the EEA's burden-of-disease framework, applied to $PM_{2.5}$ only, as no robust EU-wide data for PM_{10} health impacts is currently published, although European epidemiological evidence on PM_{10} is presented at the end of this section. The cause-specific DALY data are available for three years (2021, 2022, 2023) and are reproduced in Annex 3.

[359] Ibid.

[360] A DALY corresponds to one lost year of a healthy life due to disease or injury. DALY are obtained by adding YLL and YLD for the same disease or group of diseases. Therefore, DALY is a standardised indicator for health effects resulting from both the number of people affected by a disease and the number of people dying from it. See: EEA, *Harm to human health from air pollution in Europe: burden of disease status*, 2025. Available at: https://www.eea.europa.eu/en/analysis/publications/harm-to-human-health-from-air-pollution-burden-of-disease-status-2025.

3.2.1. Long-term trends in attributable deaths

Figure 15 presents the estimated number of premature deaths per 100,000 inhabitants aged over 30 years attributable to exposure to annual $PM_{2.5}$ concentrations above 5µg/m^3. **Across the EU, the rate of attributable deaths has approximately halved over the period**. Focusing on the 2013–2023 sub-period that is directly comparable to the exposure series, average reductions across Member States are in the 30–40% range, with the largest decreases observed in Luxembourg (–52%), Belgium (–49%), Lithuania (–45%), Czechia (–43%), Austria (–39%) and Slovakia (–38%). These Member States have approximately halved the rate of $PM_{2.5}$-attributable mortality over the past decade.

Progress is less pronounced elsewhere. Italy (–10%), Cyprus (–7%) and Spain (–5%) show only modest reductions between 2013 and 2023. Greece is the only Member State where the rate of attributable deaths has not declined over this period (0% change). These differences generally mirror the exposure trends described in section 3.1: **where $PM_{2.5}$ concentrations have fallen fastest, health gains are largest**. Where exposure reductions have stalled, health impacts have barely improved.

The absolute burden in 2023 is unevenly distributed. The highest rates of attributable deaths are recorded in Bulgaria (172 per 100,000), Romania (136), Hungary (133) and Slovakia (97). The lowest are observed in Sweden (36), Finland (39), Ireland (37) and Luxembourg (40). The east-west and north-south gradient is therefore still visible.

As an EU-wide anchor, the EEA estimates that approximately **182,000 premature deaths in the EU-27 were attributable to $PM_{2.5}$ in 2023**. This is a 57% reduction relative to 2005 and effectively meets the 55% interim target of the Zero Pollution Action Plan ahead of the 2030 horizon[361]. These trends show a continued decline in the health burden across Europe between 2022 and 2023. This is partly driven by a decrease in population exposure, as population-weighted concentrations have fallen[362] .

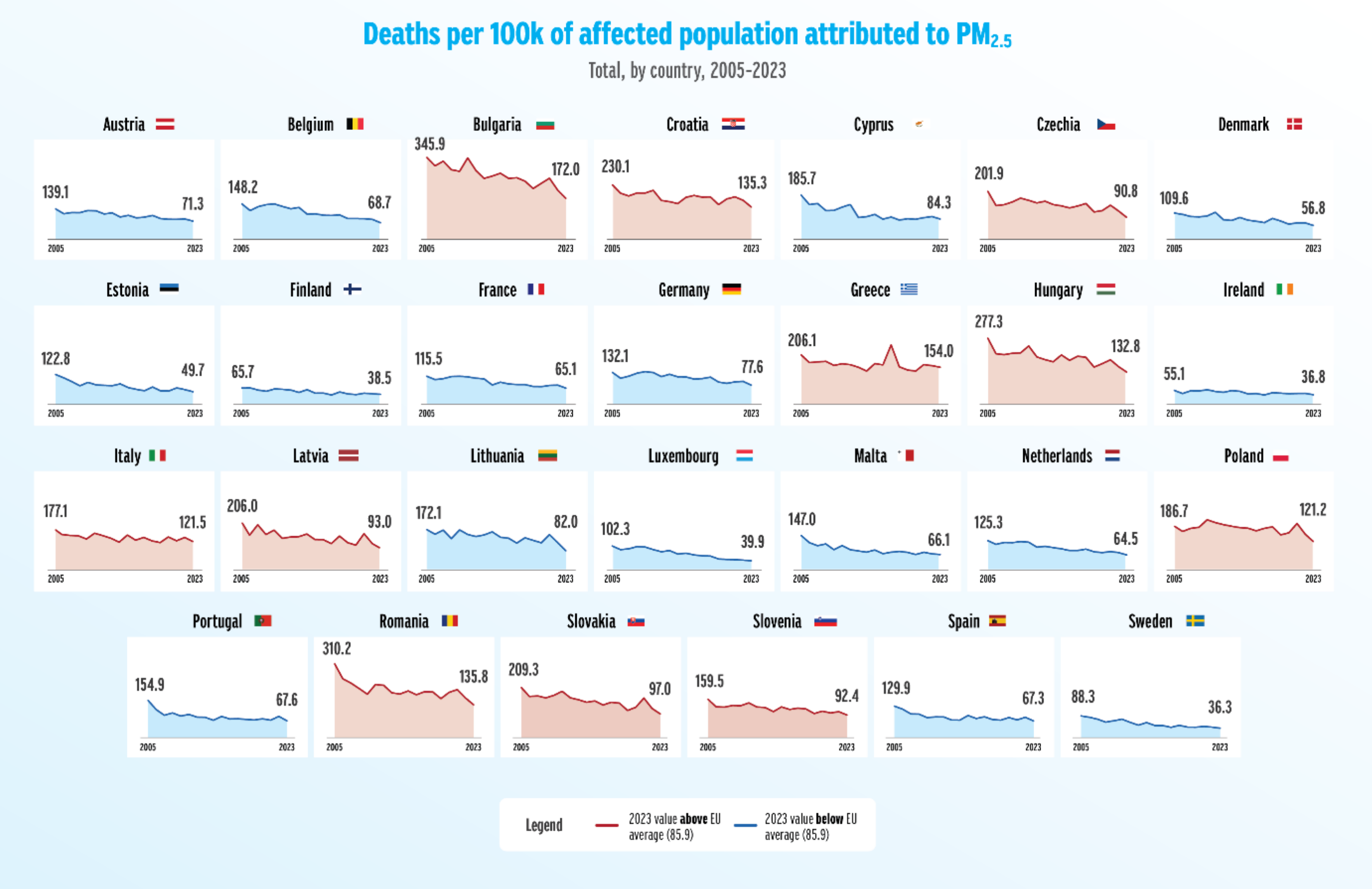
These improvements reflect sustained EU, national and local policy efforts, including the Ambient Air Quality Directive and the National Emission Reduction Commitments Directive. Together, these have contributed to a 38% reduction in PM emissions since 2005, particularly in electricity and heat production, residential fuel use, and road transport, with smaller reductions in agricultural ammonia emissions[363].

361 European Environment Agency, 2025, *Premature deaths due to exposure to fine particulate matter in Europe*. Available at: https://www.eea.europa.eu/en/analysis/indicators/health-impacts-of-exposure-to?activeAccordion=546a7c35-9188-4d23-94ee-005d97c26f2b.

362 EEA, 2025, *Harm to human health from air pollution in Europe: burden of disease status*. Available at: https://www.eea.europa.eu/en/analysis/publications/harm-to-human-health-from-air-pollution-burden-of-disease-status-2025.

363 Ibid.

Figure 15: Deaths per 100k of affected population attributed to $PM_{2.5}$[364]



[364] European Environment Agency, *Burden of disease of air pollution (Countries & NUTS), Baseline from WHO 2005 (HRAPIE 2013) and WHO 2021 AQG*. Available at: https://discomap.eea.europa.eu/App/AQViewer/index.html?fqn=Airquality_Dissem.ebd.countries_and_nuts&ScenarioDescription=Baseline%20from%20WHO%202021%20AQG&UrbanisationDegree=All%20Areas%20(incl.unclassified)&Year=2022&Sex=Total.

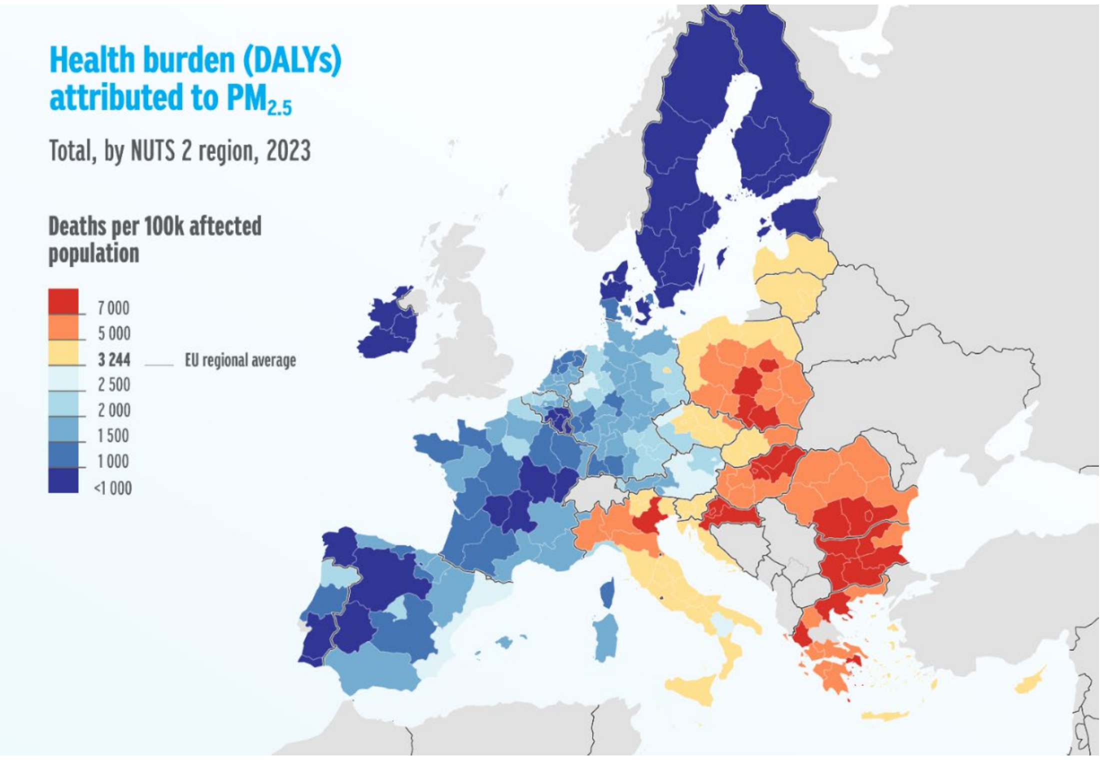
3.2.2. Recent trends in burden of disease (2021–2023)

The cause-specific DALY tables reproduced in Annex 3 cover only three years but reveal a significant divergence in the pace of change between Member States. Between 2021 and 2023, the total $PM_{2.5}$-attributable DALY rate per 100,000 fell by 81% in Finland, 67% in Sweden, 52% in Estonia, 47% in Lithuania, 43% in Denmark and 41% in Latvia. Reductions of 25–30% are recorded in Belgium, Ireland, Germany, the Netherlands, Slovakia, Czechia and Poland. At the other end of the distribution, **five Member States recorded an increase in the rate of $PM_{2.5}$-attributable DALYs over 2021–2023**: Portugal (+15%), Italy (+8%), Greece (+7%), Slovenia (+2%) and Spain (+1%). Bulgaria, Romania and Cyprus recorded only marginal reductions (between –2% and –5%). **The short window cautions against over-interpretation**, but the geography of the divergence is clear: the Mediterranean Member States that already showed slow $PM_{2.5}$ declines in section 3.1 are also the Member States where health burden is now stalling, and in some cases reversing, in the most recent data.

Regional disparities in the burden of disease

At the NUTS 2 level, the 2023 burden of disease attributable to $PM_{2.5}$ ranges across more than two orders of magnitude, as visualised in Figure 16. The lowest values are recorded in Itä- ja Pohjois-Suomi (Finland, around 14 DALYs per 100,000) and Åland (Finland, around 31). The highest values are in regions of Bulgaria, Romania, Hungary and Poland that exceed 6,000 DALYs per 100,000. Regions in Austria, Belgium, France, Germany and the Netherlands typically record values below the EU mean, with several below 2,000 DALYs per 100,000. The regional disparities map directly onto the exposure hotspots identified in section 3.1, confirming a tight link between $PM_{2.5}$ levels and population-level health burden.

Figure 16: Health burden attributed to $PM_{2.5}$ in DALYs at NUTS2 level, 2023[365]



Distribution of burden of disease by disease group

The cause-specific breakdown for 2023 is presented in Annex 3. Ischaemic heart disease and stroke together dominate the $PM_{2.5}$-attributable disease burden in every Member State, but the disease mix varies.

- **Cardiovascular diseases:** In Bulgaria, stroke alone accounts for 43% of the total $PM_{2.5}$-attributable DALY rate, with ischaemic heart disease (IHD) adding a further 29%, leading to a combined cardiovascular share of 72%. In Romania, the same combined share is 72%, but IHD (40%) is the larger driver and stroke (32%) the smaller. In Slovakia, IHD alone accounted for 49% of the burden in 2023; in Lithuania, 49% in 2023. In Western and Northern Europe, IHD and stroke together typically make up 40–50% of the total burden, which is still the largest single contributor, but with a greater relative weight of respiratory and metabolic outcomes.
- **Diabetes mellitus:** Diabetes accounts for 10–20% of the total burden in most Member States, but reaches 33% in Croatia and Cyprus, which is a finding consistent with the high baseline prevalence of type-2 diabetes in these populations and with the cardiometabolic pathway through which $PM_{2.5}$ contributes to disease.
- **Chronic obstructive pulmonary disease:** COPD contributes 5–10% of the burden in most Member States but 17–23% in Belgium, Denmark, Germany and the Netherlands, which are Member States where the cardiovascular burden has fallen relatively further, and respiratory outcomes therefore become more visible in relative terms.

[365] European Environment Agency, *Burden of disease of air pollution (Countries & NUTS), Baseline from WHO 2005 (HRAPIE 2013) and WHO 2021 AQG*. Available at: https://discomap.eea.europa.eu/App/AQViewer/index.html?fqn=Airquality_Dissem.ebd.countries_and_nuts&ScenarioDescription=Baseline%20from%20WHO%202021%20AQG&UrbanisationDegree=All%20Areas%20(incl.unclassified)&Year=2022&Sex=Total.

- **Lung cancer:** Lung cancer accounts for 9–22% of the total burden, with the highest shares in Belgium, Denmark, Italy, Greece and the Netherlands. Mortality accounts for 97% of the lung-cancer burden in the EU-27.
- **Asthma in children and adolescents:** Asthma below age 19 contributes a smaller share (3–8% in most Member States) but reaches 11–12% in Luxembourg and Poland. The total EU-27 burden in 2023 was 35,683 DALYs (95% CI 12,938–54,965), of which 99% was morbidity rather than mortality. This is a critical distinction: headline premature-death indicators understate the scale of disease burden in children, who experience the harm of $PM_{2.5}$ chiefly through chronic illness and reduced quality of life rather than premature mortality.

3.2.3. PM_{10} health impacts

There is no EU-wide time series for PM_{10}-attributable burden of disease currently published. The European evidence base on PM_{10} nonetheless documents a set of health effects in the EU related to PM_{10} exposure.

A systematic review, which updates the evidence underpinning the 2021 WHO Global Air Quality Guidelines, **links long-term PM_{10} exposure to natural-cause mortality**[366]. The certainty of evidence linking long-term PM_{10} exposure to all-cause mortality is rated "high".[367]

Second, the most recent meta-analysis of long-term criteria-pollutant exposure and infant mortality concludes that **long-term PM_{10} exposure is associated with all-cause, respiratory, and sudden-infant-death-syndrome (SIDS) infant mortality across studies, with the strongest evidence for PM_{10} of any of the criteria pollutants examined**[368]. This is consistent with the rationale for the HRAPIE-2 framework retaining post-neonatal mortality as a PM_{10}-specific outcome.

Exposure to PM_{10} in the EU is widespread. EEA's air-quality status assessment for 2023 reports that approximately **63% of the European population lived in areas exceeding the WHO 2021 PM_{10} annual guideline of 15 µg/m³**, while approximately 16% lived in areas where the 90.4th percentile of daily means exceeded the EU PM_{10} limit value of 50 µg/m³.[369] The population-weighted European annual mean PM_{10} was 20.4 µg/m³ in 2023, marginally above the revised AAQD 2030 limit value of 20 µg/m³.[370] The implication is that the residual PM_{10}-attributable burden, and in particular the post-neonatal mortality component, will not be eliminated by full compliance with the 2030 AAQD limit, because the WHO health-based guideline for PM_{10} (15 µg/m³) is more stringent than the AAQD limit and is exceeded across most of the EU territory.

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366 Orellano, P. et al., 2024, Long-term exposure to particulate matter and mortality: an update of the WHO Global Air Quality Guidelines systematic review and meta-analysis. Available at: https://pubmed.ncbi.nlm.nih.gov/39399882/.

367 Ibid.

368 Wilkie, A.A. et al., 2025, *Long-term exposure to criteria air pollutants and infant mortality: a systematic review and meta-analysis*, International Journal of Hygiene and Environmental Health, 268:114690. Available at: https://pubmed.ncbi.nlm.nih.gov/40300246/.

369 Horálek, J. et al., 2025, Air quality maps of EEA member and cooperating countries for 2023 (PM10, PM2.5, O3, NO2, NOx and BaP) — Spatial estimates and their uncertainties, Eionet ETC, HE Report 2025/5, European Topic Centre on Human Health and the Environment. Available at: https://www.eionet.europa.eu/etcs/etc-he/products/etc-he-products/etc-he-reports/etc-he-report-2025-5-air-quality-maps-of-eea-member-and-cooperating-countries-for-2023-pm10-pm2-5-o3-no2-nox-and-bap-spatial-estimates-and-their-uncertainties.

370 Ibid.

3.3. Age-based and socioeconomic disparities

KEY FINDINGS

Older adults bear the greatest burden. The vast majority of $PM_{2.5}$-attributable premature deaths and years of life lost in the EU-27 in 2023 fall in the 65+ age group, and this will increase as the EU population ages.

Dementia is now the single largest disease burden in older adults. First included in EEA estimates in 2025, PM-attributable dementia DALYs exceed every other individual disease assessed, a major previously unaccounted share of the total health burden.

Child asthma burden is highly unequal across member states. $PM_{2.5}$-attributable asthma rates in under-19s range from 0.7 per 100,000 in Finland to 141 in Poland, nearly five times the EU median, with the highest burdens concentrated in Eastern and Southern Europe.

Poorer regions face persistently higher $PM_{2.5}$ exposure. Over 2007–2022, the poorest EU quintile recorded $PM_{2.5}$ concentrations approximately 30% above the richest quintile, with no significant convergence in the gap despite both improving.

Mortality risk from pollution is up to twice as high in disadvantaged regions. Wealthier Western and Northern EU regions saw significant declines in PM-related mortality risk between 2003–2019. Poorer Southern and Eastern regions saw little or no improvement.

This section examines whether the same trends are distributed evenly across age groups and across socioeconomic groups, or whether some populations are being left behind. It assumes the biological and mechanistic evidence set out in section 2.3, which explains why children, older adults, people with pre-existing conditions and socially disadvantaged groups are more vulnerable to $PM_{2.5}$ and PM_{10} exposure, and quantifies the resulting inequalities in the most recent EU burden-of-disease and exposure data.

3.3.1. Age-specific health impacts across Member States

Section 2.3 establishes that children, adolescents and older adults are biologically more vulnerable to particulate matter than the general adult population. How unequally that vulnerability plays out across EU Member States, and whether the gradients are narrowing or widening over time, is harder to answer. Currently available data does not allow for a clear view on how health burden developed over recent years across age groups. Specifically working-age adults (25-64 years old) are left out of this analysis due to a lack of data.

Infants (0–1 year)

For infants, PM_{10}, rather than $PM_{2.5}$, is the dominant pollutant of concern, for the physiological reasons set out in section 2.3. The WHO HRAPIE-2 framework accordingly retains post-neonatal mortality (1–12 months) as a long-term PM_{10} outcome, which is the only mortality outcome in the framework that extends below adult ages[371]. No EU-wide data for PM_{10}-attributable infant mortality is currently

[371] World Health Organization, 2025, Health risks of air pollution in Europe: HRAPIE-2 project. Updated guidance on concentration–response functions for health risk assessment of air pollution in the WHO European Region. Available at: https://www.who.int/publications/i/item/9789289062633.

published, but the EEA's 2023 children's health briefing records over 1,200 deaths and over 110,000 DALYs per year in under-18s across EEA member and collaborating countries, with infant mortality the largest single contributor[372]. Compliance with the 2030 AAQD limit values will not eliminate this burden: the WHO 2021 guidelines (5 µg/m³ $PM_{2.5}$ and 15 µg/m³ PM_{10}) are the thresholds more closely aligned with foetal and infant protection, and they are exceeded across most of the EU territory (see section 3.1).

Children and adolescents (1–18 years)

For children and adolescents, asthma is the EEA's only cause-specific $PM_{2.5}$ outcome and amounts to **35,683 DALYs in the EU-27 in 2023, of which 99% is morbidity rather than mortality**. The cross-Member-State distribution of this burden is uneven. The 2023 rate per 100,000 under-19 population ranges from **0.7 in Finland** and 2.4 in Estonia at the lower end, through 13-27 in Denmark, Ireland, Lithuania, Latvia, Luxembourg, Germany, Belgium, Austria and the Netherlands, to 47–61 across the Balkans and Mediterranean, and to **141 in Poland**, which is close to five times the EU median (29.5). [373]

Older adults (65 years and older)

Older adults bear the greatest **absolute mortality burden** attributable to $PM_{2.5}$ in the EU-27, as section 2.3 establishes. The EU-level quantification is that the **182,000 $PM_{2.5}$-attributable premature deaths and approximately 1,914,000 Years of Life Lost in the EU-27 in 2023** fall in their large majority in the 65+ cohort, and that associations between $PM_{2.5}$ and cardiovascular and respiratory mortality are substantially stronger above age 75 than below it[374] .

Two points should be made for this age group. First, the EEA included **dementia morbidity in adults aged 60 and older as a separately estimated burden-of-disease outcome for the first time in 2025; its** burden was found to be **higher than that of any of the other six diseases assessed individually**[375]. This means that the health burden of dementia related to PM exposure is a huge contributor to the overall health burden. Second, as the EU population over the coming years will increase, the **absolute $PM_{2.5}$-attributable disease burden in older adults will continue to rise in the EU-27 over the next 25 years even if concentrations fall**, unless exposure reductions are sufficient to offset the epidemiological amplification of an ageing population.

3.3.2. Socioeconomic inequalities across Member States

Section 2.3 establishes that socially and economically disadvantaged groups face a "dual risk" of higher PM exposure and stronger health response, drawing on the global epidemiological literature. This section aims to quantify the distribution of that inequality across EU Member States and its evolution over time.

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[372] European Environment Agency, 2023, *Air pollution and children's health*. Available at: https://www.eea.europa.eu/en/analysis/publications/air-pollution-and-childrens-health.

[373] European Environment Agency, 2025, *Assessing the environmental burden of disease related to air pollution in Europe in 2023*. Available at: https://www.eionet.europa.eu/etcs/etc-he/products/etc-he-products/etc-he-reports/etc-he-report-2025-8-assessing-the-environmental-burden-of-disease-related-to-air-pollution-in-europe-in-2023/@@download/file/etc-he-report-2025-8-soares.pdf.

[374] European Environment Agency, 2025, Harm to human health from air pollution in Europe: burden of disease status. Available at: https://www.eea.europa.eu/en/analysis/publications/harm-to-human-health-from-air-pollution-burden-of-disease-status-2025.

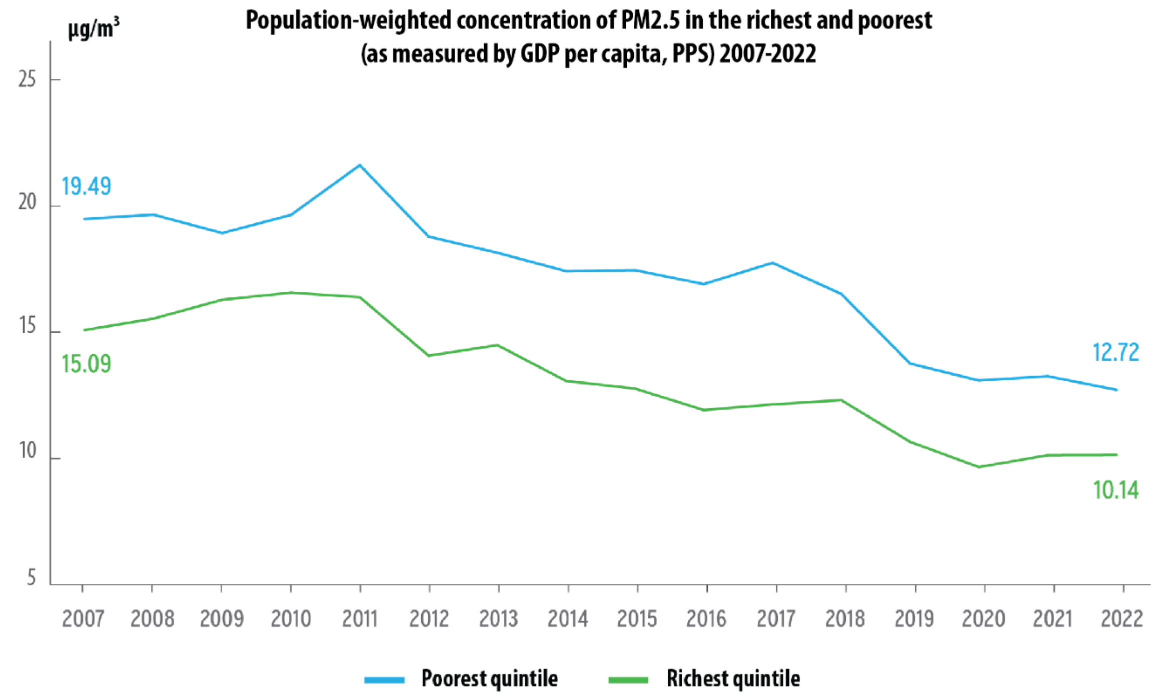
[375] Ibid.

Unequal exposure ($PM_{2.5}$)

Figure 17 and Figure 18 on the $PM_{2.5}$ concentrations in the highest- and lowest-GDP-per-capita quintile of the EU support three findings:

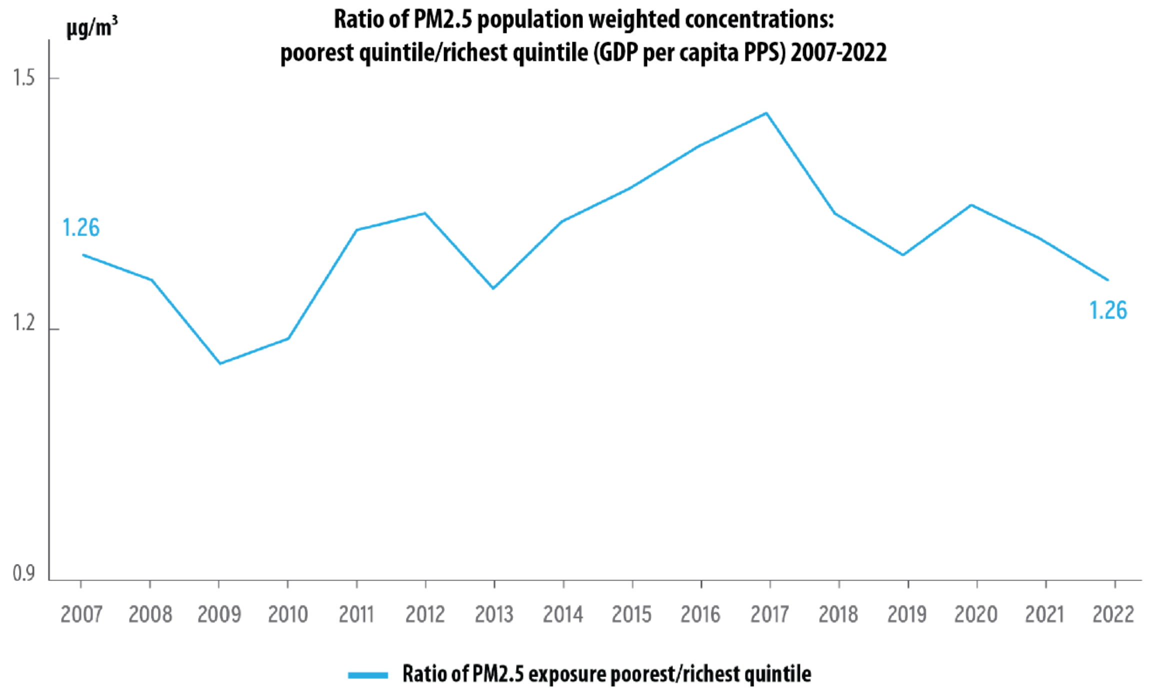
- A persistent approximately 25–35% gap. Across 2007–2022, the poorest NUTS 3 quintile recorded annual $PM_{2.5}$ concentrations roughly one-third higher than the richest quintile (ratios between 1.16 and 1.46, 16-year average 1.30) There is no significant convergence in the ratio.
- Both quintiles improved, but the absolute gap remains substantial. The richest quintile declined by 32.8% over 2007–2022 (15.1 to 10.1 µg/m³), the poorest by 34.7% (19.5 to 12.7 µg/m³). The absolute gap narrowed from 4.4 to 2.6 µg/m³, but in 2022 the poorest quintile was still 2.5 times the WHO $PM_{2.5}$ guideline of 5 µg/m³.
- Distance to the 2030 AAQD limit value diverges between quintiles. In 2022 the richest quintile sat at 10.1 µg/m, while the poorest quintile sat at 12.7 µg/m³.

Figure 17: Population-weighted concentration of $PM_{2.5}$ in the richest and poorest quintile[376]



[376] European Environment Agency, 2025, *GDP-related air pollution exposure inequalities between regions in Europe*. Available at: https://www.eea.europa.eu/en/analysis/indicators/income-related-environmental-inequalities-associated.

Figure 18: Ratio of $PM_{2.5}$ population weighted concentrations: poorest /richest quintile[377]



Unequal exposure (PM_{10})

No similar data to $PM_{2.5}$ has been published for PM_{10}. The chapter 5 fiches nonetheless show that the same socioeconomic gradient holds across the EU at Member-State level: PM_{10} annual mean ranges from **5 µg/m³ in the cleanest Finnish regions, 9 in the cleanest Spanish regions and 13 in the cleanest French regions, to 66 in the worst Polish region, 71 in the worst Spanish region and 94 in the worst Italian region (Po Valley)**. The PM_{10} hotspots, the Po Valley, the Silesian basin, and Mediterranean and Balkan urban areas, coincide closely with the regions of lowest GDP per capita identified in the EEA exposure-quintile indicator.

Unequal health impacts

The most recent EU-level evidence on health-impact inequality finds that regions with higher GDP per capita, lower poverty rates and longer life expectancy, primarily in Western and Northern Europe, showed lower and declining mortality risks associated with $PM_{2.5}$ and PM_{10}, while the most disadvantaged regions, predominantly in Southern and Eastern Europe, recorded mortality risks per 10 µg/m³ of pollutant **up to double those of the most advantaged regions**. Critically, wealthier regions experienced a significant decrease in $PM_{2.5}$, PM_{10} mortality risk between 2003 and 2019, while regions with lower income or life expectancy saw only small improvements or even increases over the same period[378] [379].

[377] European Environment Agency, 2025, *GDP-related air pollution exposure inequalities between regions in Europe*. Available at: https://www.eea.europa.eu/en/analysis/indicators/income-related-environmental-inequalities-associated.

[378] Chen, Z.Y. et al., 2026, *Socioeconomic and energy transition disparities in air pollution-related mortality across Europe*, Nature Medicine, Vol. 32, pp. 1490–1500. Available at: https://doi.org/10.1038/s41591-026-04293-x.

[379] Chen, Z.Y. et al., 2026, *Mortality from short-term exposure to particulate matter, nitrogen dioxide and ozone across Europe*, Nature Health. Available at: https://doi.org/10.1038/s44360-026-00124-y.

4. EU LEGAL AND POLICY FRAMEWORKS

KEY FINDINGS

The EU acquis for $PM_{2.5}$ and PM_{10} is multi-layered and technically sophisticated. No single instrument is sufficient; effective PM reduction depends on the coherent operation of the full framework.

Direct instruments (vehicle emission standards, the Industrial Emissions Directive – IED, the Medium Combustion Plants Directive – MCPD, and the Fuel Quality Directive) account for the majority of PM reductions achieved since 2005.

Agricultural ammonia is the most significant gap in the acquis. The National Emission Ceilings (NEC) Directive sets national ceilings but lacks sector-level measures. The Nitrates Directive contains no reference to air quality. The CAP embeds ammonia as a monitoring indicator but imposes no minimum air quality outcome.

Indirect instruments (RED, EPBD, EED, ESPR) reward progress measured in carbon, energy demand, and renewable share, but do not take into account PM emissions. This creates pressure to transform the energy system, but without setting benchmarks for PM emissions. In practice, this means that the same energy efficiency target could be satisfied by a low PM emissions heat pump or a high PM emissions wood stove. The PM outcome is left to Member State discretion, and, in cases such as the household-heating case, this can drive combustion PM up while recording progress on the energy efficiency targets.

The household biomass sector is unregulated for PM purposes. The Renewable Energy Directive's (RED) sustainability criteria exclude the entire residential wood-burning sector. The Ecodesign for Sustainable Products Regulation (ESPR) provides the legal basis for future PM limits on residential heating appliances, but no delegated acts have been adopted. Replacing fossil fuels with unregulated biomass can produce no net PM benefit or can worsen outcomes.

Several instruments contain flexibility and derogation provisions; notably Art. 18 AAQD postponement, IED BAT-AEL derogations, and NEC three-year averaging that, if widely used, could substantially reduce effective ambition.

The acquis contains no cross-instrument coherence mechanism. The most acute example is the tension between NEC ammonia reduction commitments and the Nitrates Directive derogation provisions, which can leave the same Member State simultaneously obligated to reduce ammonia and permitted to increase it.

4.1. Current EU legislation

This section **maps the EU legislative instruments relevant to $PM_{2.5}$ and PM_{10} levels and emissions for instruments with direct PM relevance** (those setting legally binding limit values, emission standards, reduction commitments for PM, or primary precursors), and instruments with indirect co-benefits (those where PM reductions arise as a secondary consequence of objectives in energy, transport, or product policy). For each instrument, the mapping covers its regulatory approach, key obligations, monitoring and planning requirements, flexibilities and derogations, and relevance to PM exposure. The mapping provides the evidential foundation for the effectiveness assessment in Section 4.2 and informs the policy recommendations in Chapter 6.

4.1.1. Key instruments (direct effects)

Directive (EU) 2024/2881 – Ambient Air Quality Directive

Field	Content
Instrument title and reference	• Directive (EU) 2024/2881 of the European Parliament and of the Council of 23 October 2024 on ambient air quality and cleaner air for Europe (recast).
Legal basis	• Article 192(1) TFEU (environmental policy, ordinary legislative procedure). Recital 49 also invokes Articles 2, 3, 35 and 37 of the Charter of Fundamental Rights in relation to the right to life, integrity of the person, healthcare, and the integration of a high level of environmental protection into Union policies.
Stated objective(s)	• To achieve a **zero-pollution objective** so that air quality is progressively improved to levels no longer considered harmful to human health, natural ecosystems and biodiversity, contributing to a **toxic-free environment by 2050** (Art. 1(1)). Air quality standards are to be **regularly reviewed** in line with WHO recommendations (Art. 1(2), Art. 3).
Type of regulatory approach	• The directive lays down **air quality standards** comprising limit values, target values, average exposure reduction obligations, average exposure concentration objectives, critical levels, alert thresholds, information thresholds and long-term objectives (Art. 1(2), Art. 4(2)), complemented by mandatory assessment, planning and reporting obligations where standards are exceeded or at risk of being exceeded.
Regulation target	• **Ambient air** (outdoor air, excluding workplaces; Art. 4(1)). Air quality standards apply to twelve pollutants: **$PM_{2.5}$**, **PM_{10}**, NO_2, SO_2, benzene, CO, lead, arsenic, cadmium, nickel, benzo(a)pyrene, and ozone. Ultrafine Particles (UFP), black carbon, ammonia, and total gaseous mercury are also monitored at supersites, but are not yet subject to limit values.
Obligations	Member States must: • Ensure pollutant levels do not exceed **limit values** throughout their zones (Art. 13(1)) • Meet **average exposure reduction obligations** in each average exposure territorial unit (Art. 13(3)) • Establish **air quality plans** within 2 years of a recorded exceedance and keep exceedance periods no longer than 4 years (Art. 19(1)). • Establish **air quality roadmaps** where 2030 standards are at risk during 2026–2029 (Art. 19(4)) • Establish **short-term action plans** where alert thresholds risk being exceeded (Art. 20) • Ensure public access to air quality information and an AQ index (Art. 22) • Report to the Commission annually (Art. 23) • Ensure access to justice and compensation for affected persons (Arts. 27–28).

Field	Content
Monitoring requirements	• Fixed measurements mandatory in zones above **assessment thresholds** (Annex II). May be supplemented or partially replaced by **modelling applications** and **indicative measurements**. In zones where limit or target values are exceeded, modelling must be used alongside fixed measurements (Art. 8(3)). • Minimum sampling point numbers are population-scaled per pollutant (Annex III); may be reduced by up to 50% where supplementary methods meet data quality requirements and values are not exceeded (Art. 9(3)). • **Monitoring supersites** mandatory: ≥1 per 10M inhabitants at urban background locations; ≥1 per 100,000 km^2 at rural background locations; measuring UFP, BC, ammonia, mercury, $PM_{2.5}$ chemical composition and deposition rates (Art. 10, Annex VII). Each zone must include at least one sampling point at an **air pollution hotspot** (Annex III, Point A). Network design must be documented and reviewed every 5 years (Annex IV, Point D).
Planning obligations	• **Air quality plans** (Art. 19(1)–(3)): required within 2 years of a recorded exceedance of any limit value, target value or average exposure reduction obligation; exceedance period must be kept no longer than 4 years; subject to public consultation; communicated to the Commission within 2 months of adoption. • **Air quality roadmaps** (Art. 19(4)): new instrument required from 2026, where 2030 standards are at risk; must include a baseline scenario, projected emissions and concentrations, selected measures with quantified impact, an indicative compliance trajectory, and a funding mobilisation strategy (Annex VIII). • **Short-term action plans** (Art. 20): required where alert thresholds risk being exceeded; must include emergency measures and specific actions for sensitive populations and vulnerable groups. All plans must, where feasible, be consistent with plans under the directives on noise, industrial emissions, and national emission ceilings (Art. 19(6)).
Flexibilities and derogations	• **Postponement** (Art. 18): the 2030 attainment deadline may be postponed, (a) up to **1 January 2040** for site-specific, orographic, climatic, transboundary, or domestic heating-stock reasons; (b) up to **1 January 2035** where projections show 2030 compliance is unattainable despite effective measures, with a possible second and final extension of up to 2 further years. Requires an air quality roadmap by 31 December 2028 and Commission notification by 31 January 2029. • **Natural source deductions** (Art. 16): exceedances attributable to natural sources may be excluded from compliance assessment upon evidence. • **Winter road treatment deductions** (Art. 17): PM_{10} exceedances from road re-suspension may be excluded where reasonable measures are in place. • **Ozone exemption** (Art. 19(2)): Member States may refrain from establishing plans for ozone exceedances where no significant reduction potential exists, and measures would be disproportionate.

Field	Content
Member State discretion	• Delimitation of zones and average exposure territorial units (Art. 6). • Selection of abatement measures within plans and roadmaps from the indicative list in Annex VIII, Point B. • Option to adopt more stringent air quality standards under Article 193 TFEU with notification to the Commission (Art. 13(7)). • Option to establish joint monitoring supersites with neighbouring Member States (Art. 10(4)).
Commission oversight mechanisms	• **Assessment of postponement notifications**: conditions deemed satisfied if no objections within 9 months. Commission may require revised roadmaps (Art. 18(4)). Adoption of implementing acts on modelling, spatial representativeness, natural source and winter road treatment methodologies, postponement projection requirements, and reporting formats (Arts. 8(7), 16(4), 17(4), 18(5), 23(5)), most by 31 December 2026. Adoption of delegated acts amending technical annexes (Art. 24). **Regular review** by 31 December 2030, then every 5 years, with power to propose revised standards and source legislation (Art. 3).
Enforcement tools in the legal design	• **Access to justice** (Art. 27): mandatory judicial or independent review of decisions on sampling point locations, air quality plans and roadmaps, and short-term action plans; NGOs promoting health or environmental protection automatically have standing. • **Compensation** (Art. 28): natural persons may claim and obtain compensation for health damage caused by intentional or negligent violation of air quality plan and short-term action plan obligations by competent authorities. • **Penalties** (Art. 29): must be effective, proportionate and dissuasive, with due regard to gravity, duration, population impact (including on sensitive and vulnerable groups), repetition, and economic benefit derived from the infringement.
Direct vs indirect relevance to PM exposure	• **Direct.** The directive sets **legally binding limit values for $PM_{2.5}$ (annual: 10 µg/m^3) and PM_{10} (annual: 20 µg/m^3), both by 1 January 2030** (Annex 2). It introduces average exposure reduction obligations and concentration objectives specifically targeting population-weighted $PM_{2.5}$ exposure. It mandates $PM_{2.5}$ and PM_{10} monitoring across all Member States, chemical speciation of $PM_{2.5}$ at supersites, and monitoring of UFP and the oxidative potential of particulate matter at supersites. It explicitly recognises that $PM_{2.5}$ has no identifiable threshold below which it poses no risk (recital 11) and that it is among the pollutants with the highest documented impact on human health (recital 23).

Directive (EU) 2024/1785 - Industrial Emissions Directive

Field	Content
Instrument title and reference	• Directive (EU) 2024/1785 – Industrial Emissions Directive (amending Directive 2010/75/EU)
Legal basis	• Art. 192(1) TFEU (environmental protection)
Stated objective(s)	• "To ensure a high level of environmental protection and the improvement of environmental quality". The 2024 amendment adds an explicit objective to 'prevent or, where not practicable, to continuously reduce emissions into air, water and land […]'
Type of regulatory approach	• Emission ceilings for integrated pollution-prevention & control (industrial installations) • Sector-specific standards (large-scale industry, livestock). • Integrated pollution prevention and control through individual installation permits (or, for livestock installations, registration plus general binding rules). • Permits must require application of the best available techniques (**BAT)**, with **emission limit values (ELVs)** set at the installation level based on **BAT-Associated Emission Levels (BAT-AELs)** from BAT conclusions. • The system is therefore not a fixed EU-wide numerical standard but a performance-based framework in which the BAT conclusions adopted by Commission Implementing Decision following the 'Seville Process' set the operative ranges.
Regulation target	• Large **industrial installations** across sectors listed in Annex I (combustion plants ≥50 MW, refineries, steel, chemicals, waste management, ceramics, paper, etc.) • Also **newly in scope**: **battery manufacturing** (≥15,000 tonnes/year), cold-rolling mills, certain mining/extraction activities, and **large-scale livestock** rearing installations listed in new Annex Ia (including pig and poultry installations above 350–380 Livestock Units).
Obligations	• Operators must hold a permit before operating. Permits must set ELVs for PM and other pollutants at the strictest achievable level within the BAT-AEL range for the specific installation. Competent authorities may no longer routinely set ELVs at the laxest end of the BAT-AEL range (a key change in Article 15(3)). • For **large combustion plants** (Annex V, Part 2), indicative PM ELVs in BAT conclusions for solid-fuel combustion typically run from 2–10 mg/Nm^3 for new plants and up to 20 mg/Nm^3 for older plants, although the binding value in each permit depends on site-specific BAT assessment. • For **livestock installations**, the Commission must adopt uniform operating rules (including NH_3 and PM ELVs) by 1 September 2026 (Article 70i). • Operators of **energy-intensive installations** must include a transformation plan in their Environmental Management System (EMS) by 30 June 2030, describing how they will contribute to climate neutrality by 2050 (Article 27d). EMS must be externally implemented and audited every 3 years (Article 14a). • Financial penalties for serious infringements must reach a maximum of at least 3% of annual EU turnover (Article 79). Individuals suffering health damage from permit breaches now have a right to compensation (Article 79a).

Field	Content
Monitoring requirements	• Operators must monitor emissions continuously (for large combustion plants) or periodically (for other sectors) in accordance with BAT conclusions and CEN/ISO standards. • Results are reported to the Industrial Emissions Portal (Regulation (EU) 2024/1244), replacing the former E-PRTR register. • Competent authorities must carry out risk-based inspections, and inspection reports must be made public. • Member States must implement electronic permitting systems by 31 December 2035 (Article 5).
Planning obligations	• National Integrated Pollution Prevention & Control (IPPC) programmes; corrective measures where ELVs are exceeded • Competent authorities must reconsider and update permits within four years of publication of new or revised BAT conclusions (Article 21). • Where an environmental quality standard (such as the AAQD limit values) requires stricter conditions than BAT alone would achieve, additional measures must be included in the permit (Article 18). • For livestock installations entering scope for the first time, Member States have phased compliance timelines: 4 years (≥600 LSU), 5 years (≥400 LSU), 6 years (all others) from entry into force of the operating rules implementing act (Article 3(5)).
Flexibilities and derogations	• Competent authorities may grant derogations from BAT-AEL-based ELVs where achieving those levels would be disproportionately costly relative to the environmental benefit, due to the installation's geographical location or technical characteristics (Article 15(5)). Such **derogations**: • Must be reassessed every four years or at each permit reconsideration. • May not be granted where they would risk non-compliance with environmental quality standards. • Temporary derogations of up to 30 months are allowed for testing emerging techniques (Article 27b). In **crisis situations** (e.g., energy supply disruptions, supply chain shortfalls), less strict ELVs may be granted for up to 6 months (Article 15(7)), subject to Commission review. **Small isolated systems** (island grids) may defer compliance with combustion plant requirements until 31 December 2029 under national compliance plans (Article 34a). Deep **industrial transformation** (e.g. facility redesign or replacement) can extend permit compliance deadlines by up to eight years (Article 27e).

Field	Content
Member State discretion	• Member States choose which BAT conclusions to apply for each sector and how to set ELVs within the BAT-AEL range[380]. • They may adopt general binding rules (national or sectoral ELVs) in lieu of individual permits for certain categories (incl. livestock installations). • For livestock, Member States may choose between a permit or registration system (Article 70c). • Member States set their own penalty regimes above the 3% turnover minimum floor. • They also determine inspection frequencies within the risk-based framework and national procedures for public participation and access to justice.
Commission oversight mechanisms	• Commission adopts BAT conclusions by Implementing Decision following the Seville Process (eight-year review cycle per document, duration capped at four years per document). • The Commission must adopt operating rules for livestock by 1 September 2026 (Article 70i), a compliance assessment methodology by 1 September 2026 (Article 15a), and a delegated act specifying the content of the transformation plan by 30 June 2026 (Article 27d). • Commission reviews implementation every five years from June 2028 (Article 73). • A new Innovation Centre for Industrial Transformation and Emissions (Incite) will monitor emerging techniques and feed into BAT reviews (Article 27a). • The Commission may object to Member State crisis derogations within two months of notification (Article 15(7)). • Infringement proceedings under Article 258 TFEU remain available.
Enforcement tools in the legal design	• Direct – ELVs for $PM_{2.5}$/PM_{10} (dust) at the source reduce ambient concentrations; monitoring of stack emissions feeds air-quality modelling. • Individual permits with binding ELVs and environmental performance limit values. • Competent authorities must suspend operations where a permit breach poses immediate danger to human health or causes significant environmental harm (Article 8(3)). • For persistent non-critical breaches, suspension is discretionary (Article 8(4)). • Financial penalties for serious infringements by legal persons must not exceed 3% of annual EU turnover (Article 79). • **Individuals now have a statutory right to compensation for health damage from permit breaches** (Article 79a). This is a new and significant enforcement mechanism. • Infringement proceedings under Article 258 TFEU for failure to transpose or apply the Directive.

[380] Subject to the Article 15(3) requirement to aim at the strictest achievable level.

Field	Content
Direct vs indirect relevance to PM exposure	• **Direct.** The IED reduces $PM_{2.5}$ and PM_{10} at source through permit-based ELVs (dust limits) for large industrial emitters. The BAT conclusions for large combustion plants, iron and steel, cement, glass, and other sectors include specific dust ELVs that, when applied, directly reduce stack PM emissions and their contribution to ambient concentrations. • The 2024 expansion to livestock rearing adds coverage of ammonia (NH_3) and PM from intensive pig and poultry facilities. Because ammonia is a key precursor of secondary $PM_{2.5}$ (ammonium salts), this is a significant new pathway for reducing PM exposure. • The IED also operates alongside the AAQD, where ambient air quality standards are not met. Article 18 requires permit conditions to be tightened beyond what BAT alone would require, creating a direct link between ambient PM targets and individual installation controls. • The new transformation plan obligation (Article 27d) should, over time, accelerate the phase-out of the most polluting industrial processes.

Directive (EU) 2016/2284 – National Emission Ceilings Directive

Field	Content
Instrument title and reference	• Directive (EU) 2016/2284 of the European Parliament and of the Council of 14 December 2016 on the reduction of national emissions of certain atmospheric pollutants, amending Directive 2003/35/EC and repealing Directive 2001/81/EC.
Legal basis	• Article 192(1) TFEU (environmental policy, ordinary legislative procedure) (recital 38).
Stated objective(s)	• To move towards levels of air quality that do not give rise to significant negative impacts on and risks to human health and the environment, by establishing national emission reduction commitments for SO_2, NO_x, NMVOC, NH_3 and **$PM_{2.5}$**, and requiring the preparation, adoption and implementation of national air pollution control programmes (Art. 1(1)). The directive also contributes to **achieving EU air quality objectives in line with WHO air quality guidelines**, EU biodiversity and ecosystem objectives, and **enhanced synergies between air quality policy and climate and energy policies** (Art. 1(2)).
Type of regulatory approach	• Binding national emission reduction commitments (as percentage reductions from a 2005 baseline), applicable from 2020 to 2029 and from 2030 onwards (Art. 4(1), Annex II). **Compliance is pursued through national air pollution control programmes, emission inventories and projections, and reporting obligations**. The directive does not impose source-level emission limit values; it **sets aggregate national ceilings** and **leaves the choice of abatement measures to Member States**.
Regulation target	• Anthropogenic atmospheric emissions from all sources occurring in the territory of Member States, their exclusive economic zones and pollution control zones (Art. 2(1)). **Pollutants subject to binding reduction commitments:** SO_2, NO_x, NMVOC, NH_3, and **$PM_{2.5}$** (Art. 1(1), Annex II). **PM_{10} is not subject to a reduction commitment** but is included in mandatory annual emission reporting (Annex I, Table A). • Emissions from the Canary Islands, French overseas departments, Madeira and the Azores are excluded (Art. 2(2)).

Field	Content
Obligations	Member States must: • Limit annual anthropogenic emissions of the five covered pollutants in accordance with Annex II commitments from 2020 (Art. 4(1)). • Take measures aimed at meeting indicative 2025 emission levels on a **linear trajectory between 2020 and 2030 commitments**; explain and remedy any deviation in subsequent informative inventory reports (Art. 4(2)). • Draw up, adopt and implement NAPCPs in accordance with Annex III Part 1, including **obligatory measures on agricultural NH_3 and on $PM_{2.5}$ and black carbon** set out in Annex III Part 2 (Arts. 6(1)–(2)). • **Prioritise black carbon reduction** measures when pursuing **$PM_{2.5}$** commitments (Art. 6(2)(c)). • Prepare and annually update **national emission inventories for $PM_{2.5}$ and PM_{10}** by NFR source category (Annex I, Table A); every four years, spatially disaggregated inventories and large point source inventories; every two years, emission projections for PM2.5 (Annex I, Tables A–C; Art. 8). • Report inventories, projections and informative inventory reports to the Commission and EEA at dates specified in Annex I (Art. 10(2)).
Monitoring requirements	• Annual $PM_{2.5}$ and PM_{10} emission inventories by source category, covering the time series from 2000, reported by 15 February (Annex I, Table A). • Spatially disaggregated inventories and large point source inventories for $PM_{2.5}$ and PM_{10} every four years by 1 May; $PM_{2.5}$ emission projections every two years by 15 March covering 2020, 2025, 2030 and where available 2040 and 2050 (Annex I, Table C). • Annual informative inventory reports covering $PM_{2.5}$, PM_{10} and black carbon by 15 March (Annex I, Table D). • All inventories must be prepared using EMEP Reporting Guidelines and the EMEP/EEA Guidebook (Annex IV, Part 1). • Member States must also monitor air pollution impacts on ecosystems through a representative network, using optional indicators in Annex V (Art. 9).
Planning obligations	• NAPCPs must cover the minimum content in Annex III Part 1: policy framework, assessment of options, selected measures with timetable and responsible authorities, and coherence with other plans. • Updates are required at least every four years (Art. 6(3)), or within 18 months of submission of the latest inventory or projections where non-compliance is identified or at risk (Art. 6(4)). • Draft programmes and significant updates must be subject to public consultation before finalisation (Art. 6(5)).

Field	Content
Flexibilities and derogations	• Inventory adjustment (Art. 5(1)): adjusted $PM_{2.5}$ inventories permitted where non-compliance results from applying scientifically updated emission inventory methods, subject to conditions in Annex IV Part 4 and Commission review. • Three-year averaging (Art. 5(2)): where exceptional weather prevents compliance, emissions may be averaged across the year in question and the preceding and following years, provided the average does not exceed the commitment. • Over-commitment flexibility (Art. 5(3)): where a commitment exceeds the cost-effective reduction in TSAP 16, a Member State may be deemed compliant for up to five years by compensating with an equivalent reduction in another covered pollutant. • Energy supply disruption (Art. 5(4)): non-compliance excused for up to three years following a sudden, unforeseeable interruption of power or heat supply capacity, subject to demonstration of all reasonable mitigation efforts. • All flexibilities require notification by 15 February of the reporting year and are subject to Commission acceptance within nine months (Art. 5(5)–(6)).
Member State discretion	• Choice of policies and measures across all relevant sectors to meet commitments (Art. 6(2), recital 19). • Optional measures in Annex III Part 2 for NH_3 and $PM_{2.5}$/black carbon may be included or replaced by equivalent measures. • Small and micro farms may be exempted from agricultural abatement measures where appropriate (Annex III Part 2, Section C). • Road transport compliance may be calculated on fuels sold or, for Member States with an existing LRTAP Convention option, fuels used (Annex II footnote).
Commission oversight mechanisms	• Review and acceptance of flexibility applications within nine months (Art. 5(6)). • Examination of NAPCPs against Arts. 4(2) and 6, with results published on the Commission website (Arts. 10(1), 14(3)(c)). • Four-yearly implementation reports to the European Parliament and Council from 1 April 2020, covering progress towards $PM_{2.5}$ commitments and health, environmental and socioeconomic impacts (Art. 11(1)). • Where non-achievement may result from ineffective Union source-based legislation, the Commission investigates and may present legislative proposals (Art. 11(2)). • Directive review by 31 December 2025 (Art. 13(1)). • Delegated acts to adapt Annexes I, III Part 2, IV and V to LRTAP and technical developments (Arts. 6(8), 8(7), 9(3)).
Enforcement tools in the legal design	• Member States must provide for effective, proportionate and dissuasive penalties for infringements of national transposition measures (Art. 18). • NAPCPs are subject to mandatory public consultation under Directive 2003/35/EC, to which Art. 6(1) of this directive is added (Art. 19). • Commission review of inventory data may result in Commission-imposed technical corrections where agreement cannot be reached (Art. 10(3)). • Infringement proceedings under Article 258 TFEU remain available for non-compliance with binding reduction commitments.

Field	Content
Direct vs indirect relevance to PM exposure	• Direct and indirect. The directive establishes **binding $PM_{2.5}$ national reduction commitments for 2020–2029** and from 2030, ranging from 19% (Sweden) to 70% (Cyprus) relative to 2005 (Annex II, Table B). **Reductions in NH_3, NO_x and SO_2 required under the same instrument are indirectly relevant**, as these are primary precursors of secondary inorganic $PM_{2.5}$ (ammonium nitrate, ammonium sulphate). **NAPCPs must address both $PM_{2.5}$ and NH_3 sources**, including through mandatory agricultural measures and optional controls on open-field burning. PM_{10} is not subject to a reduction commitment but is included in the mandatory inventory and reporting framework.

Directive (EU) 2015/2193 - Medium Combustion Plants Directive

Field	Content
Instrument title and reference	• Directive (EU) 2015/2193 of the European Parliament and of the Council of 25 November 2015 on the limitation of emissions of certain pollutants into the air from medium combustion plants.
Legal basis	• Article 192(1) TFEU (environmental policy, ordinary legislative procedure).
Stated objective(s)	• To control emissions of SO_2, NO_x and dust into the air from medium combustion plants and thereby reduce emissions to air and the potential risks to human health and the environment (Art. 1).
Type of regulatory approach	• Source-based **emission limit values (ELVs) for SO_2, NO_x and dust**, differentiated by plant type (combustion plant, engine, gas turbine), fuel type, thermal capacity class and new/existing plant status (Annex II). Compliance is secured through a permit or registration requirement prior to operation, periodic operator monitoring, and competent authority compliance checks.
Regulation target	• Combustion plants with a rated thermal input of **≥ 1 MW and < 50 MW, irrespective of fuel type** (Art. 2(1))
Obligations	• New plants must hold a permit or registration from 20 December 2018; existing plants > 5 MW by 1 January 2024; plants ≤ 5 MW by 1 January 2029 (Art. 5). • New plants must comply with Annex II Part 2 ELVs from 20 December 2018 (Art. 6(7)). Dust ELVs for new plants firing solid or liquid fuels other than gas oil: 20 mg/Nm^3 for combustion plants; 10 mg/Nm^3 for engines and gas turbines. • Existing plants > 5 MW must comply with Annex II Part 1 Tables 2 and 3 from 1 January 2025; plants ≤ 5 MW with Tables 1 and 3 from 1 January 2030. Dust ELVs for existing solid fuel plants: 30 mg/Nm^3 (> 5 MW) and 50 mg/Nm^3 (≤ 5 MW). • **Operators must carry out periodic emission monitoring** per Annex III, retain records **for at least six years** and make data available to the competent authority on request (Arts. 7(1), (5), (6)). • Where **non-compliance causes significant degradation of local air quality, operation must be suspended** until compliance is restored (Arts. 7(7), 8(3)). • Member States must report to the Commission by 1 October 2026 and 1 October 2031 on implementation, compliance and enforcement, including estimated total annual emissions of SO_2, NO_x and dust by plant type, fuel type and capacity class (Art. 11(1)).

Field	Content
Monitoring requirements	• Periodic measurements of dust (alongside SO_2, NO_x and CO) at minimum frequencies per Annex III Part 1: at least every three years for plants of 1–20 MW; at least annually for plants > 20 MW. • First measurements must be completed within four months of permit grant, registration or start of operation. • Member States may require continuous measurements in lieu of periodic ones.
Planning obligations	• National air-quality plans must incorporate MCP compliance. Where zones do not comply with Directive 2008/50/EC air quality limit values, Member States must assess the need to apply stricter ELVs (including for dust) to individual plants in those zones as part of air quality plan development under Art. 23 of Directive 2008/50/EC (Art. 6(9)).
Flexibilities and derogations	• Phased compliance deadlines apply by capacity class; multiple category-specific exemptions from dust ELVs are available until 1 January 2030, subject to fallback limits set by the competent authority (Arts. 6(3)–(6), 6(8)).
Member State discretion	• Choice of permit or registration system, with the option to use general binding rules for plant categories (Art. 5(6)). Option to require continuous rather than periodic monitoring. Option to apply stricter ELVs under Art. 193 TFEU. Decisions on whether to apply available derogations for low-use, district heating, biomass and isolated system plants (Arts. 6(3)–(6)).
Commission oversight mechanisms	• Review from 1 January 2023 and **every ten years** thereafter on whether **ELVs for new plants should be revised**; results reported to the European Parliament and Council with legislative proposals where appropriate (Art. 12(2)–(3)). • **Delegated acts may adapt** Annex III Part 2 **compliance assessment provisions** to technical and scientific progress (Art. 13). • **Infringement proceedings** under Art. 258 TFEU remain available.
Enforcement tools in the legal design	• **Permit or registration** as a precondition for operation (Art. 5). • **Mandatory suspension of operation** where non-compliance causes significant degradation of local air quality (Art. 8(3)). • Member States must provide for effective, proportionate and dissuasive **penalties** (Art. 16).
Direct vs indirect relevance to PM exposure	• Direct. The directive sets legally binding dust ELVs for combustion plants across the 1–50 MW range, directly reducing primary $PM_{2.5}$ and PM_{10} emissions at source.

Regulation (EU) 2016/1628 - Non-Road Mobile Machinery

Field	Content
Instrument title and reference	• Regulation (EU) 2016/1628 of the European Parliament and of the Council of 14 September 2016 on requirements relating to gaseous and particulate pollutant emission limits and type-approval for internal combustion engines for non-road mobile machinery (NRMM).
Legal basis	• Article 114 TFEU (internal market harmonisation).
Stated objective(s)	• "To lay down harmonised EU type-approval rules and Stage V emission limits for NRMM engines, reducing PM and NO_x emissions and achieving convergence with on-road vehicle standards." • Recital 16 explicitly identifies **NRMM as responsible for a significant share of total man-made PM** and NO_x emissions.
Type of regulatory approach	• Directly applicable Regulation setting binding Stage V emission limits as a pre-market condition. Technical specifications are delegated to Commission delegated and implementing acts (Arts. 55–56).
Regulation target	• Internal combustion engines for NRMM across ten categories (NRE, NRG, NRSh, NRS, IWP, IWA, RLL, RLR, SMB, ATS), covering construction, agricultural, inland waterway, railway, and recreational machinery.
Obligations	• Manufacturers must hold a valid EU type-approval before placing engines on the market and must ensure conformity of production (Arts. 8, 18, 26). Defeat strategies are explicitly prohibited (Art. 18(4)). In-service emission monitoring must be conducted under manufacturer responsibility from the start of production (Art. 19). OEMs must install approved engines without adversely affecting emission performance; an OEM that modifies an engine during installation is treated as the manufacturer (Art. 15).
Monitoring requirements	• Conformity of production checks by approval authorities, including at manufacturer premises (Art. 26). In-service emission monitoring by manufacturers on engines under normal operating conditions (Art. 19). National market surveillance authorities must carry out risk-based documentary, physical, and laboratory checks (Art. 7). The Commission must conduct annual monitoring programmes comparing test-cycle results with real-world emissions and publish results yearly (Art. 19(1)).
Planning obligations	• No national air quality planning obligation. Compliance is achieved through the pre-market type-approval gate. Manufacturers must submit an in-service monitoring plan to the approval authority within one month of the start of production (Art. 20(4)). Commission review reports are due on retrofit potential (by 31 December 2018), further emission reduction potential (by 31 December 2020), and in-service testing effectiveness (by 31 December 2025) (Art. 60).
Flexibilities and derogations	• Transitional periods for existing plants (e.g., ≤ 5 MW plants have later deadlines)
Member State discretion	• Limited. Member States may not impose additional emission requirements on engines meeting the Regulation's requirements (Arts. 5(4), 22(2)).
Commission oversight mechanisms	• Delegated acts covering technical specifications for test procedures, in-service monitoring, conformity of production, and measurement methodology (Art. 55). Implementing acts via the Technical Committee: Motor Vehicles (TCMV). All EU type-approval data exchanged and published via the Internal Market Information System (Art. 44). • The Commission may investigate technical service competence and require corrective action (Art. 52).

Field	Content
Enforcement tools in the legal design	• Pre-market type-approval gate is the primary enforcement mechanism (Art. 5(3)).
Direct vs indirect relevance to PM exposure	• Direct. The Regulation sets binding engine-out PM mass (g/kWh) and particle number (#/kWh) limits as a condition of market access, directly reducing PM emissions from NRMM engines.

Regulation (EC) No 715/2007 and related acts - Euro 6 vehicle emission standards

Field	Content
Instrument title and reference	• Regulation (EC) No 715/2007 of the European Parliament and of the Council of 20 June 2007 on type approval of motor vehicles with respect to emissions from light passenger and commercial vehicles (Euro 5 and Euro 6), as amended most recently by Regulation (EU) 2018/858. Consolidated text as of 1 September 2020 (02007R0715-20200901).
Legal basis	• Article 114 TFEU (internal market).
Stated objective(s)	• To reduce air pollutant emissions from motor vehicles in order to protect human health and the environment, while harmonising the technical requirements for vehicle type approval across the internal market.
Type of regulatory approach	• Binding EU regulation establishing fixed numerical emission limit values for tailpipe pollutants, enforced through a pre-market type-approval system. Manufacturers must obtain EU type approval before placing vehicles on the market; compliance is verified through standardised test procedures.
Regulation target	• Light-duty motor vehicles: passenger cars (M1), light vans (N1, three classes by reference mass), and certain light commercial vehicles (N2) with reference mass not exceeding 2,610 kg (extendable to 2,840 kg at manufacturer's request). Both petrol (positive ignition) and diesel (compression ignition) drivetrains are covered.
Obligations	• Manufacturers must ensure all new vehicles sold, registered, or put into service in the EU are type-approved in compliance with the emission limits in Annex I. Manufacturers must also ensure durability of pollution control devices over 160,000 km; in-service conformity for up to 5 years or 100,000 km; and functioning OBD systems. The use of defeat devices that reduce the effectiveness of emission control systems is prohibited (Article 5(2)).
Monitoring requirements	• Compliance verified through standardised type-approval test procedures. Manufacturers must ensure in-service conformity, verified by testing vehicles drawn from the in-use fleet. OBD systems must identify and store fault codes for emission control malfunctions. Competent national authorities oversee market surveillance and can require recall or withdrawal of type approval.
Planning obligations	• None. The regulation does not require national action plans or planning instruments at Member State level.

Field	Content
Flexibilities and derogations	• Phased implementation timelines apply, with differentiated dates for new type approvals versus all new vehicle registrations, and for N1 Class II/III and N2 vehicles. A transitional PM mass limit of 5.0 mg/km applied to vehicles type-approved under the previous measurement protocol before 1 September 2011. Member States may grant financial incentives for early compliance or for retrofitting and scrapping of older vehicles (Article 12), subject to the ceiling that incentives may not exceed the cost of the relevant technical devices.
Member State discretion	• Limited. Member States must refuse type approval or prohibit registration of non-compliant vehicles from the mandatory dates. They retain discretion over: penalty regimes for manufacturer infringements (Article 13), subject to effectiveness, proportionality, and dissuasiveness requirements; design of financial incentive schemes under Article 12, subject to Commission notification; and market surveillance and enforcement.
Commission oversight mechanisms	• The Commission adopts implementing and delegated measures on test procedures, OBD requirements, in-service conformity, and related technical matters (Article 5(3)). It keeps test procedures and cycles under review and must adapt them if they no longer adequately reflect real-world emissions (Article 14(3)). The Commission may review emission limits and propose revisions to Parliament and Council (Article 14).
Enforcement tools in the legal design	• National authorities must refuse type approval for non-compliant new vehicle types from the mandatory dates, and refuse registration, sale, or entry into service of non-compliant new vehicles from the registration-prohibition dates, treating certificates of conformity as invalid. Sale or installation of non-compliant replacement pollution control devices is prohibited (Article 11). Penalties apply to manufacturer infringements, including the use of defeat devices, falsification of test results, and withholding of data (Article 13(2)).
Direct vs indirect relevance to PM exposure	• **Direct.** The regulation sets binding numerical limits on tailpipe PM mass (mg/km) and particle number (#/km) for all new light-duty vehicles placed on the EU market, directly reducing exhaust $PM_{2.5}$ and PM_{10} emissions from the road transport sector.

Regulation (EU) 2024/1257 – Euro 7 vehicle emission standards

Field	Content
Instrument title and reference	• Regulation (EU) 2024/1257 of the European Parliament and of the Council of 24 April 2024 on type-approval of motor vehicles and engines and of systems, components and separate technical units intended for such vehicles, with respect to their emissions and battery durability (Euro 7). Published OJ L 2024/1257, 8 May 2024. Repeals Regulations (EC) No 715/2007 and (EC) No 595/2009 with effect from 1 July 2030 and 1 July 2031 respectively.
Legal basis	• Article 114 TFEU (internal market).
Stated objective(s)	• To establish common technical requirements and administrative provisions for the emission type-approval and market surveillance of motor vehicles with regard to their pollutant emissions.

Field	Content
Type of regulatory approach	• Binding EU regulation establishing fixed numerical emission limit values enforced through a pre-market type-approval system, extended to cover non-exhaust emissions (brake particle emissions and tyre abrasion) alongside exhaust emissions. The regulation consolidates the previously separate light-duty (Euro 6) and heavy-duty (Euro VI) frameworks into a single instrument.
Regulation target	• All motor vehicle categories: M1, M2, M3, N1, N2, N3, trailers of categories O3 and O4, and C1, C2 and C3 class tyres. Brake systems are also within scope as separately type-approved components.
Obligations	• Manufacturers must ensure all new vehicles are type-approved in compliance with the PM-relevant emission limits set out in Annex I for the full vehicle lifetime as defined in Annex IV. Brake particle PM_{10} limits are introduced across all vehicle categories, with limits differentiated by powertrain type and a harmonised limit applying from 1 January 2035 (Annex I, Tables 4–8). Tyre abrasion limits are to be set by delegated act (Annex I, Table 9; Article 15(2)).
Monitoring requirements	• Compliance is verified through laboratory tests and mandatory RDE tests. Brake emissions are tested in accordance with UN Global Technical Regulation No 24. In-service conformity testing covers the full vehicle lifetime. OBM systems must continuously monitor exhaust PM and communicate data via the OBD port and anonymously over the air (Article 6(6)). National authorities conduct market surveillance in accordance with Annex V.
Planning obligations	• None.
Flexibilities and derogations	• The regulation provides phased application dates, differentiating between new type approvals and registration prohibitions, and between light-duty and heavy-duty vehicles (Article 10). Small-volume manufacturers benefit from deferred application dates and may substitute certain type-approval tests with declarations of compliance (Article 8). Brake particle limits from 2030, and tyre abrasion limits are contingent on the Article 18(5) review.
Member State discretion	• Limited. Member States retain discretion over penalty regimes and market surveillance activities.
Commission oversight mechanisms	• The Commission must adopt implementing acts on test procedures for M1/N1 by 29 May 2025 and for heavy-duty vehicles by 29 November 2026 (Article 14(8) and (9)). Delegated acts are required to set brake particle emission limits after the Article 18(5) review, and tyre abrasion limits by the deadlines in Article 15(2) and (3). A report on brake particle emissions is required by 31 December 2027. An evaluation report on achieved emission reductions is required by 1 September 2031.
Enforcement tools in the legal design	• National authorities must refuse type approval for non-compliant new vehicle types and prohibit registration of non-compliant new vehicles from the mandatory dates. Sale or installation of non-compliant brake systems and components is prohibited (Article 11). Penalties under the amended Regulation (EU) 2018/858 apply to use of manipulation devices or strategies and falsifying in-service conformity test results.
Direct vs indirect relevance to PM exposure	• **Direct.** The regulation sets binding limits on exhaust PM mass from all vehicle categories, reducing primary $PM_{2.5}$ and PM_{10} from road transport.

Directive 98/70/EC – Fuel Quality Directive

Field	Content
Instrument title and reference	• Directive 98/70/EC of the European Parliament and of the Council of 13 October 1998 relating to the quality of petrol and diesel fuels and amending Council Directive 93/12/EEC (OJ L 350, 28.12.1998, p. 58). Consolidated version of 24 December 2018.
Legal basis	• Article 95 EC Treaty (internal market with high level of health and environmental protection), as applied by Directive 2009/30/EC.
Stated objective(s)	• "To improve the quality of petrol and diesel fuels in order to reduce emissions of pollutants (including PM) and protect health and the environment"
Type of regulatory approach	• **Product standard regulation.** Binding fuel quality specifications, sulphur content limits, polycyclic aromatic hydrocarbon (PAH) content limits, and metallic additive limits expressed as maximum values in Annexes I and II and Art. 8a.
Regulation target	• Suppliers placing **petrol and diesel fuels** on the market in EU Member States for use in **road vehicles**, non-road mobile machinery (including **inland waterway vessels** when not at sea), **agricultural and forestry tractors**, and **recreational craft** when not at sea (Art. 1)
Obligations	Member States must: • Prohibit the marketing of petrol with sulphur content exceeding 10 mg/kg (Annex I). • Prohibit the marketing of diesel with sulphur content exceeding 10 mg/kg (Annex II). • Ensure that diesel does not exceed 8% m/m polycyclic aromatic hydrocarbons (Annex II). • Ensure that gas oils for non-road mobile machinery, agricultural and forestry tractors, and recreational craft contain no more than 10 mg/kg sulphur from 1 January 2011 (Art. 4(2)). • The metallic additive MMT must not exceed 6 mg manganese per litre from 1 January 2011 and 2 mg manganese per litre from 1 January 2014 (Art. 8a(2)).
Monitoring requirements	Member States must: • Monitor compliance with Arts. 3 and 4. • Establish a fuel quality monitoring system (Art. 8(2)). • Submit an annual national fuel quality data report to the Commission by 31 August each year.
Planning obligations	• None.
Flexibilities and derogations	• The directive provides five derogation routes covering geographic exceptions for outermost regions, a mechanism for Member States to apply more stringent local specifications, a supply chain tolerance for minor sulphur contamination, an expired transitional provision, and an emergency Commission authorisation in the event of crude oil supply disruption. All routes that relax sulphur limits carry direct PM relevance given the dependency of diesel particulate filter operation on low-sulphur fuel.

Field	Content
Member State discretion	• Member States may: • Adopt a replacement analytical method if it demonstrates at least equivalent accuracy and precision (Annexes I and II, footnotes). • Permit diesel with a FAME content greater than 7% to be placed on the market, notwithstanding the Annex II specification (Art. 4(1)).
Commission oversight mechanisms	• Member States submit annual fuel quality data reports; the Commission makes these publicly available (Arts. 8(3)–(4)). • Commission adopts implementing acts establishing a common format for national fuel quality data reports (Art. 8(3)). • Commission reports to the European Parliament and Council by 31 December 2012 and every three years thereafter, covering fuel technology developments and metallic additives other than MMT (Art. 9). • Commission may reject a Member State vapour pressure derogation where the assessment shows it would cause non-compliance with EU air quality legislation, including relevant limit values and emissions ceilings (Art. 3(5)).
Enforcement tools in the legal design	• Member States must determine penalties applicable to breaches of national provisions; penalties must be effective, proportionate and dissuasive (Art. 9a). • Member States may not prohibit, restrict or prevent the marketing of fuels complying with the directive's requirements (Art. 5).
Direct vs indirect relevance to PM exposure	• **Direct.** Sulphur in petrol and diesel degrades catalytic converters and particulate filters; the 10 mg/kg sulphur cap in petrol (Annex I) and diesel (Annex II) enables the effective operation of diesel particulate filters (DPFs), which remove $PM_{2.5}$ and PM_{10} directly from exhaust. The cap on polycyclic aromatic hydrocarbons in diesel (≤8% m/m, Annex II) reduces the formation of carbonaceous fine particles and secondary organic aerosol precursors during combustion. The MMT limit (Art. 8a) reduces metallic particle emissions in exhaust from manganese compound combustion.

Nitrates Directive (91/676/EEC)

Field	Content
Instrument title and reference	• Council Directive 91/676/EEC of 12 December 1991 concerning the protection of waters against pollution caused by nitrates from agricultural sources (OJ L 375, 31.12.1991, p. 1)
Legal basis	• Article 130s EEC Treaty (environment)
Stated objective(s)	• To reduce water pollution caused or induced by nitrates from agricultural sources and to prevent further such pollution (Article 1).
Type of regulatory approach	• Framework directive requiring Member States to identify nitrate-vulnerable zones, establish codes of good agricultural practice, and adopt mandatory action programmes limiting nitrogen application in those zones.
Regulation target	• Agricultural nitrogen application to land, with particular focus on livestock manure and chemical fertilisers in designated vulnerable zones (Articles 3–5; Annex III).

Field	Content
Obligations	• Member States must designate vulnerable zones draining into affected waters within two years of notification and establish action programmes for those zones within a further two years (Articles 3(2) and 5(1)). Member-states must develop Nitrate Action Programmes (NAPs) with measures to reduce nitrate leaching. Limits on fertiliser application rates (≤ 170 kg N per hectare).
Monitoring requirements	• Member States must monitor nitrate concentrations in freshwaters and groundwaters at representative sampling stations at least every four years (Article 6).
Planning obligations	• Action programmes must be reviewed and revised at least every four years (Article 5(7)); vulnerable zone designations must be reviewed on the same cycle (Article 3(4)). Member States must submit four-yearly implementation reports to the Commission covering monitoring results, summaries of action programmes, and expected timescales for water quality improvement (Article 10; Annex V).
Flexibilities and derogations	• Member States may apply action programmes across their entire national territory in lieu of designating specific vulnerable zones (Article 3(5)). The 170 kg N/ha cap may be exceeded during the first four-year action programme (up to 210 kg N) and may be varied thereafter on the basis of objective agronomic criteria, including long growing seasons, crops with high nitrogen uptake, and high net precipitation, subject to Commission notification (Annex III(2)(b)).
Member State discretion	• Member States determine the geographic scope of action programmes, the specific fertiliser application restrictions within the Annex III framework, and may include additional items in codes of good agricultural practice (Annex II B). They set their own monitoring network design within the criteria of Article 6.
Commission oversight mechanisms	• The Commission publishes summary reports within six months of receiving Member State implementation reports and submits a review with proposals for revision to the Council by 1 January 1998 (Article 11). Annexes may be adapted to scientific and technical progress through committee procedure (Article 8).
Enforcement tools in the legal design	• No penalties are specified. Implementation is enforced through the reporting and review cycle and, where necessary, infringement proceedings under the Treaty.
Direct vs indirect relevance to PM exposure	• **Primary precursor relevance** as a governance gap. The Directive regulates land application of nitrogen compounds from agricultural sources exclusively for the purpose of protecting water quality; **it contains no reference to air quality, particulate matter, or ammonia emissions**. The nitrogen applied to land that the Directive seeks to keep out of water volatilises as ammonia, a dominant precursor of **secondary inorganic $PM_{2.5}$ (ammonium nitrate, ammonium sulphate).**

Common Agriculture Policy (CAP) — Regulation 2021/2115

Filed	Content
Instrument title and reference	• Regulation (EU) 2021/2115 of the European Parliament and of the Council of 2 December 2021 establishing rules on support for strategic plans to be drawn up by Member States under the common agricultural policy (CAP Strategic Plans) (OJ L 435, 6.12.2021, p. 1); and
Legal basis	• Article 43(2) TFEU (common agricultural policy)
Stated objective(s)	• To support sustainable agricultural development by establishing Union-level objectives within which Member States design national CAP Strategic Plans, contributing to climate action, environmental protection, and the preservation of natural resources (Article 5).
Type of regulatory approach	• Performance-based framework regulation establishing Union objectives and mandatory baseline requirements within which Member States design and implement national CAP Strategic Plans. Substantive environmental standards are enforced through a conditionality framework and incentivised through voluntary eco-schemes and agri-environment-climate commitments. No direct emission limit values are set.
Regulation target	• Agricultural holdings receiving CAP payments across the EU. Conditionality applies to all direct payment beneficiaries and certain rural development payment beneficiaries (Regulation 2021/2115, Article 12). Eco-schemes and agri-environment-climate interventions are voluntary for farmers but mandatory for Member States to offer (Articles 31 and 70).
Obligations	• Member States must apply conditionality requiring beneficiaries to comply with statutory management requirements (SMRs) and good agricultural and environmental conditions (GAECs) as a condition of receiving payments (Articles 12–13; Annex III). • **Of PM relevance: SMRs include compliance with Directive (EU) 2016/2284 (NEC Directive) and Directive 91/676/EEC (Nitrates Directive)**, both of which govern agricultural nitrogen and ammonia management. GAEC 2 requires maintaining a minimum soil cover, which reduces dust and particulate resuspension **from agricultural land**. • Member States must include eco-schemes offering annual payments for practices beneficial to climate and the environment, which may **include ammonia emission reduction measures** such as low-emission manure application and covered storage (Article 31). Member States must offer agri-environment-climate commitments within rural development interventions that go beyond baseline conditionality, including **precision fertilisation and livestock management practices that reduce ammonia volatilisation** (Article 70).
Monitoring requirements	• Member States must monitor implementation through a common result and impact indicator framework (Article 7; Annex I). **Impact indicator I.14 covers ammonia emissions from agriculture**, providing a direct monitoring link to $PM_{2.5}$ precursor reduction as a measurable CAP outcome. Annual performance reports must be submitted to the Commission (Article 134).
Planning obligations	• Member States must submit CAP Strategic Plans to the Commission for approval before implementation, covering the full 2023–2027 period (Articles 118–119).

Filed	Content
Flexibilities and derogations	• Member States have broad discretion in designing eco-schemes and agri-environment-climate commitments, **including whether ammonia reduction measures are offered and at what payment rate**. Conditionality penalties are subject to a proportionality principle and may be waived where non-compliance has insignificant consequences for the objective of the standard concerned (Article 85(3) of Regulation 2021/2116 as applicable).
Member State discretion	• Extensive. Member States determine which voluntary interventions to offer, at what level of ambition, and with what payment rates, in line with Union objectives and basic requirements. **Whether ammonia-reducing agricultural practices are prioritised in eco-schemes or agri-environment-climate commitments is a national decision.** Member States may also establish additional conditionality requirements beyond the Union baseline.
Commission oversight mechanisms	• The Commission approves CAP Strategic Plans and monitors performance against agreed targets through annual performance reviews and a multiannual performance monitoring framework (Articles 128 and 135). It may request action plans and, under Regulation 2021/2116, suspend or reduce payments where targets are not met.
Enforcement tools in the legal design	• Non-compliance with conditionality requirements results in proportional reductions to CAP payments. The standard reduction is 3%, rising to 15% for intentional non-compliance, as set out in Regulation 2021/2116. The Regulation itself establishes no standalone penalty mechanism.
Direct vs indirect relevance to PM exposure	• **Primary precursor relevance** via the agricultural ammonia pathway. **Agriculture is the dominant source of ammonia in the EU, and ammonia is the primary precursor to secondary inorganic $PM_{2.5}$** (ammonium nitrate and ammonium sulphate) in agriculturally intensive Member States. The Regulation's relevance to $PM_{2.5}$ operates through three channels: ○ First, the monitoring framework includes **ammonia emissions from agriculture as an explicit impact indicator** (I.16), embedding $PM_{2.5}$ precursor reduction as a measurable CAP outcome. ○ Second, eco-schemes and agri-environment-climate commitments **may incentivise practices that directly reduce ammonia volatilisation**. ○ Third, the conditionality framework makes CAP payments conditional on compliance with the NEC Directive and Nitrates Directive SMRs. The extent to which these channels translate into $PM_{2.5}$ reductions depends entirely on Member States' choices in the design of the CAP Strategic Plan and the ambition of national eco-scheme offerings. The Regulation imposes no direct emission limits and establishes no minimum environmental outcomes for air quality.

4.1.2. Other instruments with indirect co-benefits

Directive (EU) 2024/1781 - Ecodesign requirements for sustainable products

Field	Content
Instrument title and reference	• Regulation (EU) 2024/1781 of the European Parliament and of the Council of 13 June 2024 establishing a framework for the setting of ecodesign requirements for sustainable products, amending Directive (EU) 2020/1828 and Regulation (EU) 2023/1542 and repealing Directive 2009/125/EC (OJ L, 28.6.2024)
Legal basis	• Article 114 TFEU (internal market)
Stated objective(s)	• To improve the environmental sustainability of products in order to make sustainable products the norm, to reduce the overall carbon and environmental footprint of products over their life cycle, and to ensure the free movement of sustainable products within the internal market (Article 1(1)).
Type of regulatory approach	• Framework regulation empowering the Commission to adopt product-specific or horizontal delegated acts setting: o Performance requirements (quantitative or non-quantitative, based on product parameters listed in Annex I) o Information requirements (including a mandatory digital product passport). • All substantive thresholds and obligations are established through delegated acts
Regulation target	• All physical goods placed on the market, including components (Article 1(2)). The first working plan must **prioritise energy-related products** (including those for which existing measures under Directive 2009/125/EC are to be reviewed), textiles, furniture, **tyres**, and ICT products (Article 18(5)). **Of direct PM relevance**: **solid-fuel boilers**, local space **heaters** and **combustion appliances** are identified in Article 79(1)(a) as products for which preparatory work under Directive 2009/125/EC may be completed under transitional provisions until 31 December 2026.
Obligations	• Delegated acts set binding performance requirements. Of PM relevance, **Annex I explicitly lists emissions to air** released in one or more life cycle stages as a product parameter (Annex I, point (q)), providing a direct legal basis for PM emission requirements in delegated acts covering combustion products. Manufacturers must ensure products comply with all applicable performance requirements; carry out conformity assessment; draw up an EU declaration of conformity; and maintain technical documentation for ten years (Article 27). Delegated acts may require manufacturers to equip products to measure in-use energy consumption and other performance parameters (Article 37(2)–(3)) and to report non-personal in-use data to the Commission (Article 37(4)).
Monitoring requirements	• Delegated acts may require manufacturers to collect and report non-personal in-use performance data to the Commission at least annually (Article 37(4)–(5)), which for combustion appliances could include emissions-relevant parameters. Market surveillance authorities must include ecodesign-specific sections in their national market surveillance strategies (Article 66); the Commission publishes a benchmarking report every four years (Article 67(2)).

Field	Content
Planning obligations	• The Commission must adopt a working plan at least every three years listing prioritised product groups (Article 18(3)), with the first due by 19 April 2025. Energy-related products, including combustion appliances relevant to residential PM2.5, must be included (Article 18(5)(j)). **Ecodesign requirements for cement** must be adopted not earlier than 31 December 2028 and not later than 1 January 2030 (Article 18(6)).
Flexibilities and derogations	• Delegated acts must allow at least 18 months between entry into force and the date of application (Article 4(4)). Implementing measures adopted under Directive 2009/125/EC remain in force until repealed by a delegated act; transitional provisions extend this for specified combustion appliances until 31 December 2026 (Article 79).
Member State discretion	• Member States may set minimum energy performance requirements for buildings under Directive (EU) 2024/1275, notwithstanding harmonised ecodesign performance requirements (Article 3(3)), which may indirectly affect the types of heating appliances installed and therefore residential PM emissions. They may, however, prohibit market access for products that comply with performance requirements in delegated acts on grounds of non-compliance with national requirements covering the same parameters (Article 3(2)).
Commission oversight mechanisms	• The Commission adopts all substantive ecodesign requirements through delegated acts under Article 290 TFEU. It evaluates the Regulation by 19 July 2030 and every six years thereafter (Article 75(2)).
Enforcement tools in the legal design	• Market surveillance authorities may require corrective action and restrict or prohibit market access for non-compliant products (Article 69). Products designed to alter performance during testing or worsen performance after a short period of use are prohibited (Article 40). Member States must provide effective, proportionate and dissuasive penalties, including fines and time-limited exclusion from public procurement (Article 74).
Direct vs indirect relevance to PM exposure	• **Indirect**, with a pathway through delegated acts. The Regulation's relevance to $PM_{2.5}$ and PM_{10} exposure rests primarily on the performance requirements that delegated acts may establish for solid-fuel combustion appliances (solid-fuel boilers, local space heaters and related products), which are among the dominant sources of primary $PM_{2.5}$ in residential settings across the study Member States. • Annex I, point (q) explicitly lists emissions to air across life cycle stages as a product parameter, providing an unambiguous legal basis for PM-related performance thresholds in future delegated acts. • Secondary pathways include broader reductions in energy demand from improved product efficiency, which reduces fossil fuel combustion at the residential and district levels. These effects are prospective and contingent on the content of delegated acts that have not yet been adopted at the time of entry into force.

Directive (EU) 2024/1275 – Energy Performance of Buildings (recast)

Field	Content
Instrument title and reference	• Directive (EU) 2024/1275 of the European Parliament and of the Council of 24 April 2024 on the energy performance of buildings (recast) (OJ L, 8.5.2024). Repeals Directive 2010/31/EU with effect from 30 May 2026 (Article 36).
Legal basis	• Article 194(2) TFEU (energy policy)
Stated objective(s)	• To promote the improvement of the energy performance of buildings and the reduction of greenhouse gas emissions from buildings, with a view to achieving a zero-emission building stock by 2050 (Article 1(1)). Recital 10 links improved energy performance to the reduction of pollutant emissions in accordance with Directive (EU) 2016/2284 (NEC Directive).
Type of regulatory approach	Recast directive including: • Methodology for calculating energy performance (Article 4, Annex I), minimum energy performance requirements for new and renovated buildings and building elements (Articles 5, 7, 8) • Minimum energy performance standards for non-residential buildings and a renovation trajectory for the residential stock (Article 9) • Zero-emission building requirements (Article 11) • Mandatory planning through national building renovation plans (Article 3). Sets energy-performance thresholds and operational greenhouse gas thresholds, but no air-pollutant limit values.
Regulation target	• The national building stock (both residential and non-residential, public and private) with specific obligations applying to new buildings, buildings undergoing major renovation, and non-residential buildings above heating/cooling output thresholds. National building renovation plans address the full building stock, including worst-performing segments (Article 3).
Obligations	• Member States must establish a national building renovation plan including a national building stock overview, a roadmap with 2030/2040/2050 targets, policies and measures, investment needs, and an evidence-based estimate of expected energy savings and wider benefits. • This includes those related to indoor environmental quality (Article 3(2)). • When a technical building system is installed (or replaced or upgraded), the overall energy performance of the altered system must be assessed and documented for the building owner (Article 13(6)).
Monitoring requirements	• No dedicated ambient air quality or PM monitoring is required by this Directive.
Planning obligations	• National building renovation plans (Article 3): first draft by 31 December 2025 (Article 3(3)) and first plan by 31 December 2026 (Article 3(7)), then every five years within the integrated national energy and climate plan cycle.

Field	Content
Flexibilities and derogations	• Member States may meet inspection obligations through equivalent alternative measures, provided equivalence of impact is documented by a report to the Commission (Article 23(6)). Defined categories of building may be exempted from minimum energy performance requirements and standards (protected and heritage buildings, places of worship, temporary buildings, stand-alone buildings under 50 m^2, and defence buildings; Articles 5(2)-(3), 9(6)).
Member State discretion	• Member States may introduce more stringent measures compatible with Union law, subject to notification to the Commission (Article 1(3)).
Commission oversight mechanisms	• The Commission assesses draft national building renovation plans and may issue country-specific recommendations. It adopts delegated acts, and reviews the Directive by 31 December 2028, including whether mandatory minimum energy performance standards across the whole stock are needed (Article 28).
Enforcement tools in the legal design	• Member States must lay down effective, proportionate and dissuasive penalties for infringements (Article 34), with specific monitoring mechanisms and penalties for breaches of minimum energy performance standards (Article 9(7)).
Direct vs indirect relevance to PM exposure	• **Indirect.** Recital 10 notes that buildings account for about half of primary PM2.5 emissions in the Union and ties improved energy performance to pollutant reduction under Directive (EU) 2016/2284. The Directive reduces residential PM2.5 mainly by displacing fossil-fuel combustion: new buildings must produce no on-site fossil-fuel emissions from 2030 (Articles 7, 11), boiler incentives are withdrawn from 1 January 2025 (Article 17(15)), and plans must phase out fossil fuel boilers by 2040 (Annex II). Minimum energy performance standards and the residential renovation trajectory (Article 9) target the worst-performing, combustion-dependent stock. The benefit is contingent on the replacement technology, however, as biomass heating is not subject to air-pollutant criteria under this instrument.

Directive (EU) 2023/2413 on the promotion of energy from renewable sources

Field	Content
Instrument title and reference	• Directive (EU) 2023/2413 of the European Parliament and of the Council of 18 October 2023 amending Directive (EU) 2018/2001, Regulation (EU) 2018/1999 and Directive 98/70/EC as regards the promotion of energy from renewable sources, and repealing Council Directive (EU) 2015/652 (OJ L, 31.10.2023)
Legal basis	• Articles 114, 192(1) and 194(2) TFEU
Stated objective(s)	• To raise the binding Union renewable energy target to at least 42,5% of gross final consumption by 2030 (collective endeavour target: 45%), accelerate deployment through streamlined permit-granting and designation of renewables acceleration areas, and strengthen biomass sustainability and greenhouse gas savings.
Type of regulatory approach	• Binding Union-level and sectoral targets with mandatory permit-granting deadlines and strengthened biomass sustainability criteria. No direct air pollutant emission limit values are set. PM-relevant effects arise indirectly through biomass combustion rules and provisions that accelerate the replacement of fossil and solid-fuel heating systems.

Field	Content
Regulation target	• Energy from renewable sources across all sectors. Biomass sustainability criteria apply to solid biomass installations with a total rated thermal input of 7,5 MW or more (lowered from 20 MW) and gaseous biomass installations of 2 MW or more (Article 1(19), amending Article 29 of Directive (EU) 2018/2001).
Obligations	• Each Member State must increase the share of renewable energy in the heating and cooling sector by at least 0,8 percentage points annually on average over 2021–2025 and at least 1,1 percentage points annually on average over 2026–2030, with Member State-specific indicative top-ups set out in new Annex Ia (Article 1(13), amending Article 23(1)). • Member States must introduce measures in building codes and support schemes to increase renewable heating and cooling and may require minimum renewable energy levels in new buildings and buildings undergoing major renovation (Article 15a, inserted by Article 1(6)).
Monitoring requirements	• Economic operators must submit to mandatory independent auditing of compliance with sustainability and greenhouse gas savings criteria (Article 1(21), amending Article 30(3)). A Union database for tracing liquid and gaseous renewable fuels must be operational by 21 November 2024; the Commission must publish annual reports on quantities, geographic origin and feedstock type (Article 1(22), inserting Article 31a).
Planning obligations	• Member States must carry out coordinated spatial mapping of areas necessary for renewable energy deployment by 21 May 2025 and adopt plans designating renewables acceleration areas, subject to strategic environmental assessment, by 21 February 2026 (Articles 15b–15c, inserted by Article 1(6)). Member States must assess renewable energy and waste heat and cold potential in the heating and cooling sector as part of their integrated national energy and climate plans (Article 1(13), amending Article 23(1b)).
Flexibilities and derogations	• Member States may derogate from the cascading use of biomass principle where required for energy security or where local industries cannot make higher-value use of certain feedstocks, subject to annual Commission notification (Article 1(2), amending Articles 3(3a)–(3b)). Outermost regions may apply specific sustainability criteria for biomass fuels for a limited period (Article 1(19), amending Article 29(13)). Existing installations that started operating before 1 January 2021 benefit from phased greenhouse gas savings thresholds, reaching 80% after 15 years of operation, at the earliest from 1 January 2026 (Article 1(19), amending Article 29(10)).
Member State discretion	• Member States select the mix of measures to achieve heating and cooling sector targets, implementing at least two from the list in amended Article 23(4), which includes fossil heating replacement schemes. Member States may apply sustainability and greenhouse gas savings criteria to biomass installations below the mandatory 7,5 MW threshold but are not required to do so (Article 1(19), amending Article 29(1)).
Commission oversight mechanisms	• The Commission must assess Member States' biomass support schemes and publish a report by 2027 (Article 1(2), amending Article 3(3d)). Compliance with the binding target operates through the governance framework of Regulation (EU) 2018/1999, as amended by Article 2.

Field	Content
Enforcement tools in the legal design	• No direct penalties are specified. Compliance with the binding Union target and national contributions operates through the governance and gap-filling mechanisms of Regulation (EU) 2018/1999, as amended by Article 2.
Direct vs indirect relevance to PM exposure	• **Indirect**. PM relevance operates through two pathways. First, lowering the solid biomass sustainability threshold to 7,5 MW extends feedstock and greenhouse gas savings criteria to a broader range of combustion installations; recital 2 identifies pollution reduction as an explicit co-benefit of the transition. Second, the binding heating and cooling sector targets and the indicative 49% renewable energy share in buildings (Article 15a) create structural incentives to replace fossil-fuel heating systems. • However, the **directive's most significant PM limitation is the absence of any sustainability requirement for household biomass combustion**. Below the 7,5 MW threshold (which excludes the entire residential wood-burning sector) no feedstock, greenhouse gas savings, or air pollutant performance criteria apply. **Household biomass installations may count toward Member State renewable energy targets with no accompanying air quality safeguard**.

Directive (EU) 2023/1791 on energy efficiency

Field	Content
Instrument title and reference	• Directive (EU) 2023/1791 of the European Parliament and of the Council of 13 September 2023 on energy efficiency and amending Regulation (EU) 2023/955 (recast).
Legal basis	• Article 194(2) TFEU.
Stated objective(s)	• To establish a common framework of measures to promote energy efficiency across all sectors of the Union economy, consistent with achieving at least a 55% reduction in GHG emissions by 2030 and climate neutrality by 2050, and reducing dependence on energy imports, including fossil fuels (Article 1).
Type of regulatory approach	• Binding and indicative energy efficiency targets at Union and Member State level, combined with sectoral obligations on public bodies, building renovation, energy savings, and metering and billing.
Regulation target	• All sectors of the Union economy. Specific obligations apply to public bodies, obligated parties under energy efficiency obligation schemes, large enterprises subject to energy audits, and operators of district heating and cooling networks.

Field	Content
Obligations	• **Energy savings obligation** (Article 8): Member States must achieve cumulative end-use energy savings of at least 1.3% of final energy consumption from 1 January 2024, rising to 1.5% from 2026 and 1.9% from 2028. **Member States are discouraged from directing public funds toward fossil fuel technologies**. Building renovation measures may include **replacing fossil-fuel heating systems, together with fabric improvements, limited to technologies that meet** applicable national building codes (Annex V and recital 65). • **Public sector buildings** (Articles 5–6): Member States must reduce total final energy consumption of public bodies by at least 1.9% per year compared to 2021 (Article 5(1)). At least 3% of the total floor area of heated or cooled public buildings must be renovated annually to a nearly zero-energy building standard; Member States are encouraged to include the replacement of old and inefficient heaters (Article 5(9), Article 6(1). • **Air quality co-benefit acknowledged** (recital 61): Energy efficiency improvements in buildings are identified as contributing to a reduction in demand for heating fuels, including solid heating fuels, and thereby to indoor and outdoor air quality improvements consistent with the objectives of Directive (EU) 2016/2284 (NEC Directive).
Monitoring requirements	• Member States must report annually on public body energy consumption reductions under Regulation (EU) 2018/1999 (Article 5(5)). The Commission assesses NECP progress reports and may issue recommendations where policy measures are insufficient (Article 8(12)).
Planning obligations	• Member States must include public body energy reduction targets and cumulative end-use energy savings measures in their NECPs (Articles 5(5), 8(11)). Regional and local authorities must incorporate energy efficiency measures into long-term planning tools such as decarbonisation plans (Article 5(6)). Member States must publish an inventory of heated or cooled public buildings above 250 m², including energy consumption data and energy performance certificates, by 11 October 2025 (Article 6(5)).

Field	Content
Flexibilities and derogations	• Member States may exclude public transport and the armed forces from the public sector reduction obligation (Article 5(1)). Social housing may be exempted from the 3% building renovation rate if renovations would not be cost-neutral or would result in disproportionate rent increases (Article 6(1)). Cyprus and Malta face lower energy savings rates. Member States may apply the 1.9% annual public sector reduction obligation on an indicative basis until 11 October 2027 (Article 5(2)).
Member State discretion	• Member States choose how to phase cumulative energy savings over each obligation period, and may combine energy efficiency obligation schemes with alternative policy measures or a national energy efficiency fund (Article 8(2)). Member States may apply an alternative approach to the 3% renovation rate provided equivalent energy savings are demonstrated (Article 6(6)).
Commission oversight mechanisms	• The Commission assesses NECP progress reports and may issue recommendations where Member State policy measures are insufficient to meet energy savings obligations (Article 8(12)). By 11 October 2028, the Commission must report on the thresholds for application of the energy efficiency first principle with a view to downward revision (Article 3(2)).
Enforcement tools in the legal design	• No direct penalties specified. Compliance operates through the governance and gap-filling mechanisms of Regulation (EU) 2018/1999. Shortfalls in cumulative end-use energy savings must be made up in the following obligation period (Article 8(13)).
Direct vs indirect relevance to PM exposure	• **Indirect**. The directive's PM relevance operates primarily through the energy savings obligation and the building renovation rate, both of which create incentives to reduce consumption of solid and fossil heating fuels, a principal source of residential $PM_{2.5}$ emissions. The explicit link to Directive (EU) 2016/2284 in recital 61 acknowledges this co-benefit. However, the directive sets no conditions on the type of heating technology used to meet energy savings targets beyond the transitional restriction on direct fossil fuel combustion; **replacement heating systems may include solid biomass, which is not subject to air pollutant performance criteria under this instrument**.

4.2.

4.3. The ambition and effectiveness of the AAQD

This section assesses the EU air quality acquis in terms of both its **ambition** (the extent to which regulatory standards align with the latest health evidence) and its **effectiveness** (the degree to which these standards translate into reductions in population exposure, premature mortality, disease incidence and DALYs). Building on the legislative mapping in section 4.1, the analysis evaluates whether existing instruments collectively deliver air quality outcomes consistent with the WHO guidelines. For each major directive and regulatory instrument, the assessment considers the level of ambition embedded in legal targets, the implementation and enforcement mechanisms, and the resulting health impacts. The section thus provides an integrated view of the extent to which the EU framework closes the gap between regulatory compliance and health-optimal exposure levels, which serves as the basis for the conclusions and policy recommendations in subsequent chapters.

4.3.1. Assessment of the ambition of the acquis[381]

- Current EU limits are 5-8× less strict for $PM_{2.5}$ and approximately 2½× less strict for PM_{10} than the WHO AQG.
- The 2024 revision (EU 2024/2881) proposes a $PM_{2.5}$ limit of 10 µg/m³ by 2030, still twice the WHO recommendation but a major step forward.
- This translates into 180,000 premature deaths that could be avoided if air quality in EU countries were closer to the WHO guidelines.

The 2021 WHO Air-Quality Guidelines set the health-based annual limits for fine particles at 5 µg/m³ for $PM_{2.5}$ and 15 µg/m³ for PM_{10}, whereas the EU's current ambient-air-quality standards (Directive 2008/50/EC) allow up to 25 µg/m³ of $PM_{2.5}$, about five times higher than the WHO recommendation, and 40 µg/m³ of PM_{10}, roughly 2.5 times the WHO level. The 2024 revision of the Ambient-Air-Quality Directive (EU 2024/2881) proposes a tightened $PM_{2.5}$ ceiling of 10 µg/m³ by 2030, which, although still double the WHO guideline, marks a substantial step toward greater health protection, while the EU-wide 2030 target for PM_{10} has been set at 20 µg/m³, leaving a persistent gap between EU policy and the WHO's more stringent limits.

Table 2: PM limit values

Pollutant	WHO 2021 Air Quality Guideline (AQG) (µg/m³)	EU current limit (Directive 2008/50/EC, in force, to be attained by 11 December 2026) (µg/m³)	EU 2030 target (proposed by AAQD 2024/2881, to be attained by 1 January 2030) (µg/m³)
$PM_{2.5}$ (annual mean)	**5**	**25**	**10**
PM_{10} (annual mean)	**15**	**40**	**20**

Source: Authors' own elaboration.

[381] Turner, M.C. et al., 2023, Clean air in Europe for all! Taking stock of the proposed revision to the ambient air quality directives: a joint ERS, HEI and ISEE workshop report, European Respiratory Journal, Vol. 62(4), 2301380. Available at: https://pubmed.ncbi.nlm.nih.gov/37827574/.

Table 3: Summary of the gap between EU policy and WHO health evidence on PM2.5

Aspect	EU status	WHO recommendation	Health-impact implication
Ambient limit	25 µg/m³ (current) → 10 µg m⁻³ (target 2030)	5 µg/m³ (annual)	Even the 2030 target leaves ~5 µg/m³ of excess exposure, translating into **≈ 60 k–70 k preventable premature deaths** per year.
Source-side emission ceilings	IED, NEC, Euro 7, Fuel Quality Directive (FQD) – progressively tighter but still allow **regional hotspots** above WHO levels.	No explicit WHO ceiling; health evidence calls for **near-zero primary PM** in densely populated zones.	Continued need for **localised stricter limits** (e.g., low-emission zones, port/airport emission caps).
Monitoring & reporting	EU-wide network (EEA) meets minimum EU standards; new AAQD will tighten **alert thresholds**.	WHO stresses the need for **high-resolution, population-weighted monitoring** to capture intra-urban gradients.	Better spatial data would enable **targeted interventions** to more quickly close the remaining health gap.
Policy ambition	55% premature-death reduction by 2030 (already achieved in 2023) → **Zero-pollution vision for 2050**.	WHO's AQG reflects a **risk-based, health-optimal level**; no political target but the scientific benchmark.	The EU's 2050 "no significant impact on health" goal aligns conceptually with WHO, but **intermediate milestones (e.g., 2025, 2030) remain above WHO**.

Source: Authors' own elaboration.

Ambition per Directive, challenges in implementation and direct health impacts

The European Union's air quality legislation is complex and multi-layered and has successfully decoupled economic growth from emissions. Over the past two decades, this framework has cut premature deaths from fine particulate matter ($PM_{2.5}$) by 57%. It has effectively met the interim targets of the Zero Pollution Action Plan ahead of schedule.

However, a **critical gap** remains **between the technical ambition of emission controls and the health-based ambition of exposure limits**. In other words, we are good at controlling emissions, but bad at setting safe exposure limits. While the recent Ambient Air Quality revisions from 2024 mark a shift toward stricter standards, the current legal ceiling for $PM_{2.5}$ (10 µg/m³ by 2030) remains twice as high as the level recommended by the WHO as safe. As a consequence, despite robust source-control mechanisms, we can expect that the **current acquis will** lead to **approximately 60,000 to 70,000 preventable premature deaths annually in the EU-27 by 2030**.

The EU has the world's most advanced technical standards for industrial and transport emissions, but it needs **to recalibrate its health targets and implement a more ambitious enforcement mechanism** to fully align with the scientific consensus that there is no 'safe' level of PM exposure.

New research from the WHO (2021) and EEA (2024) changed how we see $PM_{2.5}$ risks. The evidence now shows a linear, non-threshold link between PM exposure and mortality, affecting cardiovascular, respiratory, and neurodegenerative health outcomes even at concentrations well below 5 µg/m³.

Newest data indicate that **94% of the EU urban population is exposed to $PM_{2.5}$ levels exceeding the WHO guideline**. This gap keeps growing, despite significant emission reductions. This leads to the conclusion that the current regulatory rules are acting as a **"permission to pollute" rather than a health-protective safety net**.

The following paragraphs show the **efficacy and ambition** of the primary instruments governing PM emissions and concentrations in the EU, highlighting their actual ambition, where they fall short in practice, and the real health costs.

Ambient Air Quality Directive ((EU) 2024/2881)

Assessment: Moderate ambition due to progressive trajectory.

The AAQD (EU) 2024/2881 represents a significant, if hesitant, change in EU environmental law by tightening the annual $PM_{2.5}$ limit from 25 µg/m³ to 10 µg/m³ by 2030. This update shows a "progressive trajectory" (a step-by-step approach) that acknowledges the scientific consensus that lower concentrations bring major health benefits, expected to prevent around 30,000 to 40,000 premature deaths annually compared to the status quo. Now, the revised directive requires Member States to accelerate the deployment of air quality plans and remediation measures in non-compliant zones, moving the EU closer to the health-protective standards set out in the Zero Pollution Action Plan. However, **the assessment of "moderate ambition" is based on the fact that the 10 µg/m³ target is twice the level recommended by the WHO as safe (5 µg/m³)**. While this represents a significant improvement over previous standards, it essentially locks in an exposure level that still poses a measurable risk of cardiovascular and respiratory disease.

On top of issues of not meeting the 'no-safe-levels', the directive's ambition includes transitional periods and flexibility mechanisms that allow Member States to delay compliance in specific zones, creating a "regulatory lag" in which legal compliance does not equate to optimal health protection, especially in high-pollution **zones.** Consequently, while the trajectory is positive, the 2030 endpoint is a political compromise rather than a reflection of what health science demands. The health impact assessment shows that despite this progressive shift, a significant health burden remains. Even if the 10 µg/m³ target is fully met, an estimated 60,000 to 70,000 avoidable deaths per year in the EU will still be attributable to $PM_{2.5}$ exposure above the WHO guideline. This gap underscores that the directive, while a necessary step forward, is insufficient to fully eliminate the preventable health burden of air pollution. To move from "moderate" to "high" ambition, the EU needs to close this gap by accelerating the timeline to reach the 5 µg/m³ guideline, ensuring that the legal limits align with the evidence-based scientific recommendations that there's no safe PM level.

National Emission Ceilings (NEC) Directive ((EU) 2016/2284)

Assessment: Moderate ambition due to implementation risk.

The NEC Directive (EU) 2016/2284 sets legally binding reduction targets for key air pollutants, including $PM_{2.5}$, with a goal of a 49% cut by 2030 relative to 2005 levels. While these targets are theoretically ambitious enough to drive the 55% reduction in premature deaths envisioned by the Zero Pollution Action Plan, **the directive's actual health impact is severely compromised by a critical "implementation gap"**. The NEC Directive relies heavily on Member States to design their own National Air Pollution Control Programmes, resulting in a fragmented landscape where political will and administrative capacity vary widely. That, in reality, translates to some countries having the will to act, while others do not. As a consequence, across EU wide **gaps still exist between countries.** While the EU as a whole may meet aggregate targets on paper, several Member States are failing to implement the necessary structural reforms, leaving millions of citizens exposed to unsafe air quality levels despite the existence of binding national ceilings. The main bottleneck is the lack of progress in stagnation of ammonia (NH_3) emissions from the agricultural sector, which is the main driver of secondary inorganic aerosols and accounts for 50% of ambient $PM_{2.5}$ mass in Europe. While industrial NO_x and SO_2 have dropped steadily due to technological improvements, ammonia emissions have remained stubbornly flat since 2005. This fact undermines the effectiveness of the entire directive. Health impact assessments indicate that without a drastic, enforceable reduction in agricultural ammonia, the $PM_{2.5}$ ceilings will be mathematically unattainable in many regions of the European Union and beyond.

This failure to curb a single precursor sector cancels out the health benefits gained from reductions in other sectors. This affects the opportunity to avoid risks to human health. From a health perspective, the moderate ambition of the NEC Directive is evident in the high mortality rates in regions where implementation lags. Modelling suggests that if current trends in ammonia and $PM_{2.5}$ continue, the EU will miss its 2030 health targets, leaving approximately 60,000 to 70,000 preventable premature deaths annually. The directive's reliance on voluntary measures and soft incentives for agriculture, combined with weak enforcement mechanisms for non-compliance, creates a situation in which the Directive's set-up "ceiling" serves as a distant goal rather than a real protection and health safeguard. Until the directive is strengthened with binding, sector-specific measures for agriculture and stricter sanctions for non-compliance, its ambition will remain moderate, failing to translate its legal targets into the real-world health protection required by the latest WHO scientific consensus.

Industrial Emissions Directive (Directive (EU) 2024/1785)

Assessment: High technical ambition, but several structural and operational challenges threaten to dilute its health impact.

The updated BAT conclusions require almost complete elimination of primary PM from large industrial sources. This effectively addresses point-source "hotspots" in regions like the Po Valley and Silesia. By requiring advanced filtration technologies such as bag filters and electrostatic precipitators, the directive aims to address "point source" emissions from sectors such as steel, cement, and power generation. These changes should be projected to reduce localised pollution hotspots, addressing a major contributor to acute health risks in industrial zones across the Union. However, the directive's impact on public health is hampered by critical structural blind spots, particularly regarding "fugitive emissions" such as dust from material handling and open processes. These can account for up to 40% of local industrial PM. On top of uneven capacity and political will for the enforcement across Member States, these gaps risk creating a "compliance theatre": legal limits appear to be met, yet pollution levels in nearby communities remain a serious threat to the population and their health. IED effectiveness is undermined by a lack of integration with secondary PM precursors and leaving out smaller industrial clusters. For the Directive to properly protect health, it needs to shift from a technology-focused approach to outcomes that mandate real-time monitoring, close fugitive emission loopholes, and strictly regulate industrial ammonia and VOCs. Without addressing these implementation barriers and the "moving target" of BAT definitions, the directive will fail to deliver the optimal health protection required by the latest scientific consensus on the non-threshold nature of PM toxicity.

Medium Combustion Plants Directive (MCPD) ((EU) 2015/2193)

Assessment: High technical ambition but a critical implementation gap for winter smog.

The MCPD is regulating combustion plants between 1 and 50 MW – a sector responsible for significant heating emissions in Central and Eastern Europe. This sector is a major source of winter $PM_{2.5}$. The directive sets strict ELVs for PM, NO_x and SO_2, expected to cut $PM_{2.5}$ emissions by 1520% by 2030. The European Commission estimates that full implementation could prevent 1,300 to 1,600 premature deaths annually across the EU. Emission reduction in this sector would especially mitigate winter smog episodes in urban and semi-urban districts.

However, in reality the directive faces severe implementation challenges that threaten to undermine these health benefits. The high cost of retrofitting older plants often leads operators to choose closure over compliance. This is not good news for air pollution, as it can lead to a "displacement effect" in which heating demand shifts to smaller, unregulated domestic boilers that are more polluting. Additionally, the transition to biomass, encouraged by climate goals, risks increasing local $PM_{2.5}$ and black carbon emissions if fuel quality controls are not strict enough. This has the potential to create a net negative health impact in local communities near these plants.

Rules are also applied unevenly across Member States. Many Member States are relying on periodic rather than continuous monitoring for smaller units within the directive's scope. This allows for **"compliance theatre" where plants meet limits on paper but exceed them during peak heating seasons when health risks are the highest**. Without mandatory real-time, continuous monitoring and stricter fuel quality controls, the MCPD could end up being just another loophole rather than solving anything, leaving the projected health benefits largely unrealised in the regions that need them most.

Non-Road Mobile Machinery & Vehicle Emission Standards (Euro 6 & Euro 7) (Regulation (EU) 2016/1628 & Regulation (EC) No 715/2007 / (EU) 2024/1257)

Assessment: High technical ambition with fleet turnover lag.

The vehicle and mobile machinery regulations represent the most advanced technical standards in the acquis, with Euro 7 marking a major change by explicitly limiting non-exhaust emissions (brake and tyre wear) for the first time. Euro 6d (this standard means a car meets modern, EU pollution rules and stays low-emission even in real driving conditions, not just in controlled tests) successfully reduced tailpipe PM and NO_x by approximately 90% compared to previous standards, while Euro 7 (this standard means the next, stricter EU pollution standard that reduces emissions even more and controls new sources like brake and tyre particles, while making sure cars stay clean for longer) addresses the blind spot of non-exhaust particles (those are small particle from tires, breaks, road abrasion), which now constitute the majority of traffic-related PM in cities.[382] Health modelling suggests that once the fleet is updated with new vehicles, standards in these directives could reduce urban $PM_{2.5}$ concentrations by 20–30%, preventing a number of early deaths associated with vehicle exhaust.

Despite their technical sophistication, the **health gains are limited by the slow pace of vehicle fleet turnover**. The average lifespan of a heavy-duty vehicle or construction machine is 15–20 years, meaning the full health benefits of those standards will be felt only after 2035–2040. In the interim, older vehicles and machinery continue to dominate the roads and construction sites, particularly in lower-income Member States where removal schemes struggle and perpetuate high exposure levels for vulnerable populations.

Additionally, the regulation compliance relies largely on pre-market testing, which in the real world is hampered by driving variability or maintenance neglect. While Real Driving Emissions (RDE) testing has improved accuracy, enforcing rules on working vehicles remains uneven across the EU. Without robust market surveillance and accelerated scrappage programs for high-emitting vehicles, the ambitious technical limits of these regulations will fail to translate into immediate health improvements, leaving a significant gap between regulatory design and public health reality.

Fuel Quality Directive (FQD, (EU) 2009/30/EC)

Assessment: High legacy success with diminishing marginal utility.

The Fuel Quality Directive **set the basic standard for clean fuels** in the EU. It mandates ultra-low sulphur content (<10 ppm) in gasoline and diesel, effectively stopping sulphate pollution from forming from road transport. This instrument is credited with a large part of the PM reduction achieved since the early 2000s, preventing an estimated 10,000–15,000 premature deaths annually by removing a major precursor of particulate matter formation. Its strength lies in its straightforwardness and enforceability, while at the same time creating a uniform fuel standard across the Single Market.

However, **the directive's ambition is now running into fewer gains with each step forward, as the primary pollutants it targets (sulphur) have already been largely eliminated**. Current revisions focus on biofuel blending targets, which bring new challenges for air quality. Some advanced biofuels can increase emissions of unburned hydrocarbons and particulate matter if not properly managed, meaning the switch to renewables could unintentionally worsen local air quality, especially in some regions, as these fuels are introduced more prominently.

Furthermore, the directive does not address upstream emissions from fuel production and refining, which contribute to the total PM burden of the fuel lifecycle. As the EU moves toward electrification, the relevance of fuel quality standards for road transport will decline, shifting the focus to aviation and maritime fuels, where electrification is less feasible. To maintain health ambition, the FQD must evolve to include lifecycle PM assessments and stricter controls on biofuel combustion characteristics, so the move to cleaner fuels doesn't reverse past improvements.

[382] Grigoratos T. and Martini G., 2014, *Non-exhaust traffic related emissions – Brake and tyre wear*, Publications Office of the European Union, JRC89231. Available at. JRC Publications - Non-exhaust traffic related emissions – Brake and tyre wear PM.

Ecodesign for Sustainable Products Regulation (ESPR, (EU) 2024/1781)

Assessment: Emerging ambition with long-term potential.

The ESPR is designed to reduce the overall environmental footprint of products from start to finish. The directive also targets industrial emissions associated with manufacturing and disposal. By focusing on durability, reparability, or the volume of the materials entering the market (y), as well as recycled content, the ESPR indirectly reduces PM emissions from industrial processes and waste management, which account for approximately 15% of EU PM emissions. While its immediate effect on outdoor air quality remains unclear, it represents a strategic move toward tackling pollution at its source.

Implementation challenges stem from the complexity of defining and verifying "sustainability" criteria across diverse product categories. The regulation relies on delegated acts to set specific requirements for each product group, **a process that is slow and open to industry lobby and pressure that could lower environmental standards**. Without rigorous, science-based criteria that explicitly account for air pollution impacts, the ESPR risks focusing solely on carbon footprint, overlooking the co-benefits of PM reduction.

From a health perspective, the ESPR offer of decoupling growth from resource extraction as a long-term strategy might fail to address the immediate toxicity of current industrial processes. However, the health benefits are delayed at best and difficult to quantify in the short term. To maximise its impact, the regulation must integrate air quality impact assessments into the eco-design criteria, ensuring that product standards explicitly minimise emissions of PM precursors during manufacturing, thereby supporting other more direct air quality instruments in the acquis.

Energy Performance of Buildings Directive (EPBD, (EU) 2024/1275)

Assessment: High ambition with structural implementation barriers.

The EPBD plays a central role in lowering PM emissions from the building sector, which is a major source of residential heating pollution, particularly in Eastern Europe. Requiring renovations of existing buildings and phasing out fossil fuel boilers, the directive directly targets the combustion sources responsible for winter smog. Health impact models suggest that the potential for full implementation could reduce $PM_{2.5}$ exposure in cold regions of Europe by 15–20% by 2030, greatly reducing heart and lung disease cases.

Yet the Directive encounters serious practical hurdles, the **main hurdle being the high cost of renovation and the lack of financing for low-income households**. The anticipated "renovation wave" has progressed more slowly, with many Member States struggling to find and utilise the necessary investment. Additionally, in some regions lacking affordable alternatives, removing polluting gas and coal boilers meets strong opposition, ultimately leading to delays in implementation, prolonged low air quality in those regions, and increased human exposure to high emissions from heating systems.

Furthermore, the directive's focus on energy efficiency may not align with air quality goals if replacement systems are not properly regulated. For example, switching from coal to biomass without strict emission controls can worsen local air quality. To ensure health benefits, the EPBD must be tightly integrated with air quality standards, prioritising low-emission heating technologies and penalising non-compliant installations that threaten public health.

Renewable Energy Directive (RED, (EU) 2009/28/EC)

Assessment: Very high ambition in need of implementing systemic transformation.

The RED stands out as the most powerful instrument for long-term PM reduction, as it addresses the root cause of combustion emissions **by decarbonising the energy mix**. By setting binding targets for renewable energy shares (42.5% by 2030), the directive aims to push **coal and gas out of the mix**, eliminating their PM emissions entirely. The EEA attributes approximately 40% of the PM reduction since 2005 to this energy transition, moving away from coal and gas to renewable energy, highlighting its central role in the health protection strategy.

Delays in grid expansion and permitting slow things down, and permit approvals struggle to keep up with growth targets. Delays in connecting new wind and solar farms to the grid can prolong reliance on fossil-fuel backup generation, prolonging PM emissions during critical periods. Additionally, bioenergy rules need strict enforcement to prevent the use of low-quality biomass that could increase local PM emissions.

From a health perspective, **the RED offers the greatest potential to prevent premature deaths in the long term, primarily by reducing PM emissions through the transition away from fossil fuels.** However, the benefits and **success depend entirely on how fast the EU as a whole can transition to non-polluting renewable energy**. To maximise health outcomes, the directive must be supported by accelerated permitting and grid infrastructure investments, ensuring that renewable energy replaces fossil fuels rapidly enough to meet the 2030 health targets. Without this systemic transformation, the ambition of the RED will remain theoretical rather than realised.

Energy Efficiency Directive (EED, (EU) 2023/1791)

Assessment: High ambition for integration with air quality planning.

The EED acts as a lever to cut overall energy demand for air quality improvement, reducing the total volume of fuel burned across all sectors. Setting an energy savings target of 1.49% annual reduction, the Directive proportionally reduces PM emissions from heating, industry, and power generation. **Health impact modelling suggests that a 1% reduction in energy demand corresponds to a comparable reduction in PM emissions, making the EED a powerful** tool for immediate health protection.

Main implementation challenges include the difficulty of measuring and verifying energy savings, most difficult in the services and public sectors. Member States often struggle to implement effective policies that drive behavioural change and investment in efficiency, leading to a gap between targets and actual savings. On top of that, higher efficiency sometimes leads to higher consumption, which can partially offset the emission reductions.

From a public health perspective, the EED adds to the RED's clean, renewable energy approach by ensuring that reduced energy demand is met with cleaner sources. However, its effectiveness depends on integration with air quality plans to ensure that efficiency gains are not lost to increased consumption. To reach health benefits, the EED must be enforced with strict monitoring and linked to air quality outcomes, ensuring that energy savings translate directly into reduced pollution and improved public health[383].

[383] European Commission, 2026, *Energy Efficiency Directive.* Available at: https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficiency-targets-directive-and-rules/energy-efficiency-directive_en.

Nitrates Directive (91/676/EEC)

Assessment: Low ambition with a critical implementation gap.

The Nitrates Directive is an essential instrument, but is failing to deliver results in the air quality acquis. It regulates agricultural ammonia emissions, the primary precursor for secondary inorganic aerosols, which constitute approximately 50% of $PM_{2.5}$ mass. Despite its importance, the directive has failed to drive significant reductions in ammonia emissions. Evidence shows that ammonia emissions have remained stagnant since 2005. This failure weakens the impact of other air quality measures. Gains in NO_x and SO_2 reductions are offset by the persistence of ammonia, preventing attainment of $PM_{2.5}$ ceilings.

The implementation fails in the farming sector due to resistance to implementing the regulation and the lack of binding reduction targets for Member States. The directive relies on voluntary measures and action programmes that are often weakly enforced, allowing intensive farming practices to continue unchecked. The health benefits of industrial and transport emission controls are negated by agricultural emissions.

Health impact assessments indicate that without a drastic reduction in ammonia, the EU will miss its 2030 $PM_{2.5}$ targets, leaving tens of thousands of preventable deaths unaddressed. To rectify this, the Nitrates Directive must be strengthened with binding ammonia reduction targets and stricter monitoring, treating agricultural emissions with the same urgency as industrial pollutants. Until this gap is closed, the overall ambition of the air quality acquis remains compromised.

A farmer in full compliance with the Annex III nitrogen caps and application restrictions bears no obligation under this instrument to consider, minimise, or report the air quality consequences of their nitrogen management. The Directive shows how EU rules are split into silos: water and air quality are addressed through separate instruments with no cross-reference between them. In assessing the study's effectiveness, this gap underscores a structural limitation of the current regulatory framework: rules designed to protect water quality end up harming air quality. For the recommendations chapter, it points to a concrete intervention: incorporating ammonia-emission-reduction objectives into action programme requirements or codes of good agricultural practice under this Directive, to back up the existing national limits already established under Directive (EU) 2016/2284 (NEC Directive).

4.3.2. Assessment of the effectiveness of the acquis

From legal targets to health outcomes

While the ambition of the EU air quality acquis has evolved from "moderate" to "high" in its regulatory design, its **effectiveness** (actual reduction in population exposure and the consequent avoidance of premature mortality) remains uneven. The EU has successfully decoupled economic growth from emissions in the industrial and mobile sectors, yet translating these reductions into improvements in ambient air quality is hampered by **implementation gaps, sectoral blind spots** (particularly agriculture), and the slow turnover of legacy infrastructure.

1. Overall health impact and the persistent exposure gap

The most compelling indicator of the acquis's effectiveness is the reduction in premature deaths. According to the EEA, the EU legislative framework has successfully driven a 57% reduction in premature deaths attributable to fine particulate matter ($PM_{2.5}$) over the past two decades. This achievement effectively met the interim targets of the Zero Pollution Action Plan ahead of schedule[384].

However, effectiveness is currently capped by the remaining health damage that persists even after regulatory targets are met. Despite these gains, current projections indicate that **even if the 10 µg/m³ target is fully met, an estimated 60,000 to 70,000 premature deaths per year in the EU will still be attributable to $PM_{2.5}$ exposure above the WHO guideline**[385]. It represents the critical gap between the health improvements achieved under existing laws and the optimal protection that would be realised if exposure were lowered to scientifically recommended levels outlined in the WHO guidelines. Moreover, effectiveness depends on the Member States' ambition to transpose the new AAQD into their national law with new binding limit values (not "targets"), without delay. This figure shows that while the acquis suggests it is effective at preventing high levels of pollution, it is currently ineffective at eliminating chronic, lower-level exposure, which constitutes the majority of the health burden. The EEA reports that **94% of the EU urban population remains exposed to $PM_{2.5}$ levels exceeding the WHO guideline**[386], suggesting that current effectiveness is insufficient to meet the scientific consensus that **there is no threshold for PM exposure**[387].

The overarching conclusion regarding the effectiveness of the EU air quality acquis is that **technical ambition does not automatically translate to health protection**[388]. The EU possesses **the world's most advanced technical standards,** yet the framework is **projected to leave approximately 60,000 to 70,000 preventable premature deaths annually in the EU-27 by 2030**[389]**.**

The primary driver of this ineffectiveness is not a lack of regulation, but a **lack of enforcement and sectoral integration**. More concretely:

1) **Agricultural blind spot:** The failure to regulate ammonia (via the Nitrates and NEC Directives) negates gains made in industry and transport.
2) **Implementation lag:** Slow fleet turnover (vehicles) and slow renovation waves (buildings) delay health benefits by decades.
3) **Compliance theatre:** Periodic monitoring and loopholes in fugitive emissions allow pollution to persist despite legal compliance.

Finally, the current acquis **acts as a 'permission to pollute' rather than a health-protective boundary** for the remaining 94% of the urban population exposed to levels above WHO guidelines. **To move from "moderate" to "high" effectiveness, the EU must shift from setting progressive**

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384 European Commission, 2021, Report from the Commission to the Council and the European Parliament on the implementation of Council Directive 91/676/EEC concerning the protection of waters against pollution caused by nitrates from agricultural sources, based on Member State reports for the period 2016–2019. European Commission, Brussels, Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52021DC1000.

385 European Commission, 2021, *Zero Pollution Action Plan: Towards zero pollution for air, water and soil*, COM(2021) 400 final. Available at: https://environment.ec.europa.eu/strategy/zero-pollution-action-plan_en.

386 European Commission, 2022. *Impact Assessment accompanying the proposal for a Directive on ambient air quality (SWD(2022) 345 final)*. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52022SC0345.

387 European Environment Agency, 2024. *Europe's air quality status 2024*, Publications Office of the European Union. Available at: https://data.europa.eu/doi/10.2800/5970.

388 European Environment Agency, 2025. *Air pollution in Europe 2025: reporting status under the National Emission Reduction Commitments Directive*. Available at: https://www.eea.europa.eu/en/analysis/publications/air-pollution-in-europe-2025-reporting-status-under-the-national-emission-reduction-commitments-directive.

389 World Health Organization, 2021, WHO global air quality guidelines: particulate matter (PM2.5 and PM10), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide. Available at: https://www.who.int/publications/i/item/9789240034228.

trajectories to enforcing immediate, binding reductions in the sectors that currently drive the residual health burden[390].

2. Directive-specific effectiveness

Ambient Air Quality Directive (AAQD) (EU) 2024/2881

Effectiveness rating: Moderate with delays

The AAQD is effective in forcing Member States to act where limits are exceeded, but its effectiveness is diluted by the "regulatory lag" inherent in its transitional periods. The directive's effectiveness is currently limited by the fact that the 2030 target (10 µg/m³) is a political compromise rather than a health-optimal boundary. As noted in the European Commission's Impact Assessment, the directive **requires Member States to accelerate the deployment of air quality plans**[391], yet the **inclusion of flexibility mechanisms allows for delays.** Consequently, the AAQD is effective at reducing *peak* pollution but less effective at ensuring *continuous* compliance with health-based standards. The text warns that without accelerating the timeline to 5 µg/m³, the directive will **fail to fully eliminate the preventable health burden of air pollution**[392].

National Emission Ceilings (NEC) Directive (EU) 2016/2284

Effectiveness rating: Low to moderate, severely compromised by agriculture

The NEC Directive suffers from a critical implementation gap that severely undermines its effectiveness. While aggregate EU targets may be met on paper, the EEA identifies a **fragmented landscape where political will and administrative capacity vary drastically**[393]. The most significant failure is the stagnation of **ammonia (NH_3) emissions from the agricultural sector**, which accounts for roughly **50% of ambient $PM_{2.5}$ mass in Europe**[394].

The EEA states that **unlike industrial NO_x or SO_2, which have seen steady declines, ammonia emissions have remained stubbornly flat since 2005**[395]. This failure means that **the projected avoidance of tens of thousands of premature deaths remains largely theoretical rather than realised**[396]. The directive is ineffective because it lacks **binding, sector-specific measures for agriculture**, leaving the "ceiling" as a **distant goal rather than an immediate health safeguard**.

390 European Respiratory Society, 2021. WHO air quality guidelines: global update 2021 – Joint statement by medical, public health, scientific societies and patient representative organisations. Available at: https://www.ersnet.org/wp-content/uploads/2021/10/WHO-AQG_Joint-Society-Statement_1st-UPDATE-13th-October.pdf.

391 European Commission, 2022. *Impact Assessment accompanying the proposal for a Directive on ambient air quality (SWD(2022) 345 final)*. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52022SC0345.

392 Ibid.

393 European Environment Agency, 2023. *National emission reduction commitments directive 2023*. Available at: https://www.eea.europa.eu/en/analysis/publications/national-emission-reduction-commitments-directive-2023.

394 European Environment Agency, 2024. *Europe's air quality status 2024*, Publications Office of the European Union. Available at: https://data.europa.eu/doi/10.2800/5970.

395 European Environment Agency, 2020. *Air quality in Europe, 2020 report*. Available at: https://www.eea.europa.eu/en/analysis/publications/air-quality-in-europe-2020-report.

396 European Commission, 2022. *Impact Assessment accompanying the proposal for a Directive on ambient air quality (SWD(2022) 345 final)*. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52022SC0345.

Industrial Emissions Directive (IED) (EU) 2024/1785

Effectiveness rating: High for point sources, low for fugitive emissions

The IED is highly effective at eliminating primary PM from large industrial stacks through BAT, effectively addressing point-source hotspots in regions like the Po Valley and Silesia. However, its overall effectiveness is compromised by structural blind spots[397].

The JRC notes that **fugitive emissions such as dust from material handling and open processes can account for up to 40% of local industrial PM[398].** This creates a scenario of **compliance theatre where stack emissions drop on paper while actual ambient pollution levels remain dangerously high**. The directive is ineffective at protecting communities from non-stack emissions due to integration with secondary PM precursors and weak enforcement of fugitive controls[399].

Medium Combustion Plants Directive (MCPD) (EU) 2015/2193

Effectiveness rating: Moderate, threatened by displacement effects

The MCPD has high technical potential, with the European Commission estimating that full implementation could prevent **approximately 1,300 to 1,600 premature deaths annually**. However, its practical effectiveness is threatened by the displacement effect[400].

High retrofit costs often lead operators to close plants, causing heating demand to shift to **smaller, unregulated domestic boilers that are more polluting**. Furthermore, the transition to biomass, if not strictly controlled, poses a high risk for increasing local $PM_{2.5}$ and black carbon emissions, potentially creating a **net negative health impact**. The reliance on periodic rather than continuous monitoring allows plants to **meet limits on paper but exceed them during peak heating seasons**, rendering the directive ineffective during the periods of highest health risk[401] [402].

Vehicle Emission Standards (Euro 6/7) & Non-Road Mobile Machinery

Effectiveness rating: High, delayed by fleet turnover

Technically, these regulations are the most effective in the acquis, with Euro 6d reducing tailpipe PM and NO_x by **approximately 90%**. Euro 7's inclusion of non-exhaust emissions (brake/tyre wear) addresses a critical blind spot. However, the *realised* health effectiveness is constrained by the **slow pace of vehicle fleet turnover**. Given that heavy-duty vehicles have a lifespan of 15–20 years, the text notes that **full health benefits will not materialise until the 2035–2040 period**. This delay disproportionately affects lower-income Member States, where scrappage schemes are less

[397] IMPEL, 2024, *Best Available Techniques (BAT) and derogations from BAT*. Available at: https://impel.eu/en/topic/industry-and-air/industrial-emission-directive-ied/projects/best-available-techniques-bat-and-derogations-from-bat.

[398] Department for Environment, Food & Rural Affairs, 2020. *Industrial emissions standards and best available techniques*. Available at: https://www.gov.uk/guidance/industrial-emissions-standards-and-best-available-techniques.

[399] European Environment Agency, 2024. *Europe's air quality status 2024*, Publications Office of the European Union. Available at: https://data.europa.eu/doi/10.2800/5970.

[400] European Union, 2015, *Directive (EU) 2015/2193 on the limitation of emissions of certain pollutants into the air from medium combustion plants*. Available at: https://eur-lex.europa.eu/eli/dir/2015/2193/oj/eng.

[401] Byrne Ó Cléirigh, 2017, *Medium Combustion Plant (MCP) Directive*. Available at: https://boc.ie/News-And-insights/Medium-Combustion-Plant--MCP--Directive.

[402] Fern, 2018, *Burning biomass: the impact on European health.* Available at: https://www.fern.org/fileadmin/uploads/fern/Documents/briefingnote%20burning%20biomass.pdf.

effective, deepening inequalities and allowing older vehicles to **continue to dominate the roads, perpetuating high exposure levels for vulnerable populations**[403 404 405 406].

Fuel Quality Directive (FQD)

Effectiveness rating: High

The FQD is cited as a **foundational baseline** that virtually eliminates **sulphate-based secondary PM formation**. It is credited with preventing an estimated **10,000–15,000 premature deaths annually** by removing sulphur.

Its effectiveness is now limited by **diminishing marginal utility** as primary targets are met. The text warns that current revisions focusing on biofuels **introduce new complexities,** with some advanced biofuels potentially **increasing emissions of unburned hydrocarbons and particulate matter**. The directive is increasingly ineffective at driving *new* health gains unless it evolves to include lifecycle PM assessments[407 408 409].

Energy Performance of Buildings Directive (EPBD)

Effectiveness rating: Low current realisation

The EPBD is a critical lever for reducing winter smog, with models suggesting it could **reduce $PM_{2.5}$ exposure in cold regions by 15–20% by 2030**. Effectiveness is currently hampered by structural barriers, primarily the high cost of renovation and limited financing. The renovation wave has progressed more slowly than anticipated. There is a risk that **switching from coal to biomass without strict emission controls can worsen local air quality**. Without tight integration with air quality standards, the directive risks being ineffective or even counterproductive in specific contexts[410 411 412 413].

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403 European Commission, 2022. *Impact Assessment accompanying the proposal for a Directive on ambient air quality (SWD(2022) 360 final)*. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:52022SC0360.

404 European Parliament Research Service, 2023, *Updating Euro emission standards (Euro 7)*. Available at: https://www.europarl.europa.eu/RegData/etudes/BRIE/2023/740246/EPRS_BRI(2023)740246_EN.pdf.

405 European Environment Agency, 2023, *Transport and environment reporting mechanism (TERM)*. Available at: https://www.eea.europa.eu/en/topics/in-depth/transport-and-mobility/transport-and-environment-reporting-mechanism-term.

406 European Commission, 2022, Proposal for a Directive of the European Parliament and of the Council on ambient air quality and cleaner air for Europe (COM(2022) 586 final). Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:52022PC0586.

407 European Environment Agency, 2024, *Europe's air quality status 2024*, Publications Office of the European Union. Available at: https://data.europa.eu/doi/10.2800/5970.

408 European Commission, 2021, Support Study on the Evaluation of Article 7A of the Fuel Quality Directive and Assessment of Approaches to Reduce Greenhouse Gas Emissions from Transport Fuels. Available at: https://op.europa.eu/en/publication-detail/-/publication/aea4d643-48ed-11ec-91ac-01aa75ed71a1/language-en.

409 European Commission, 2021, Support Study on the Evaluation of Article 7A of the Fuel Quality Directive and Assessment of Approaches to Reduce Greenhouse Gas Emissions from Transport Fuels. Available at: https://op.europa.eu/en/publication-detail/-/publication/aea4d643-48ed-11ec-91ac-01aa75ed71a1/language-en.

410 European Commission, 2021, Impact Assessment Report accompanying the proposal for a Directive of the European Parliament and of the Council on the energy performance of buildings (recast) (SWD(2021) 453 final). Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:52021SC0453.

411 European Environment Agency, 2023, *Europe's air quality status 2023*. Available at: https://www.eea.europa.eu/en/analysis/publications/europes-air-quality-status-2023.

412 European Commission, 2023, *8th report on the State of the Energy Union*. Available at: https://energy.ec.europa.eu/strategy/energy-union/8th-report-state-energy-union_en.

413 European Environment Agency, 2024, *Europe's air quality status 2024*. Available at: https://www.eea.europa.eu/en/analysis/publications/europes-air-quality-status-2024.

Renewable Energy Directive (RED)

Effectiveness rating: Very high (long-term driver)

The RED is identified as **arguably the most effective instrument for long-term PM reduction**, addressing the root cause of combustion. The EEA attributes **approximately 40% of the PM reduction since 2005 to this energy transition**. Effectiveness is contingent on the speed of the transition. Delays in connecting new wind and solar farms to the grid can prolong reliance on fossil-fuel backup generation. Without accelerated, environmentally safe permitting and grid infrastructure investments, the ambition of the RED will remain theoretical rather than realised[414] [415] [416].

Nitrates Directive

Effectiveness rating: Low

The Nitrates Directive is assessed as having **Low Ambition with Critical Implementation**. Despite regulating the primary precursor for secondary PM, it has failed to drive significant reductions in ammonia emissions, which have remained stagnant since 2005. This failure **undermines the effectiveness of other air quality measures**, as reductions in NO_x and SO_2 are **offset by the persistence of ammonia**. Without a drastic reduction in ammonia, the EU will miss its 2030 $PM_{2.5}$ targets, rendering the directive ineffective in its current form[417] [418] [419].

Energy Efficiency Directive (EED)

Effectiveness rating: High (conditional on integration)

The EED acts as a demand-side multiplier, with every 1% reduction in energy demand resulting in **a comparable reduction in PM emissions**. Effectiveness is threatened by the **rebound effect, in which efficiency gains lead to increased consumption, and by** the difficulty of verifying savings. The text argues that the EED is only effective if **linked to air quality outcomes**, ensuring that **efficiency gains are not lost to increased consumption**[420] [421] [422].

Directive (EU) 2023/2413 on the promotion of energy from renewable sources.

The **directive's most significant PM limitation is the absence of any sustainability requirement for household biomass combustion**. Below the 7,5 MW threshold (which excludes the entire residential

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414 European Union, 2023, Directive (EU) 2023/2413 amending Directive (EU) 2018/2001, Regulation (EU) 2018/1999 and Directive 98/70/EC as regards the promotion of energy from renewable sources. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32023L2413.

415 European Environment Agency, 2024, *Europe's air quality status 2024*, Publications Office of the European Union. Available at: https://data.europa.eu/doi/10.2800/5970.

416 European Commission, 2023, *State of the Energy Union 2023 (COM(2023) 650 final)*. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2023:650:FIN.

417 European Commission, 2021, *Report on the implementation of the Nitrates Directive (COM(2021) 1000 final)*, European Commission. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52021DC1000.

418 European Environment Agency, 2024, *Europe's air quality status 2024*, Publications Office of the European Union. Available at: https://data.europa.eu/doi/10.2800/5970.

419 European Commission, 2022, *Impact Assessment accompanying the proposal for a Directive on ambient air quality (SWD(2022) 545 final)*. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:52022SC0545.

420 European Commission, 2021, Impact Assessment Report accompanying the Proposal for a Directive of the European Parliament and of the Council on energy efficiency (recast) (SWD(2021) 623 final). Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:52021SC0623.

421 European Commission, 2023, Directive (EU) 2023/1791 of the European Parliament and of the Council of 13 September 2023 on energy efficiency (recast), Official Journal of the European Union, L 231. Available at: https://eur-lex.europa.eu/eli/dir/2023/1791/oj/eng.

422 European Environment Agency, 2023, *Trends and projections in Europe 2023*. Available at: https://www.eea.europa.eu/en/analysis/publications/trends-and-projections-in-europe-2023.

wood-burning sector), no feedstock, greenhouse gas savings, or air pollutant performance criteria apply. **Household biomass installations may count toward Member State renewable energy targets with no accompanying air quality safeguard**. At the same time, the heating sector's targets and building-level renewable energy obligations create policy pressure to increase renewable heating uptake in Member States where biomass is the dominant accessible option, which risks expanding small-scale biomass combustion, the primary source of residential $PM_{2.5}$. The directive's sustainability framework is calibrated exclusively to greenhouse gas performance, itself based on a methodology that treats biogenic stack CO_2 as zero, and contains no mechanism to differentiate between low- and high-PM renewable heating pathways. PM control for household biomass falls under the Ecodesign Regulation rather than this instrument, and the two frameworks are not coordinated at the household scale. This gap is directly relevant to any assessment of the effectiveness of the EU regulatory framework in reducing population $PM_{2.5}$ exposure.

Table 4: Summary of ambition and effectiveness

Directive / Instrument	Ambition (regulatory design)	Effectiveness (Actual health impact)
AAQD	**Moderate**	**Moderate (with delays)**
(EU 2024/2881)	Progressive trajectory ($PM_{2.5}$ 25→10 µg/m³ by 2030) but remains twice the WHO guideline. Includes flexibility mechanisms causing "regulatory lag."	Forces action on non-compliant zones but fails to eliminate the "residual burden" of ~60k–70k premature deaths/year due to the gap between legal limits and safe levels.
NEC	**Moderate**	**Low to moderate**
(EU 2016/2284)	Theoretically ambitious (49% cut by 2030) but relies on fragmented national programs and lacks binding sector-specific measures for agriculture.	Severely compromised by the stagnation of agricultural ammonia (50% of $PM_{2.5}$). Aggregate targets are met on paper, but health benefits remain largely theoretical.
IED	**High (technical)**	**Mixed**
(EU 2024/1785)	Enforces near-total elimination of primary PM from large stacks via BAT.	Highly effective for point-source hotspots but **Low** for fugitive emissions (up to 40% of local PM). Creates "compliance theatre" in which stack emissions drop while ambient levels remain high.
MCPD	**High (technical)**	**Moderate**
(EU 2015/2193)	Strict ELVs for 1–50 MW plants; targets winter smog reduction (15–20% $PM_{2.5}$ cut).	Threatened by "displacement effects" (shift to unregulated domestic boilers) and biomass risks. Periodic monitoring allows for exceedances during peak heating seasons.

Directive / Instrument	Ambition (regulatory design)	Effectiveness (Actual health impact)
Vehicle Emission Standards	**High**	**High (delayed)**
(Euro 6/7 & NRMM)	Most advanced standards; Euro 7 addresses non-exhaust emissions (brake/tire wear) for the first time.	Technically sound (~90% reduction), but realized health benefits are delayed until 2035–2040 due to slow fleet turnover (15–20 year lifespan).
FQD	**High (legacy)**	**Diminishing**
	Foundational success in eliminating sulphur; now focuses on biofuel blending.	High legacy success (prevented 10k–15k deaths/year) but now limited by "diminishing marginal utility." Biofuel transitions introduce new complexities and risks.
ESPR	**Emerging**	**Low (short-term)**
	Forward-looking; aims to reduce lifecycle emissions via durability and recycled content.	Diffuse direct impact; benefits are delayed and difficult to quantify. Risks of focusing on carbon footprint while overlooking air quality co-benefits.
EPBD	**High**	**Low (current realisation)**
	Mandates renovation and the phase-out of fossil fuel boilers to tackle winter smog.	Stifled by financing barriers and the slow "renovation wave." Risks worsening air quality if coal is replaced by unregulated biomass.
RED	**Very high**	**Very high (long-term)**
	Addresses root cause by decarbonising the energy mix (42.5% target by 2030).	Attributed to ~40% of PM reduction since 2005. Effectiveness depends on grid expansion speed; delays risk keeping fossil fuel backups online.
Nitrates Directive	**Low**	**Low (critical failure)**
	Regulates ammonia but lacks binding reduction targets; relies on voluntary action programs.	Agricultural ammonia emissions have remained stagnant since 2005. This failure offsets gains in other sectors, undermining the entire acquis.
EED	**High**	**High (conditional)**
	Demand-side multiplier; every 1% energy saving translates to a proportional PM reduction.	Potential is high but is threatened by the "rebound effect" (increased consumption) and by difficulties verifying savings. Requires tight integration with air quality planning.

Source: Authors' own elaboration.

5. CASE STUDIES

KEY FINDINGS

Legal transposition of EU air quality standards does not equate to health-protective outcomes. All eight EU Member State case studies have populations exposed above the WHO $PM_{2.5}$ guideline; five remain above the 2024 AAQD 2030 limit of 10 µg/m³.

Performance varies widely across the case study set from Finland, the only Member State meeting the WHO guideline, to Bulgaria and Poland, which record the highest per-capita premature mortality (143.8 and 99.5 per 100,000, respectively).

No Member State has adequately addressed agricultural ammonia as a $PM_{2.5}$ precursor. Ammonia concentrations have remained broadly flat across the case study set since 2005, despite NEC Directive commitments.

In most cases, enforcement is missing, as air quality plans exist but lack concrete targets, assigned responsibilities, and/or funding. Low-emission zones are legally mandated but inconsistently implemented.

Residential solid-fuel combustion remains an important unresolved PM source in Poland, Bulgaria, and France, where cultural entrenchment, economic barriers, and political contestation have slowed progress.

Art. 18 postponement of the 2030 deadline is a credible or likely outcome for Poland, Bulgaria, and zones within Italy, with significant consequences for the populations bearing the highest health burden.

The non-EU comparators provide examples of the performance ranges: Norway approaches WHO guideline levels through structural energy and transport policy; China shows how rapid large-scale reductions are achievable through central government-directed action, but the health burden remains an order of magnitude above EU levels; the UK faces progressive divergence from the EU framework trajectory following Brexit.

5.1. EU Member States

This section presents case studies for eight EU Member States: Poland, Bulgaria, Denmark, Finland, Spain, Italy, Germany, and France, which have been selected to represent a range of geographical regions, population sizes, PM exposure levels, and health burdens. Together they cover approximately 314 million people and account for the majority of the EU's total PM-attributable premature mortality.

Each case study examines national exposure and health burden, the regulatory and institutional framework, the principal implementation challenges, observed air quality and health trends, and policy-relevant insights for the EU level. A summary alignment table is provided in section 5.1.9. The case studies draw on desk research, EEA and the Institute for Health Metrics and Evaluation (IHME) data, and information gathered from the semi-structured interviews with national competent authorities, research institutions, and civil society organisations.

Poland

POPULATION	$PM_{2.5}$ ANNUAL MEAN	PM_{10} ANNUAL MEAN	ABOVE WHO GUIDELINE	PREMATURE DEATHS	MORTALITY REDUCTION
37.5M	**15 μg/m³** range 6–20 (2023)	**33 μg/m³** range 13–66 (2023)	**100%** of population	**99.5** per 100,000 (2023)	**−39%** 2005→2023 (41k→25k)

EXPOSURE & HEALTH

Primary source Residential solid-fuel heating (coal & wood)

Other sources Road transport, heavy industry, agriculture/NH_3

Hotspots Silesia, Kraków

Top morbidity Ischaemic heart disease (37.8/100k) · Stroke (21/100k) · Diabetes (13.3/100k) · Lung cancer (12.6/100k)

Equity Lower-income households face compounded exposure; coal heating concentrated in older housing stock and rural areas

REGULATORY STANDING

EU alignment **Low** transposes AAQD but exceeds PM_{10} limits in multiple zones; infringement proceedings ongoing.

WHO alignment **Low** $PM_{2.5}$ ~3-4× WHO guideline; structural transition required

2024 AAQD Deadline Dec 2026; no draft act; presidential veto risk

Key instruments Air Protection Act (2019) · National Air Protection Programme (2022) · 16 regional AQ plans

Binding sectors IED · Euro 6 · Fuel quality regulation

Non-binding Clean Air Programme (heating subsidies) · Agricultural NH_3 commitments

IMPLEMENTATION REALITY

Competent bodies Chief Inspectorate for Env. Protection · 16 Regional Inspectorates · Municipalities

Health link National Institute of Public Health. No central platform linking AQ monitoring to health data

Enforcement **Weak** limited inspection capacity for dominant $PM_{2.5}$ source

Main barrier Coal path dependency. Residential heating subsidies insufficient without thermal modernisation

Programme risk Clean Air Programme suspended 3 months, restarted under new rules. Uptake and trust are low.

Monitoring ~200 EEA-compliant stations

↗ AIR QUALITY TREND

$PM_{2.5}$ down ~15% since 2010 — improving but among worst-performing EU Member States; winter smog episodes persist in southern regions; pace insufficient for 2030 targets.

↗ HEALTH OUTCOMES TREND

Premature deaths down ~10% since 2015; 39% reduction since 2005 is significant but Poland remains an EU outlier. Respiratory admissions elevated; cardiovascular mortality trend unchanged.

! 2030 OUTLOOK

$PM_{2.5}$ 10 μg/m³ EU limit value unlikely to be reached without acceleration. 100% of urban population above WHO guideline. Potential Derogation under Art. 18 is a risk given absent transposition act.

POLICY-RELEVANT INSIGHTS

1 Transposition and derogation risk

Poland has no draft transposing act for the 2024 AAQD, a presidential veto precedent (Drinking Water Directive), and regional AQ plans due in 2028 on pre-AAQD standards, making Art. 18 postponement a possible outcome that would defer compliance to 2035–2040.

2 Budgetary alignment is a compliance prerequisite

Reaching $PM_{2.5}$ 10 μg/m³ by 2030 requires MFF and national budget alignment with the heating transition (not just legal transposition). Without it, derogation will be inevitable in many coal-dependent regions.

3 Health literacy and misinformation

Low public awareness of health effects of air quality and active political misinformation about LEZs and the Clean Air Programme are reducing citizen uptake and support for air quality initiatives.

4 Transferable lesson: the Kraków model

Targeted residential heating subsidies combined with thermal modernisation requirements (not boiler replacement alone) produced measurable improvements in Kraków. Applicable to other coal-dependent Member States.

Sources: EEA Air Quality in Europe 2024; IHME Global Burden of Disease 2023; European Commission AAQD impact assessment. Interview HEAL Poland.

Bulgaria

POPULATION	$PM_{2.5}$ ANNUAL MEAN	PM_{10} ANNUAL MEAN	ABOVE WHO GUIDELINE	PREMATURE DEATHS	MORTALITY REDUCTION
6.5M	15 µg/m³	40 µg/m³	100%	143.8	−63%
	range 9–21 (2023)	range 17–61 (2023)	of population	per 100,000 (2023)	2005→2023 (18k→6.7k)

EXPOSURE & HEALTH

Primary source Residential heating (coal & biomass)

Other sources Coal-fired power plants, road transport, industry

Hotspots Sofia, Plovdiv, industrial zones — Dimitrovgrad reaches 21.8 µg/m³

Top morbidity Stroke (71.7/100k - highest in EU) · Ischaemic heart disease (44.1/100k) · Diabetes (11/100k)

Equity Urban lower income in older apartment blocks face highest exposure; workers in coal power plant regions

REGULATORY STANDING

EU alignment Low transposes AAQD but has exceeded PM_{10} limits historically; 2024 AAQD presents a compliance challenge

WHO alignment Low $PM_{2.5}$ ~3-4× WHO guideline; significant gap remains despite improvements

2024 AAQD Transposition deadline Dec 2026; dual coal dependency makes 2030 target structurally challenging

Key instruments Air Protection Act (2002, amended 2020) · National Air Quality Programme (2021-2025) · City AQ plans

Binding sectors IED · Euro 6 · Fuel quality regulation

Non-binding Residential heating modernisation subsidies · Coal phase-out roadmap

IMPLEMENTATION REALITY

Competent bodies Executive Environment Agency (monitoring) · Regional Inspectorates · Municipalities

Health link National Center of Public Health and Analyses. Limited health–environment data integration

Enforcement Weak limited residential source enforcement capacity; administrative fines for industrial exceedances

Main barrier Dual coal dependency: residential heating (~45%) and power generation (~20%) require simultaneous transition

Capacity gap Sparse monitoring network (~50 stations) relative to population and pollution challenge

Monitoring ~50 EEA-compliant stations · national air quality portal

↗ AIR QUALITY TREND

$PM_{2.5}$ down ~20% since 2010 — gradual improvement but still above EU 2030 target; seasonal winter peaks driven by residential solid-fuel combustion remain problematic.

↗ HEALTH OUTCOMES TREND

Premature deaths down ~15% since 2015; 63% reduction since 2005. Respiratory admissions broadly stable. Limited health sector integration in monitoring and evaluation.

! 2030 OUTLOOK

$PM_{2.5}$ 10 µg/m³ EU limit value challenging without structural action on heating and power. Art. 18 postponement is a credible risk. No national competent authority interview conducted.

POLICY-RELEVANT INSIGHTS

1 **Dual coal dependency is a structural barrier**
Bulgaria faces a compounding challenge: coal contributes through both residential heating and power generation. Measures targeting simultaneous energy and heating transitions are required.

2 **Highest per-capita health burden**
At 143.8 premature deaths per 100,000 and a stroke burden (71.7/100k) that is the highest in the EU, Bulgaria's health cost is acute.

3 **Art. 18 postponement risk**
Current $PM_{2.5}$ levels (~15 µg/m³) and structural barriers to transition make Bulgaria a plausible candidate for Art. 18 postponement. This can allow delays of up to 10 years, extending an already severe health burden.

4 **Enforcement and capacity building as prerequisites**
With ~50 monitoring stations and limited residential enforcement capacity, Bulgaria requires technical and financial support for administrative capacity building as a condition of compliance by 2030.

Sources: EEA Air Quality in Europe 2024; IHME Global Burden of Disease 2023; European Commission AAQD impact assessment. No national competent authority interview conducted.

Denmark

POPULATION	$PM_{2.5}$ ANNUAL MEAN	PM_{10} ANNUAL MEAN	ABOVE WHO GUIDELINE	PREMATURE DEATHS	MORTALITY REDUCTION
6M	8 µg/m³ range 6–9 (2023)	21 µg/m³ range 18–38 (2023)	67% of population	18.3 per 100,000 (2023)	−76% 2005→2023 (2.9k→703)

EXPOSURE & HEALTH

Primary source Residential wood burning; transboundary from other EU Member States

Other sources Road transport, industry, agriculture/NH_3

Hotspots Copenhagen and Aarhus urban areas; rural areas significantly lower

Top morbidity COPD (3.5/100k) · Stroke (2.9/100k) · Diabetes (2.8/100k) · IHD (2.7/100k)

Equity Relatively equitable distribution due to district heating coverage; COPD patients and elderly most at risk at low exposure

REGULATORY STANDING

EU alignment **High** meets all current EU limit values; strong transposition and enforcement; on track for 2030 targets

WHO alignment **Medium** $PM_{2.5}$ ~1.5× WHO guideline are narrowing the gap but not yet compliant

Internal tension Nitrates Directive derogations permit higher agricultural ammonia, directly conflicting with NEC reduction commitments

Key instruments Environmental Protection Act · National Air Quality Strategy (2020–2030) · Local AQ action plans

Binding sectors IED · Euro 6 · Fuel quality · Agricultural ammonia (NEC)

Non-binding Residential heating efficiency · Shipping emissions management

IMPLEMENTATION REALITY

Competent bodies Danish Environmental Protection Agency (Miljøstyrelsen) · Municipalities · Transport authorities

Health link National Board of Health. Integrated health surveillance linked to AQ monitoring

Enforcement **Strong** strong compliance culture; enforcement rarely contested; vehicle inspection programmes active

Main barrier Agricultural ammonia reduction — politically sensitive; Nitrates derogations limit NEC effectiveness

Good practice Vehicle taxation as demand-side instrument; district heating eliminates residential combustion at scale

Monitoring ~30 EEA-compliant stations · real-time national portal · integrated health surveillance

↘ AIR QUALITY TREND

$PM_{2.5}$ down ~60% since 2005 — exceeded EU 2030 55% reduction target. Consistent improvement trajectory. Transboundary contribution (30–40%) is now the binding constraint on further progress.

↘ HEALTH OUTCOMES TREND

Premature deaths down ~60% since 2005 (2,935 → 703). Respiratory hospital admissions declining. Health benefits of clean air policy among best-documented in EU.

↗ 2030 OUTLOOK

On track for EU targets; closing remaining gap to WHO guideline (5 µg/m³) requires EU-level action on transboundary sources and domestic agricultural ammonia reduction.

POLICY-RELEVANT INSIGHTS

1 Denmark as a ceiling case: what sustained sectoral alignment achieves

A 76% reduction in premature deaths since 2005 results from alignment across energy, transport, and industrial policy, not air quality legislation alone. Sectoral coherence is the main success driver.

2 Transboundary PM as the main constraint on further progress

With 30–40% of Denmark's PM load from other Member States, domestic action has diminishing returns. Closing the gap to the WHO guideline requires EU-level action on Eastern European solid-fuel combustion and coal power.

3 Internal EU policy contradiction: Nitrates derogations vs NEC ammonia targets

Denmark simultaneously benefits from Nitrates Directive derogations permitting higher agricultural nitrogen application while being held to NEC ammonia reduction targets. This is a documented tension in EU policy coherence.

4 Transferable practices

Vehicle taxation as a demand-side PM instrument; district heating for elimination of residential combustion; strong compliance culture built through decades of consistent enforcement.

Sources: EEA Air Quality in Europe 2024; IHME Global Burden of Disease 2023; EEA country profile (Denmark 2025). Interview: DCE/Aarhus University; EU-level interviews (EEA, DG ENV).

Finland

POPULATION	$PM_{2.5}$ ANNUAL MEAN	PM_{10} ANNUAL MEAN	ABOVE WHO GUIDELINE	PREMATURE DEATHS	MORTALITY REDUCTION
5.5M	5 µg/m³ range 1–6 (2023)	18 µg/m³ range 4–41 (2023)	0% of population	0.9 per 100,000 (2023)	−97% 2005→2023 (1,198→34)

EXPOSURE & HEALTH

Primary source Road transport — primarily non-exhaust road dust from winter maintenance

Other sources Industry, residential heating, agriculture/NH_3

Hotspots Helsinki metropolitan area (road dust); episodic $PM_{2.5}$ peaks from Russian wood burning/fires (easterly winds)

Top morbidity Ischaemic heart disease (0.3/100k) · Stroke (0.2/100k) · Lung cancer (0.1/100k)

Equity Equitable distribution due to universal district heating; urban arterial residents exposed to seasonal road dust episodes

REGULATORY STANDING

EU alignment **High** meets all EU outdoor limit values and exceeds 2030 targets; excellent transposition record

WHO alignment **High** $PM_{2.5}$ at or approaching WHO annual guideline (~5 µg/m³); best EU performer

Indoor reform Housing Health Decree under revision to align with WHO 2021 indoor guidelines; WHO vs EU levels still under discussion

Key instruments Environmental Protection Act · NAPCP (2021–2030) · No active national AQ plans needed

Binding sectors IED · Euro 6 · Fuel quality regulation

Non-binding Residential heating efficiency · Road maintenance procurement specifications

IMPLEMENTATION REALITY

Competent bodies Ministry of Environment (outdoor/NAPCP) · Ministry of Social Affairs & Health (indoor) · SYKE · ELY Centres · Municipalities

Health link Finnish Institute for Health and Welfare. Indoor Air and Health Programme produces substantial research body

Enforcement **High** processes in place for indoor and outdoor AQ; rarely invoked as all limit values are met

Main barrier Seasonal PM_{10} road dust from winter maintenance and spring cleaning (studded tyres, sanding/salting)

Key gap Lack of reliable low-cost sensors for indoor/outdoor supplementary monitoring — limits municipal enforcement capacity

Monitoring ~40 EEA-compliant stations · real-time national portal · supersite ammonia measurement pending

→ AIR QUALITY TREND

$PM_{2.5}$ consistently at or below WHO guideline (~5 µg/m³) — stable since 2010. Best outdoor AQ performance in EU case study set. PM_{10} episodic peaks during road dust season are principal remaining challenge.

↘ HEALTH OUTCOMES TREND

Premature deaths 97% below 2005 levels; 34 attributable deaths in 2023. Morbidity rates an order of magnitude below EU average.

→ 2030 OUTLOOK

Already compliant with all 2030 EU targets. Remaining challenges: seasonal road dust, Russian transboundary PM (uncontrollable domestically), and indoor air reform outcome (WHO vs EU levels decision pending).

POLICY-RELEVANT INSIGHTS

1 Non-exhaust PM_{10} as the main challenge

Finland's primary remaining PM challenge is road dust from winter maintenance, which is not addressed by existing EU emissions legislation. Euro 7's non-exhaust provisions do not cover road dust from maintenance materials. Procurement specifications for sanding material quality are a potential lever.

2 Need for low-cost sensors

Finland identifies absent EU guidance on reliable affordable low-cost monitoring equipment — for both indoor and outdoor use — as a barrier to enforcement capacity across Member States. A guidance and standardisation intervention at EU level would benefit all Member States at low cost.

3 EU platform for AQ plan good-practice sharing

Despite strong performance, Finnish administrations report limited experience developing AQ plans (as plans have not been needed). Even well-performing countries would benefit from an EU-level platform sharing plan content and structure, particularly ahead of the 2024 AAQD's new roadmap requirements.

Sources: EEA Air Quality in Europe 2024; IHME Global Burden of Disease 2023. Interview: Ministry of Environment and Ministry of Social Affairs and Health, Finland.

Spain

POPULATION	$PM_{2.5}$ ANNUAL MEAN	PM_{10} ANNUAL MEAN	ABOVE WHO GUIDELINE	PREMATURE DEATHS	MORTALITY REDUCTION
47M	9 µg/m³ range 3–18 (2023)	30 µg/m³ range 9–71 (2023)	75% of population	41.1 per 100,000 (2023)	−58% 2005→2023 (32k→13k)

EXPOSURE & HEALTH

Primary source Road transport

Other sources Industry, agriculture/NH_3, residential heating, ports/shipping

Hotspots Madrid, Barcelona, Seville; PM_{10} spikes during Saharan dust intrusions; rural-urban gradient significant

Top morbidity Ischaemic heart disease (6.8/100k) · Stroke (6.5/100k) · Diabetes (6.2/100k) · Lung cancer (5.2/100k)

Equity Urban poor in dense neighbourhoods face higher exposure; low-income households own older vehicles, lack of LEZ transition support

REGULATORY STANDING

EU alignment **Medium** many regions within EU limit values; major cities exceed 10 µg/m³ limit; PM_{10} exceeded in some zones; Saharan dust deductions applied; good transposition

WHO alignment **Medium-Low** $PM_{2.5}$ ~1.8× WHO guideline (5 µg/m³); moderate gap

Governance MITECO coordinates nationally but cannot mandate measures; autonomous communities are the primary competent authorities

Key instruments Law 34/2007 · National AQ Programme (2022–2030) · 17 autonomous community AQ plans · National Environmental Health Strategy (PESMA)

Binding sectors IED · Euro 6 · Fuel quality regulation

Non-binding Residential heating · Agricultural ammonia · Saharan dust protocols (under revision)

IMPLEMENTATION REALITY

Competent bodies MITECO (coordination/EU reporting) · Autonomous communities (primary enforcement) · Municipalities (LEZs)

Health link Ministry of Health: joint transposition with MITECO; PESMA framework for cross-sectoral coordination; joint public communication

Enforcement **Fragmented** ~20 of 350+ eligible cities have implemented LEZs; judicial pressure weak; reliance on EU infringement

Main barrier Heterogeneous enforcement across 17 autonomous communities; MITECO cannot mandate measures at regional level

Agricultural gap Ammonia concentrations may be increasing in agriculture; urea-based vehicle exhaust treatment adds NH_3

Monitoring 600+ EEA-compliant stations (among largest EU networks) · chemical speciation since 1999 · FAIRMODE/TAIEX

↗ AIR QUALITY TREND

$PM_{2.5}$ down ~25% since 2010. Urban hotspots persist in Madrid, Barcelona, Seville. Saharan dust events cause periodic PM_{10} spikes (legally deductible). Agricultural ammonia showing no improvement.

↗ HEALTH OUTCOMES TREND

Premature deaths down ~20% since 2015; 58% since 2005. Respiratory admissions stable. Urban-rural health disparities. Health impact quantification (costs, quality of life) identified as a priority gap

↗ 2030 OUTLOOK

2030 EU target achievable but requires acceleration on LEZ enforcement, agricultural ammonia, and biomass burning.

POLICY-RELEVANT INSIGHTS

1 Decentralised governance

coordinates but cannot mandate measures. National compliance with 2030 AAQD limits therefore depends on consistent action across 17 jurisdictions with varying resources and political will.

2 LEZ implementation gap

Despite a legal obligation for cities over 50,000 inhabitants, only ~20 of 350+ eligible municipalities have implemented LEZs. This reflects the implementation-enforcement gap.

3 PESMA as a transferable health-environment governance model

Spain's Strategic Plan on Health and Environment (PESMA) provides a cross-sectoral framework enabling joint transposition, coordinated public health communication, and scientific collaboration. This institutionalised health integration is relatively rare in the case study set and may be transferable.

4 Agricultural ammonia: the unresolved sector

Ammonia concentrations are not decreasing — driven by intensive farming, livestock, and urea-based vehicle exhaust treatment. NEC commitments exist but CAP alignment is weak. Ammonia-driven secondary PM is identified by EEA as the sector with the greatest remaining EU-wide reduction potential.

Sources: EEA Air Quality in Europe 2024; IHME Global Burden of Disease 2023. Interviews: MITECO, 2024; IsGlobal (CSIC); EU-level interviews (EEA, DG ENV).

Italy

POPULATION	$PM_{2.5}$ ANNUAL MEAN	PM_{10} ANNUAL MEAN	ABOVE WHO GUIDELINE	PREMATURE DEATHS	MORTALITY REDUCTION
59M	13 µg/m³	37 µg/m³	100%	100.6	−39%
	range 1–26 (2023)	range 1–94 (2023)	of population	per 100,000 (2023)	2005→2023 (71k→43k)

EXPOSURE & HEALTH

Primary source Road transport; industry

Other sources Residential heating; agriculture/NH_3

Hotspots Po Valley: Milan ~19.3 µg/m³; thermal inversion traps pollutants

Top morbidity Stroke (23.1/100k) · IHD (22.2/100k) · Diabetes (20.8/100k) · Lung cancer (11.2/100k) · COPD (9.5/100k)

Equity Po Valley residents face highest $PM_{2.5}$ exposure in EU; elderly and children in northern industrial cities; workers in manufacturing

REGULATORY STANDING

EU alignment **Medium** meets EU limits overall but frequent Po Valley exceedances; multiple infringement procedures ongoing

WHO alignment **Low** $PM_{2.5}$ 2–3× WHO guideline (5 µg/m³); Po Valley hotspots up to ~19 µg/m³

Po Valley Long-standing compliance challenge; thermal inversion, agricultural ammonia, and transport/industry combine in worst EU exceedance zone

Key instruments Legislative Decree 155/2010 · National AQ Programme (2022–2030) · 20 regional AQ plans

Binding sectors IED · Euro 6 · Fuel quality regulation

Non-binding Residential heating incentives · Agricultural ammonia · LEZs (Milan, Bologna, Turin, with measurable NO_2 reductions)

IMPLEMENTATION REALITY

Competent bodies Ministry of Environment and Energy Security · 20 Regional Environmental Agencies (ARPA) · Municipalities

Health link Ministry of Health for health impact assessment. Limited systematic integration of health data into AQ policy design

Enforcement **Weak** local authorities overburdened; insufficient national incentives; described as "ignoring the cap" in some instances

Main barrier Po Valley geography (thermal inversion) combined with intensive agriculture, transport, and industry

Coordination 20 ARPA regions with uneven capacity; responsibility placed on local authorities without national incentives

Monitoring ~600 EEA-compliant stations · national portal · ARPA regional networks

↗ AIR QUALITY TREND

$PM_{2.5}$ down ~20% since 2010. Po Valley remains most problematic EU exceedance zone. Seasonal winter peaks driven by temperature inversion. Agricultural ammonia shows no improvement trend.

↗ HEALTH OUTCOMES TREND

Premature deaths down 39% since 2005 but Italy retains highest absolute toll (43,083). Highest morbidity for COPD, lung cancer, and diabetes in case study set. No significant improvement in Po Valley.

! 2030 OUTLOOK

$PM_{2.5}$ 10 µg/m³ EU limit unlikely met without major structural action on Po Valley agriculture, heating, and transport. Art. 18 postponement for Po Valley zones is a probable outcome.

POLICY-RELEVANT INSIGHTS

1 The Po Valley geography is not an excuse but it is a constraint

Thermal inversion creates a natural pollution trap amplified by Europe's highest concentration of industrial activity, intensive agriculture, road transport, and residential heating in a single basin. It requires coordinated cross-sectoral action and realistic postponement expectations.

2 Agriculture and secondary PM as the unresolved sector

Po Valley intensive livestock and arable farming generate ammonia that reacts with NO_x and SO_2 to form secondary PM. Addressing this requires coherence between NEC, CAP, and IED. EEA identifies Italy as the most concentrated case of this systemic EU problem.

3 Governance deficit: local authority overload, and lack of national incentives

Primary implementation responsibility rests on local authorities who lack financial and capacity resources. Italy's 20 ARPAs operate with uneven capacity. Sources point to excessive reliance on local authorities without sufficient national coordination.

4 EU infringement as an insufficient lever for structural problems

Italy has faced multiple CJEU proceedings for PM exceedances. Infringement demonstrates that legal enforcement does not correct for lagging transitions in energy, agriculture, and urban planning.

Sources: EEA Air Quality in Europe 2024; IHME Global Burden of Disease 2023; European Commission AAQD impact assessment. EU-level interviews (EEA, DG ENV, EEB). National level interview: ISPRA

Germany

POPULATION	PM$_{2.5}$ ANNUAL MEAN	PM$_{10}$ ANNUAL MEAN	ABOVE WHO GUIDELINE	PREMATURE DEATHS	MORTALITY REDUCTION
84M	8 µg/m^3 range 4–12 (2023)	21 µg/m^3 range 9–37 (2023)	99.5% of population	37.1 per 100,000 (2023)	−67% 2005→2023 (51k→22k)

EXPOSURE & HEALTH

Primary source Road transport; industry;

Other sources Residential heating; agriculture/NH_3

Hotspots Major urban areas (Berlin ~9.4 µg/m³); eastern Germany higher due to transboundary influence; coal power plant zones

Top morbidity Ischaemic heart disease (11.3/100k) · Diabetes (6.0/100k) · Stroke (5.7/100k) · COPD (4.1/100k)

Equity Socio-economically disadvantaged populations tend toward higher-exposure traffic areas

REGULATORY STANDING

EU alignment **High** largely compliant with all EU PM limit values; strong transposition and enforcement

WHO alignment **Low** PM$_{2.5}$ ~1.5–2× WHO guideline; full alignment assessed by UBA as "extremely difficult" under current conditions

Key tension Courts give greater evidential weight to measured data than modelled estimates — limits model-based enforcement under 2024 AAQD

Key instruments Federal Immission Control Act (BImSchG) · National AQ Programme (2021–2030) · 16 Länder AQ plans

Binding sectors IED · Euro 6 · Fuel quality regulation

Non-binding Residential heating efficiency · Agricultural practices · National AQ app (public communication)

IMPLEMENTATION REALITY

Competent bodies Federal Environment Agency (UBA, coordination) · Länder agencies (monitoring/enforcement) · Municipalities (attainment responsibility)

Health link National AQ index developed, aligned with WHO; Robert Koch Institute for public health (not directly in AQ enforcement)

Enforcement **Strong** administrative penalties; vehicle inspection; industrial permits; short-term action plans at threshold breach

Main barrier Agricultural ammonia: seasonal fertiliser peaks (Feb/March) driven by weather and transboundary inflow — difficult to address with local measures

Data gap Lack of detailed localised wood burning fuel-use data weakens modelling and targeted intervention design

Monitoring ~500 EEA-compliant stations · UBA portal · national AQ app with real-time alerts · long-term chemical speciation

↗ AIR QUALITY TREND

PM$_{2.5}$ down ~30% since 2010. Steady improvement trajectory. Eastern Germany slightly higher, influenced by transboundary inflow. NH_3 seasonal peaks remain.

↗ HEALTH OUTCOMES TREND

Premature deaths down ~25% since 2015; 67% since 2005. Respiratory hospitalisations declining. Morbidity burden is undercounted as standard reporting focused only on mortality.

↗ 2030 OUTLOOK

Compliant with revised 2024 AAQD targets. Closing the WHO gap is extremely difficult without natural background accounting. Agricultural ammonia remains the principal unresolved sector.

POLICY-RELEVANT INSIGHTS

1 Germany as a mid-range performer: compliant with EU but far from WHO

Germany meets all EU PM limit values but PM$_{2.5}$ remains 1.5–2× the WHO guideline. UBA assesses full WHO alignment as "extremely difficult", as even rural background stations measure above 5 µg/m³.

2 Courts favour measured over modelled evidence

A structurally significant finding: German courts give greater evidential weight to measured concentration data than to modelled estimates. Exceedances identified only through modelling may not be actionable in legal proceedings — an interesting finding as the 2024 AAQD expands the role of modelling in compliance assessment.

3 Agricultural ammonia and data gaps

Seasonal fertiliser application generates pronounced PM peaks that are partially transboundary and weather-driven, limiting local response. This is compounded by insufficient localised data on wood burning fuel use. Both gaps reduce the evidence base for designing targeted mitigation measures.

4 Morbidity is undercounted as a health metric

Economic valuations are drawn from Commission HIAs, rather than epidemiological work. Broader use of morbidity metrics would strengthen the policy case for standard setting.

Sources: EEA Air Quality in Europe 2024; IHME Global Burden of Disease 2023. Interviews: UBA; European Respiratory Society.

France

POPULATION	$PM_{2.5}$ ANNUAL MEAN	PM_{10} ANNUAL MEAN	ABOVE WHO GUIDELINE	PREMATURE DEATHS	MORTALITY REDUCTION
68M	9 µg/m³	25 µg/m³	96%	34.2	−62%
	range 3–15 (2023)	range 7–86 (2023)	of population	per 100,000 (2023)	2005→2023 (38k→15k)

EXPOSURE & HEALTH

Primary source Road transport, residential wood burning

Other sources Agriculture/NH_3, industry, ports and shipping

Hotspots Paris, Lyon, Marseille, industrial north, Île-de-France, PACA, Auvergne-Rhône-Alpes above national urban average

Top morbidity Stroke (5.0/100k) · IHD (4.3/100k) · Diabetes (4.3/100k) · Lung cancer (4.1/100k) · COPD (1.8/100k)

Equity Lower-income households reliant on wood heating and older vehicles face compounded exposure; LEZ transition support withdrawal worsens inequity

REGULATORY STANDING

EU alignment **High – Medium de facto** all directives transposed; national $PM_{2.5}$ limit (10 µg/m³) stricter than 2008 AAQD; CJEU condemnation for PM_{10} and NO_2 exceedances in Paris, Marseille, Toulouse

WHO alignment **Medium** $PM_{2.5}$ ~2× WHO guideline (5 µg/m³); Paris, Lyon, Marseille exceed even the national 10 µg/m³ limit

PREPA National emissions reduction plan — lacks concrete targets, assigned responsibilities, funding, and enforcement mechanisms; risk of 2024 AAQD transposition delay

Key instruments Federal Immission Control Act (BImSchG) · National AQ Programme (2021–2030) · 16 Länder AQ plans

Binding sectors IED · Euro 6 · Fuel quality regulation

Non-binding Residential heating efficiency · Agricultural practices · National AQ app (public communication)

IMPLEMENTATION REALITY

Competent bodies Ministry of Ecological Transition (policy) · Regional Prefects (enforcement, emergency powers) · 18 AASQAs coordinated by Atmo France · Municipalities

Health link Santé publique France: independent health surveillance and impact assessment.

Enforcement **Weak on urban sources** LEZs poorly enforced; compliance unverifiable; CJEU condemned France for persistent exceedances in major cities despite legal framework

Main barrier Residential wood burning culturally entrenched; politically difficult to regulate; biomass incentives under RED II conflict with $PM_{2.5}$ reduction objectives

Data gap Instrumentalisation of social fairness against LEZs; transposition of 2024 AAQD at risk of delay

Monitoring ~650 stations · 18 regionally funded AASQAs (independent model) · Atmo France national portal · AQ index

↗ AIR QUALITY TREND

$PM_{2.5}$ emissions down ~50% (2005–2022); concentrations down ~42% (2009–2022). On track for EU 55% reduction target. Paris, Lyon, Marseille still exceed the national 10 µg/m³ limit. Agricultural ammonia not adequately addressed.

↗ HEALTH OUTCOMES TREND

Premature deaths down 62% since 2005. Respiratory admissions declining. ~30,000 asthma cases/year avoidable at WHO guideline levels (5 µg/m³), estimate avoidable ~€3bn in medical costs

↗ 2030 OUTLOOK

On track for EU 55% $PM_{2.5}$ reduction target but major cities will require significant additional action to meet 10 µg/m³ by 2030. CJEU exceedances unresolved. 2024 AAQD transposition risk. LEZ roll-back is a real political scenario.

POLICY-RELEVANT INSIGHTS

1 Major cities compliance gap

Driven by wood burning, traffic, and agricultural ammonia, it shows that legislative ambition does not automatically translate into health outcomes. Implementation requires local behavioural and infrastructure change.

2 PREPA as a cautionary model for national reduction programmes

France's national emissions reduction plan lists measures but has shortcomings on target concretion, assigned responsibilities, funding mechanisms, and enforcement instruments. The French case is not unique, but it illustrates how the AAQD, which requires AQ roadmaps (Art. 19) has the potential to raise the floor for Member States in translating policy intent into implementable commitments.

3 LEZ politicisation: a common vulnerability across Member States

Politization risks roll back of LEZ commitments. Equity provisions including vehicle replacement support, phased implementation for low-income households, are core associated social fairness topics.

Sources: EEA Air Quality in Europe 2024; IHME Global Burden of Disease 2023. Interviews: UBA; European Respiratory Society.

5.2. Summary table on alignment

Table 5: Country summary – $PM_{2.5}/PM_{10}$ case studies

Country	$PM_{2.5}$ 2023 µg/m³	PM_{10} 2023 µg/m³	Premature deaths per 100,000	EU 2030 alignment (≤10/≤20 µg/m³)	WHO alignment (≤5/≤15 µg/m³)	Primary $PM_{2.5}$ source
Poland	**15**	**33**	**99.5** (76–111)	**Low**	**Low**	Residential solid-fuel heating (coal and biomass).
Bulgaria	**15**	**40**	**143.8** (110–160)	**Low**	**Low**	Residential heating (coal and biomass), and power generation (coal)
Denmark	**8**	**21**	**18.3** (14–20.5)	**High**	**Medium**	Residential heating (wood burning); transboundary inflow.
Finland	**5**	**18**	**0.9** (0.7–1.0)	**High**	**High**	Non-exhaust road dust from winter maintenance (studded tyres, sanding)
Spain	**9**	**30**	**41.1** (31.3–45.9)	**Medium**	**Medium-Low**	Road transport; Saharan dust events (PM_{10}); ports and shipping
Italy	**13**	**37**	**100.6** (77–112)	**Low**	**Low**	Road transport and industry; agricultural ammonia
Germany	**8**	**21**	**37.1** (28.1–41.4)	**High**	**Medium**	Road transport and industry; agricultural ammonia
France	**9**	**25**	**34.2**† (26–38.2)	**Medium**	**Medium-Low**	Road transport, residential wood burning; agricultural ammonia; ports and shipping

Note: EU 2030: 2024 AAQD limit values to be attained by 1 Jan 2030 ($PM_{2.5}$ ≤10 µg/m³ annual; PM_{10} ≤20 µg/m³ annual). WHO: 2021 guidelines ($PM_{2.5}$ ≤5 µg/m³ annual; PM_{10} ≤15 µg/m³ annual). Ratings reflect observed concentration levels, transposition status, and enforcement record as documented in country fiches. † EEA/IHME methodology. Santé publique France estimates ~40,000 deaths/year using a broader exposure scope.

Source: Authors' own elaboration.

5.3. Non-EU countries

This section looks at three non-EU examples: the United Kingdom, Norway, and China. Those countries are selected to cover the range of regulatory contexts and performance levels relevant to the study's main questions. The UK and Norway both implement standards closely aligned with the EU framework: the UK retained some EU laws following Brexit, and Norway does so through the EEA Agreement. China shows a radically different regulatory system, with much weaker air quality standards and a much larger health burden. Together, the three cases show how EU-standard regulation can or cannot achieve on its own, and what works well elsewhere for the implementation of a regulatory framework.

5.3.1. United Kingdom

The United Kingdom presents a distinctive example in this report: a country that has achieved substantial air quality improvements over the past 30 years, now independent of the EU regulatory framework, making it a perfect comparison for testing whether EU-wide rules bring real benefits.

Exposure and health burden

With annual mean $PM_{2.5}$ levels of approximately 10–12 µg/m³,[423] the UK has similar pollution levels as France and Spain (above the 2024 AAQD 2030 limit of 10 µg/m³ and roughly double the WHO annual guideline of 5 µg/m³). Most of the population is exposed to levels above the WHO guidelines. Attributable premature mortality is estimated at 34,000–36,000 per year (51–54 per 100,000)[424]. The primary $PM_{2.5}$ sources are road transport (particularly diesel), residential wood burning, and agricultural ammonia, contributing to secondary particle formation.

Regulatory framework and post-Brexit divergence

The UK adopted the 2008 AAQD through the Air Quality Standards Regulations 2010, and kept those standards upon exit from the EU. Today in the UK, air quality is governed by the Clean Air Strategy 2019 and the Local Air Quality Management system, which maintains broadly similar limit values. DEFRA coordinates national policy, and implementation rests with local authorities, which are constrained by budget limitations. The devolved administrations in Scotland, Wales, and Northern Ireland introduce further variation in ambition and capacity.

The practical consequence of post-Brexit divergence is not a difference in standards, but a drift apart in timing and ambition. The 2024 AAQD tightened EU $PM_{2.5}$ limits to 10 µg/m³ by 2030 and introduced new instruments (area-based exposure reduction objectives, mandatory supersites, AQ roadmaps) which the UK is not bound to replicate. Whether the UK independently aligns more closely toward similar levels of ambition or moves away from those standards may have implications for cross-border pollution dynamics and for the competitiveness framing of UK-EU environmental policy.

Implementation and enforcement

The most significant and impactful domestic implementation instrument in recent years has been **the Ultra Low Emission Zone (ULEZ) in London, which has reduced street-level traffic pollution and is being replicated in other cities**. Vehicle emission standards and industrial controls have been

[423] Department for Environment, Food and Rural Affairs (Defra), 2025, *Air quality statistics in the UK, 1987 to 2024*, Defra, London. Available at: https://www.gov.uk/government/statistics/air-quality-statistics.

[424] Department for Environment, Food and Rural Affairs (Defra), 2023, *Air Pollution in the UK 2023*, Defra, London. Available at: https://uk-air.defra.gov.uk/assets/documents/annualreport/air_pollution_uk_2023_issue_1.pdf/.

effective. The principal implementation challenges are the growing number of residential wood-burning stoves (an emerging source not yet effectively regulated) and funding constraints that limit local authority capacity to deliver the Local Air Quality Management system. Agricultural ammonia reduction, as in several EU Member States, remains the least progressed sector.

Trends and outlook

The long-term trend is clearly improving overall: PM_{10} at the urban background has declined from 36.1 µg/m^3 in 1992 to 11.8 µg/m^3 in 2024, a record low. $PM_{2.5}$ has declined consistently since 2011. Premature mortality is also declining in absolute terms. However, 100% of the urban population remains above the WHO guideline, and London continues to exceed national targets in several zones.

Policy-relevant insights

The UK case offers three lessons relevant to EU policy.

The UK case proves big health wins are possible through vehicle emission standards and industrial controls, but it also shows that closing the remaining gap to WHO guideline levels requires action on residential combustion and agricultural sources, which is politically more difficult and has not yet been delivered at the required scale in any of the case study countries, inside or outside the EU.

Second, the ULEZ model (a geographically bounded, charging-based instrument that targets the highest-emission vehicles) has been effective in reducing exposure in population-dense urban areas and is now being adopted progressively in UK cities. It represents a stronger enforcement (in reality backed up by cameras and penalties) than broad LEZ designations that lack charging or camera enforcement, and is directly relevant to the implementation gaps documented in Spain and France.

Finally, Brexit raises a key question: does being part of the EU and the legal obligation to update air quality standards lead to faster or more durable improvements than a comparably resourced country operating under its own framework? The early evidence does not yet answer this definitively. However, the UK's non-adoption of the 2024 AAQD, and in particular its absence of binding 2030 targets at the 10 µg/m^3 level, means the difference between the EU and UK approaches will become clearer over the next five years.

5.3.2. Norway

Norway is **the highest-performing country in this case study set and, alongside Finland, one of only two countries where $PM_{2.5}$ levels are close to or meet the WHO annual guideline of 5 µg/m^3**. As an EEA member, Norway implements EU air quality directives through the EEA Agreement, which makes it a useful comparator for assessing what EU-standard regulation, combined with a structurally clean energy system, can achieve at the upper bound of performance.

Exposure and health burden

The annual mean $PM_{2.5}$ is approximately 5.8–6 µg/m^3 (2023–2024),[425] placing Norway at roughly 1.2× of the WHO guideline level. PM_{10} levels (approximately 13–14 µg/m^3) are also among the lowest recorded. Approximately 60.5% of the population is exposed to levels above the WHO guideline levels, a figure substantially lower than in all EU case study countries except Finland (0%).[426]

[425] European Environment Agency, 2024. *Europe's air quality status 2024*. Available at: https://www.eea.europa.eu/en/analysis/publications/europes-air-quality-status-2024.

[426] Ibid.

Attributable premature mortality is estimated at 5–7 per 100,000, with a total of approximately 30–40 deaths, which is the lowest absolute per-capita toll in the study.

Non-fatal health burdens are correspondingly low. Ischaemic heart disease is the predominant condition linked to $PM_{2.5}$ exposure (approximately 52 cases; 1.3/100,000), followed by COPD (44 cases; 1.1/100,000), stroke (36 cases; 0.9/100,000), and lung cancer and diabetes (31 cases each; 0.8/100,000). These figures are broadly comparable to Finland.

Regulatory framework

Norway implements the EU AAQD and associated directives through the EEA Agreement, administered primarily by the Norwegian Environment Agency (Miljødirektoratet), with the Norwegian Institute of Public Health (Folkehelseinstituttet) responsible for health impact assessment and municipalities accountable for local plan implementation. The institutional architecture mirrors the EU model, with strong cross-agency coordination. Norway, similar to Finland and Denmark, share a compliance culture in which enforcement mechanisms are rarely invoked because limit values are consistently met.

The primary domestic policy instruments driving Norway's performance are not, however, air quality regulations as such, but more structural features of the energy and transport system: **near-total reliance on hydropower for electricity, one of the world's highest rates of electric vehicle adoption, and a district heating infrastructure that substantially reduces residential combustion in urban areas**. These drivers have reduced $PM_{2.5}$ to levels where the remaining gap to the WHO guideline is attributable to a small number of residual sources.

Implementation and remaining challenges

The principal unresolved challenges are winter residential wood burning in rural areas, shipping emissions in coastal cities (particularly Bergen) and cross-border pollution from continental Europe. Road traffic management in Oslo also remains a localised concern. None of these sources exceeds EU limit values, but they collectively explain why Norway is approximately 1.2× the WHO guideline rather than at or below it.

Norway's electric vehicle transition is the most frequently cited transferable practice in this context. Norway achieved over 80% new electrical vehicles (EV) sales share by 2023 through a sustained combination of tax exemptions, toll waivers, preferential access to bus lanes, and public charging infrastructure investment (a demand-side policy package rather than a supply-side standard). The approach differs from Euro emission standards in that it accelerates fleet turnover rather than constraining what can be sold, and has produced faster actual emissions reductions in the Norwegian context than technology mandates alone would have.

Policy-relevant insights

Norway's case offers three lessons of direct relevance to EU policy.

It demonstrates that the WHO $PM_{2.5}$ guideline of 5 µg/m³ is achievable and realistic at scale in a European context, including urban centres with significant industrial and maritime activity. **Their key has been a clean electricity system combined with high EV penetration and district heating, not regulatory stringency alone**. This is a relevant finding for the debate on the 2024 AAQD's 2030 limit of 10 µg/m³: Norway's performance suggests that 5 µg/m³ is a realistic long-term objective for high-income European countries with clean energy systems, even if the 2030 timeframe is not achievable across the EU.

Second, the EV transition model illustrates that demand-side fiscal instruments (rather than supply-side emission standards alone) can accelerate fleet turnover. The EU's Euro 7 regulation and 2035 ICE phase-out address supply, but the Norwegian experience suggests that demand-side measures such as taxation, infrastructure, and access privileges are necessary complements.

Third, Norway's residual gap (wood burning, shipping, and transboundary pollution) illustrates that even the best-performing countries face source categories that are difficult to address. Shipping emissions in particular are subject to international rather than national or EU governance, and Norway's coastal geography makes this a challenging constraint. The parallel with Denmark's transboundary constraint (30–40% of PM load from other EU countries) reinforces the study's broader finding that closing the final gap to WHO guideline levels requires coordinated action at EU and international levels.

5.3.3. China

China is included in this study as a non-European comparator case to provide a view of a fundamentally different stage of the air quality-development trajectory, and with a health toll from $PM_{2.5}$ that far exceeds any EU country. Its value to the study is as a reference point that contextualises the scale of what EU regulation has achieved, and as a source of observations about rapid large-scale interventions that are relevant to the study's effectiveness assessment.

Exposure and health burden

Annual mean $PM_{2.5}$ is approximately 33–35 µg/m³ (2023–2024), roughly 6–7× the WHO annual guideline of 5 µg/m³, and more than three times the current EU 2030 limit of 10 µg/m³. PM_{10} levels are approximately 68–70 µg/m³. Exposure is highest in the eastern industrial corridor, namely the Beijing-Tianjin-Hebei region and the Yangtze River Delta. In those regions, concentrations are even higher and substantially exceed national averages. Rural populations reliant on coal for heating face higher overall exposure and health risks.

Attributable premature mortality is estimated at approximately 1.3–1.4 million deaths per year (around 100 per 100,000), the largest national $PM_{2.5}$ health burden in the world in absolute terms. Manufacturing activities account for over 50% of $PM_{2.5}$-related deaths, with coal combustion, biomass burning, and transportation as secondary contributors.

Regulatory framework

China's national $PM_{2.5}$ limit under legislation GB 3095-2012 is 35 µg/m³ annually (precisely the current national mean) compared to the EU's 2030 target of 10 µg/m³ and the 2008 AAQD limit of 25 µg/m³. China's standard reflects a different starting point: it matches current pollution levels, acting more as a safety net to prevent things from getting worse than as a goal to improve public health. By contrast, the EU AAQD sets standards below current levels in most Member States to drive improvement, with the 2024 revision explicitly anchored in the WHO evidence base.

The Ministry of Ecology and Environment (MEE) coordinates national policy, with provincial environmental bureaus responsible for regional enforcement and municipal governments for local implementation. The National Health Commission monitors health impacts. The principal national instruments have been the Air Pollution Prevention and Control Law (revised 2015), the Blue Sky Defence War action plan (2018–2020), and successive Five-Year Plan emission reduction targets.

Implementation and observed outcomes

China's main success in delivering results since 2013 is a $PM_{2.5}$ reduction of approximately 35% from its peak. This was **driven primarily by bold moves to close coal plants or their upgrades, industrial emission controls, and the introduction of vehicle emission standards**. The approximately 1,500-station national monitoring network is the largest in the world and supports real-time public AQI reporting.

The main obstacles to implementation are the struggle to balance economic growth and environmental protection targets. Strong historical reliance on coal for both energy generation and residential heating in northern regions remains a major hurdle. Factory shutdowns and vehicle restrictions during severe haze events represent a reactive rather than planned approach to control peak pollution periods, which is effective in the short term but not a substitute for source reduction.

Policy-relevant insights

China's trajectory offers a relevant lesson: rapid large-scale $PM_{2.5}$ reductions (35% over approximately a decade) are achievable through central government-directed industrial restructuring and **coal phase-out when political will is clear.** Another lesson is that enforcement needs to be backed by administrative rather than judicial mechanisms. This rate of improvement far outstrips gains seen across the EU over the previous decade and is directly attributable to phasing out coal power plants and implementing industrial controls, rather than to regulatory standard-setting alone. The potential lesson for the EU is that **strict air limits alone don't guarantee results. What actually moves the needle is political will backed by real enforcement, which in turn can consistently reduce emissions and improve the population's health.**

6. POLICY RECOMMENDATIONS

This chapter sets out evidence-based policy recommendations arising from the study's four research questions. The recommendations are grounded in the health evidence synthesised in Chapter 2, the trend analysis in Chapter 3, the effectiveness assessment of the EU and national regulatory frameworks in Chapter 4, and the cross-country evidence from case studies in Chapter 5.

The study's overarching finding is that the EU possesses a mature, technically sophisticated air quality regulatory architecture and that this framework has delivered a 57% reduction in premature deaths attributable to $PM_{2.5}$ since 2005.The effectiveness of individual policy measures may vary depending on baseline pollution levels and the starting point from which further improvements are pursued. However, technical ambition in regulatory design has not translated consistently into health outcomes. Three structural problems recur across the evidence base:

1) The gap between EU limit values and WHO health-based guidelines remains large: even the 2024 AAQD's 2030 target of 10 µg/m³ for PM2.5 is double the WHO annual guideline, and current projections indicate approximately 60,000 to 70,000 premature deaths per year will remain attributable to PM2.5 even if the 2030 target is fully met.
2) The agricultural sector, as the dominant source of ammonia (the primary precursor to secondary inorganic PM2.5), has been outside enforceable air quality emissions control. Ammonia concentrations have remained broadly unchanged since 2005.
3) Implementation and enforcement at the Member State level is uneven, and in several cases relies on instruments (national emission plans, local air quality plans) that **lack concrete targets, assigned responsibilities, or funding mechanisms**.
4) **Environmental and socioeconomic inequalities remain significant across the EU.** Evidence reviewed in this study indicates that socioeconomically disadvantaged populations are often exposed to higher levels of $PM_{2.5}$ and PM_{10} and may experience a disproportionate share of the associated health burden. Policies that target areas and populations with the highest exposures are therefore likely to maximise health benefits while reducing environmental inequalities. Particular attention should be given to urban transport corridors, transportation hubs and lower-income areas, where exposure levels and health risks can be concentrated.

The recommendations summarised in the table below reflect the level of action required and the type of intervention. Across all intervention areas, priority should be given to measures that deliver the greatest health benefits in the most affected populations and regions, while ensuring a fair and socially inclusive transition.

Summary of recommendations

Table 6: Summary of recommendations

#	Recommendation	Category	Addressed to
R1	Commit to a clear trajectory toward the WHO $PM_{2.5}$ guideline beyond 2030	**Standards ambition**	European Commission (Art. 3 review, 2024 AAQD); European Parliament
R2	Address the PM_{10} annual standard and establish a post-2030 trajectory	**Standards ambition**	European Commission (Art. 3 review; Art. 16 implementing acts); European Parliament
R3	Restrict the scope and use of Art. 18 postponement provisions	**Standards ambition**	European Commission (Art. 18 implementing acts); European Parliament; Member States
R4	Establish binding, sector-specific ammonia reduction obligations linked to $PM_{2.5}$ health targets	**Agricultural ammonia**	European Commission (NEC Directive amendment; Nitrates Directive revision); European Parliament
R5	Integrate air quality conditions into the CAP Strategic Plan requirements	**Agricultural ammonia**	European Commission (CAP post-2027 proposal; Strategic Plan approval conditions); Member States
R6	Extend IED scope to medium livestock installations; strengthen Art. 70i operating rules	**Agricultural ammonia**	European Commission (IED Art. 70i; Art. 73 implementation review)
R7	Require AQ roadmaps to include concrete, funded, and enforceable measures	**Implementation**	European Commission (Art. 19(4) implementing acts); EEA
R8	Strengthen the LEZ implementation framework and address politicisation risk	**Implementation**	European Commission (AAQD implementing acts; urban AQ guidance); EEA; Member States
R9	Address the affordability of monitoring equipment and support network adequacy	**Implementation**	European Commission (Art. 8(7) implementing acts; cohesion fund conditions); EEA; Member States
R10	Develop an EU-level platform for sharing AQ plan and roadmap good practices	**Implementation**	European Commission; EEA; FAIRMODE

#	Recommendation	Category	Addressed to
R11	Address the household biomass regulatory gap in the Renewable Energy Directive	**Sectoral coherence**	European Commission (RED revision; ESPR delegated act for residential heating); Member States
R12	Require integration of air quality outcomes into building renovation strategies	**Sectoral coherence**	European Commission (EPBD post-2030 revision); Member States
R13	Accelerate fleet turnover to realise the health benefits of Euro 6 and Euro 7	**Sectoral coherence**	European Commission; Member States
R14	Integrate health authorities systematically into AQ policy design at the Member State level	**Health integration**	European Commission (AQ roadmap content requirements); Member States
R15	Strengthen morbidity and economic metrics in the EU air quality burden assessment	**Health integration**	European Commission; EEA; Member States (national health surveillance agencies)
R16	Establish EU-wide standards for public air quality information and health communication	**Health integration**	European Commission (Art. 22 implementing acts); EEA; Member States
R17	Address equity systematically in AQ plans, roadmaps, and health assessments	**Health integration**	European Commission (AQ roadmap and plan content requirements); Member States

Source: Authors' own elaboration.

6.1.1. Strengthening the ambition and coherence of EU air quality standards

R1 Commit to a clear trajectory toward the WHO $PM_{2.5}$ guideline beyond 2030

The 2024 AAQD sets a $PM_{2.5}$ limit of 10 µg/m³ by 2030, which is significant progress from 25 µg/m³ but still double the WHO annual guideline of 5 µg/m³. The epidemiological evidence establishes that no safe threshold of $PM_{2.5}$ exposure has been identified: health effects are consistently observed at concentrations below current EU limit values and below the WHO guideline itself. Critically, the concentration-response relationship is non-linear for long-term exposure, with the relative risk per unit of $PM_{2.5}$ being steeper at lower concentrations (meaning that reductions in the range of 10 to 5 µg/m³ yield proportionally greater health gains per unit of reduction than equivalent reductions at higher exposure levels). This strengthens rather than weakens the case for setting an ambitious post-2030 trajectory. Approximately 94% of the EU urban population remains exposed to levels above the WHO guideline levels.

The Commission should use the Art. 3 review mechanism to establish a binding intermediate milestone of 7.5 µg/m³ by 2035 and full alignment with the WHO guideline of 5 µg/m³ by 2040. This trajectory should take account of the strong health evidence base, subject to a technology and feasibility assessment to determine the appropriate pace and instrument mix for each Member State. Finland and Norway demonstrate that 5 µg/m³ is attainable at scale in Europe, including residential and industrial settings. The primary structural prerequisites are a clean electricity system, electrification of heating and transport, and sustained enforcement.

Addressed to: European Commission (Art. 3 review, 2024 AAQD); European Parliament (legislative resolution)

R2 Address the PM_{10} annual standard and establish a post-2030 trajectory

The 2024 AAQD aligns with the WHO 2021 guideline on the PM_{10} daily limit (45 µg/m³, ≤18 exceedances per year), but the annual limit of 20 µg/m³ remains above the WHO recommendation of 15 µg/m³. No post-2030 trajectory for PM_{10} has been established, leaving an unaddressed gap at a point where the post-2030 trajectory.

PM_{10} exceedances remain a compliance challenge in several Member States. Bulgaria and Italy face persistent annual and daily PM_{10} exceedances from residential combustion and industrial sources, respectively (Italy's Po Valley challenge is compounded by thermal inversion). In cases like Spain, Saharan dust intrusions (legally deductible under natural-source provisions) complicate compliance, but urban transport and industrial sources also contribute to PM_{10} exceedances independently of natural episodes.

The Commission should ensure that the Art. 3 review explicitly includes the PM_{10} annual standard, with a view to aligning it with the WHO guideline of 15 µg/m³ by 2040 at the latest. The daily PM_{10} limit of 45 µg/m³ should be maintained without weakening through postponement. Where Member States apply natural source deductions under Article 16, the Commission's implementing acts should ensure that quantification methodologies are sufficiently rigorous to prevent deductions from masking compliance failures driven by controllable domestic sources.

Addressed to: European Commission (Art. 18 implementing acts; Art. 18(4) roadmap review); European Parliament; Member States

R3 Restrict the scope and use of Art. 18 postponement provisions
Article 18 of the 2024 AAQD allows the 2030 deadline to be postponed by up to 10 years. Case study evidence from Poland, Bulgaria, and Italy indicates that postponement is a likely outcome for multiple Member States across zones covering large populations. If widely used, it would extend health exposure to non-compliant levels for a further decade in regions with the highest existing burden. The Commission should adopt a restrictive interpretation of the eligibility criteria in Art. 18, require reporting on the concrete health costs of each postponement request (expressed in attributable premature deaths and disease cases, made publicly available), and establish mandatory interim compliance milestones. The European Parliament should exercise its scrutiny role to ensure that Art. 18 remains an unavoidable last resort.
Addressed to: European Commission (Art. 18 implementing acts; Art. 18(4) roadmap review); European Parliament; Member States

6.1.2. Closing the agricultural ammonia gap through cross-instrument policy coherence

R4 Establish binding, sector-specific ammonia reduction obligations linked to $PM_{2.5}$ health targets
Agricultural ammonia is the main precursor to secondary inorganic $PM_{2.5}$, and has remained broadly unchanged since 2005, even as other pollutants have decreased substantially. The NEC Directive relies on Member State-designed programmes without binding sector-level measures. The Nitrates Directive governs nitrogen for water quality and contains no reference to air quality. The Commission should propose amendments to the NEC Directive to introduce binding sub-national or sectoral ammonia-reduction obligations, and to the Nitrates Directive to include ammonia volatilisation from land application as a regulated outcome. The cases of Spain (ammonia concentrations increasing despite NEC commitments) and Denmark (Nitrates Directive derogations undermining NEC ammonia targets in the same Member State) illustrate that the current framework creates self-contradicting obligations.
Addressed to: European Commission (NEC Directive amendment; Nitrates Directive revision); European Parliament

R5 Integrate air quality conditions into CAP Strategic Plan requirements
The CAP Regulation (EU) 2021/2115 includes ammonia as an impact indicator and makes payments conditional on compliance with the NEC and the Nitrates Directive. However, it does not require Member States to demonstrate that their strategic plans will achieve the ammonia reductions necessary to meet NEC commitments. The Commission should require, as a condition of CAP Strategic Plan approval for the post-2027 period, that each Member State demonstrates how its plan will contribute to meeting NEC ammonia reduction commitments, and should make non-compliance with NEC ammonia commitments a trigger for CAP payment suspension.
Addressed to: European Commission (CAP post-2027 legislative proposal; CAP Strategic Plan approval conditions); Member States

R6 Extend IED scope to medium livestock installations; strengthen Art. 70i operating rules
The 2024 IED revision extends the scope to large livestock installations with 350–380 Livestock Units or more. Ammonia-generating installations below this threshold remain unregulated at the EU level. The Commission should ensure that operating rules adopted under Article 70i (due by 1 September 2026) include binding ammonia and PM emission limits rather than registration requirements alone, and should use the Article 73 implementation review (due from June 2028) to assess whether the livestock threshold should be extended to medium-scale installations on the basis of their contribution to secondary $PM_{2.5}$ formation.
Addressed to: European Commission (IED livestock operating rules, Article 70i; Article 73 implementation review).

6.1.3. Strengthening implementation and enforcement at Member State level

R7 Require AQ roadmaps to include concrete, funded, and enforceable measures
The 2024 AAQD introduces Air Quality Roadmaps (Article 19(4)) from 2026. Experience from France, Poland, Italy, Spain, and Bulgaria shows that national plans consistently fall short: either because of listing generic measures without specific targets, or because they lack clearly assigned responsibilities and enforcement instruments. The Commission should adopt minimum content requirements for roadmaps that are operationally specific (e.g. each measure must be accompanied by a quantified $PM_{2.5}$ reduction estimate, a budget allocation, a responsible authority, and an interim milestone date). Roadmaps that do not meet these requirements should be returned for revision. The EEA should maintain a publicly accessible roadmap tracker. Stakeholder interviews conducted for this study indicate that national and subnational competent authorities frequently request further guidance on what AQ roadmaps should contain and how measures should be designed, sequenced, and costed. Guidance instruments and fora for experience-sharing between Member States and regions would be a helpful support tool.
Addressed to: European Commission (Article 19(4) implementing acts; roadmap content standards); EEA

R8 Strengthen the LEZ implementation framework and address politicisation risk
LEZs are among the most effective urban instruments for reducing traffic PM exposure, as demonstrated by ULEZ in London and LEZs in Milan, Bologna, and Barcelona. Evidence from the case studies shows they are often poorly enforced, disproportionately affect the most vulnerable, and can become contested in light of social fairness and equity considerations. The Commission should provide guidance on LEZ design, covering scope, vehicle eligibility criteria, enforcement technology (camera systems, charging mechanisms), and social equity provisions that Member States can adopt, along with ways to improve public communication of health benefits.
Addressed to: European Commission (AAQD implementing acts; urban AQ guidance); EEA; Member States

R9 Address the affordability of monitoring equipment and support network adequacy
The 2024 AAQD introduces more demanding monitoring requirements, including hourly $PM_{2.5}$ measurement and expanded supersite obligations. Two gaps risk undermining their effectiveness. First, the cost of compliant monitoring equipment is a challenge for most Member States and subnational authorities. Several Member States (including higher-income Member States) have explicitly identified the absence of EU-level guidance on reliable, affordable, low-cost sensors as a barrier to enforcement capacity for both outdoor and indoor monitoring. Second, monitoring network coverage remains inadequate in several Member States relative to their pollution challenge, limiting the evidence base for enforcement and plan design. The Commission should adopt minimum performance specifications for low-cost monitoring devices under Article 8(7) implementing acts, mandate the EEA to maintain a publicly accessible register of validated devices, and provide co-financing through cohesion funds for monitoring network upgrades in lower-capacity Member States.
Addressed to: European Commission (Art. 8(7) implementing acts; cohesion fund conditions); EEA; Member States

R10 Develop an EU-level platform for sharing AQ plan and roadmap good practices
Several Member States (including Finland, which has not previously needed national AQ plans) will be developing these for the first time under the 2024 AAQD. Lower-capacity Member States require support and would benefit from an EU-level platform for sharing AQ plans and roadmaps, modelling methodologies, and source-attribution approaches. TAIEX should be specifically extended to support AQ roadmap.
Addressed to: European Commission; EEA; FAIRMODE

6.1.4. Closing sectoral policy gaps and addressing policy coherence failures

R11 Address the household biomass regulatory gap in the Renewable Energy Directive
The RED (EU) 2023/2413 extends sustainability criteria to solid biomass installations with a capacity of 7.5 MW or more. The entire residential wood-burning sector (an important source of PM in France, Germany, Italy, and Poland) falls below this threshold and is subject to no air pollutant performance criteria. Household biomass installations may count toward Member State renewable energy targets with no accompanying air quality safeguard. The Commission should propose, in the next RED revision, a revision of the sustainability taxonomy of residential biomass installations, and how they count toward targets (e.g. only if they meet minimum PM emission standards). The ESPR should establish binding PM emission limits for solid-fuel residential heating appliances at the earliest opportunity.
Addressed to: European Commission (RED revision; ESPR delegated act for residential heating appliances); Member States

R12 Require integration of air quality outcomes into building renovation strategies
The EPBD requires renovation strategies to include an estimate of expected air quality benefits but does not ensure that replacement heating systems meet air quality standards. Switching from coal to unregulated biomass can even worsen local $PM_{2.5}$ outcomes. The Commission should require, in the post-2030 EPBD revision, that national renovation strategies specify eligible heating technologies and that all eligible systems meet minimum PM emission standards consistent with the 2024 AAQD 2030 targets. Renovation subsidies should be conditioned on the adoption of low-emission technologies, including PM.
Addressed to: European Commission (EPBD post-2030 revision); Member States

R13 Accelerate fleet turnover to realise the health benefits of Euro 6 and Euro 7
The full health benefits of Euro 7 will not materialise until 2035–2040 due to slow fleet turnover. In lower-income Member States, scrappage schemes are less effective, and older vehicles remain the majority. The Commission should establish EU-wide minimum standards for vehicle scrappage schemes, calibrated to accelerate the removal of the oldest and most polluting vehicles and to make them accessible to lower-income households. The Norway model is a good example of demand-side fiscal instruments, including tax exemptions, toll waivers, and charging infrastructure. It demonstrates that the pace of fleet transition can be substantially accelerated by addressing demand-side factors.
Addressed to: European Commission; Member States

6.1.5. Improving health integration, evidence, and public communication

R14 Integrate health authorities systematically into AQ policy design at the Member State level
Case study evidence from Germany, Poland, Italy, and Bulgaria identifies a consistent gap where health authorities are involved in surveillance and communication but are not embedded in AQ policy design, monitoring, or enforcement. The Commission should require, as part of the AQ roadmap, that each roadmap include a documented health integration mechanism (e.g. identifying which health authority is responsible for health impact assessment, how health data is linked to AQ monitoring data, and how public health objectives inform the selection of abatement measures). Spain's Strategic Plan for Health and the Environment (PESMA) framework could serve as a transferable governance model for collaboration between the Ministry of Environment and the Ministry of Health.
Addressed to: European Commission (AQ roadmap content requirements); Member States

R15 Strengthen morbidity and economic metrics in EU air quality burden assessment
Standard EU policy reporting focuses predominantly on premature mortality. The evidence in Chapter 2 demonstrates a substantially broader disease burden: cardiovascular conditions, COPD, diabetes, lung cancer, neurological outcomes, adverse pregnancy outcomes, and childhood development effects. The Commission and EEA should expand the health burden assessment framework to include standardised morbidity indicators alongside mortality, and commission an updated economic valuation of the full PM health burden (including morbidity costs, years of healthy life lost, and labour productivity impacts) to inform the 2030 AAQD review. The French case illustrates the scale of this: Santé Publique France estimates approximately 40,000 attributable deaths annually (vs. 14,741 in the EEA figure) using a broader methodological scope, and documents approximately 30,000 avoidable asthma cases and an estimated EUR 3 billion in medical costs.
Addressed to: European Commission; EEA; Member States (national health surveillance agencies)

R16 Establish EU-wide standards for public air quality information and health communication
The 2024 AAQD requires public access to air quality information and an AQ index (Article 22), but does not specify minimum content standards for public health communication. Germany's national AQ index and France's AASQA network (18 independent, regionally funded monitoring associations) represent governance models with potential for replication across the EU. The Commission could adopt, under Article 22, implementing acts specifying minimum standards for public AQ information, such as real-time availability, health-effect descriptions at each index level, guidance for sensitive and vulnerable groups, and alert thresholds aligned with WHO interim targets.
Addressed to: European Commission (Article 22 implementing acts); EEA; Member States

R17 Address equity systematically in AQ plans, roadmaps, and health assessments
The health evidence and socioeconomic disparities documented in Chapters 2 and 3 confirm that PM exposure is not uniformly distributed: lower-income populations, residents of dense urban areas, outdoor workers, children, and the elderly face disproportionately higher exposures. Several case studies document specific equity failures: for example, low-income households in Poland are unable to afford heating upgrades; LEZ transition support was withdrawn in France; and socio-economically disadvantaged populations in Germany are concentrated in higher-exposure areas. The Commission should extend equity assessment requirements to AQ roadmaps and AQ plans, requiring identification of high-exposure population groups, targeted measures, and financial support mechanisms for low-income households as mandatory plan content.
Addressed to: European Commission (AQ roadmap and plan content requirements); Member States.

7. CONCLUSIONS

Fine particulate matter (PM_{10} and $PM_{2.5}$) is among the most thoroughly documented environmental threats to human health. The evidence synthesised in this study, drawing on 198 systematic reviews and meta-analyses published over the past decade, establishes a consistent and broad-based picture. Long-term exposure to $PM_{2.5}$ is associated with an 8–10% increase in all-cause mortality per 10 µg/m^3 increase in concentration. The mechanisms through which this occurs (oxidative stress, systemic inflammation, vascular damage, and disruption of neurological and immune function) are shared across disease categories, which explains why the health consequences of particulate exposure extend well beyond the lungs. The strongest and most consistent evidence links $PM_{2.5}$ to cardiovascular disease, including heart attacks and stroke, and to chronic respiratory conditions, including pulmonary disease (such as COPD), and lung cancer.

A growing and now substantial body of evidence also connects long-term $PM_{2.5}$ exposure to cognitive decline, dementia, depression, and neurodevelopmental disorders in children, including ADHD and autism spectrum disorder. Exposure during pregnancy is associated with increased risks of preterm birth, low birth weight, and preeclampsia. Across all these outcomes, no safe threshold of exposure has been identified: health effects are consistently observed at concentrations below current EU legal limits and below the WHO's own guidelines. The burden of harm is not evenly distributed: children, older adults, people with pre-existing conditions, and socioeconomically disadvantaged populations face systematically higher risks, reflecting a combination of greater biological susceptibility, higher exposure levels, and reduced capacity to adapt.

Exposure has declined substantially across the EU over the past two decades. $PM_{2.5}$ attributable premature deaths have fallen by approximately 57% since 2005, meeting the Zero Pollution Action Plan's 55% interim target ahead of schedule, and every Member State recorded declining $PM_{2.5}$ concentrations between 2013 and 2023. In 2023, approximately 182,000 premature deaths and approximately 1.9 million years of life lost in the EU-27 remained attributable to $PM_{2.5}$. Progress has been uneven and, in recent years, diverging. Some Member States, including Luxembourg, Belgium, Czechia, Austria, Germany, and Slovakia, have achieved reductions of 40–50% over the past decade, while others, including Greece, Spain, Malta, and Italy, recorded milder reductions (10-22%). Between 2021 and 2023, five Member States recorded an increase in the $PM_{2.5}$-attributable disease burden: Portugal, Italy, Greece, Slovenia, and Spain. Regional hotspots persist in the Po Valley, the Silesian basin, and a Balkans–South-Eastern area centred on Bucharest, Sofia, and Athens, where concentrations continue to exceed the 2030 EU limit. Across the EU, 210 of 234 NUTS2 regions exceeded the WHO annual guideline for $PM_{2.5}$ in 2023, and 94% of the EU urban population remains exposed above that guideline. The poorest fifth of EU regions is exposed to approximately 30% more $PM_{2.5}$ than the wealthiest, with mortality risks from a given level of pollution up to twice as high in the most disadvantaged regions, a gap that has not narrowed over the period for which data are available. Dementia, included for the first time in EU burden-of-disease estimates in 2025, is now the single largest individual disease contributor to $PM_{2.5}$-attributable ill health in adults aged 60 and over (a finding that substantially revises upward previous estimates of the total health burden and that will grow in significance as the EU population ages).

The EU has a mature, technically sophisticated legislative framework for controlling particulate matter. The framework is delivering: the majority of PM reductions since 2005 are attributable to legally binding standards covering vehicle emissions, large industrial installations, and fuel quality, alongside the energy transition away from coal and gas under renewable energy legislation, to which the EEA attributes approximately 40% of total PM reductions since 2005. The 2024 revision of the

Ambient Air Quality Directive, which tightens the annual $PM_{2.5}$ limit from 25 µg/m^3 to 10 µg/m^3 by 2030, marks a significant step forward. Nevertheless, three structural problems recur across the evidence and the case studies. First, even the 2030 EU limit remains double the WHO annual guideline of 5 µg/m^3, and current projections indicate that approximately 60,000 to 70,000 premature deaths per year will remain attributable to $PM_{2.5}$ exposure even if the 2030 target is fully met. Second, agricultural ammonia (the primary precursor to secondary inorganic $PM_{2.5}$) has remained broadly unchanged since 2005. The NEC Directive sets national reduction commitments but lacks binding sector-level measures; the Nitrates Directive, which governs agricultural nitrogen management, contains no reference to air quality; and the acquis contains no cross-instrument coherence mechanism, leaving the same Member State able simultaneously to hold a legal commitment to reduce ammonia and a legal derogation permitting practices that increase it. Third, implementation and enforcement at the Member State level is consistently uneven. Air quality plans frequently lack concrete targets, assigned responsibilities, and dedicated funding. Low-emission zones are legally required in many Member States but are inconsistently enforced. Residential wood burning (a major and growing $PM_{2.5}$ source in France, Germany, Italy, and Poland) falls entirely outside EU sustainability and product standards for air quality purposes. The case studies of Poland, Bulgaria, and Italy indicate that the use of the Art. 18 postponement mechanism, which permits delays of up to 10 years in meeting the 2030 $PM_{2.5}$ limit, is a probable outcome precisely for the Member States with the highest existing health burden.

The 17 recommendations set out in Chapter 6 address these structural problems across five areas. On the standards ambition, the Commission should use the Art. 3 review mechanism to establish a binding trajectory toward the WHO $PM_{2.5}$ guideline, with an intermediate milestone of 7.5 µg/m^3 by 2035 and full alignment at 5 µg/m^3 by 2040; the Art. 18 postponement provisions should be applied restrictively and subject to mandatory public reporting on the health costs of any delay. On agricultural ammonia, binding sector-level reduction obligations should be introduced through targeted amendments to the NEC and Nitrates Directives, and CAP Strategic Plan approval should be made conditional on demonstrated contribution to NEC ammonia reduction commitments. On implementation, the Art. 19 Air Quality Roadmap requirements should include mandatory minimum content (quantified measures, budget allocations, responsible authorities, and interim milestones) and an EU-level good-practice platform should support lower-capacity Member States in meeting the 2024 AAQD's new planning obligations. On sectoral coherence, the household biomass regulatory gap should be addressed in the next RED revision and through ESPR delegated acts for residential heating appliances; renovation subsidies under the EPBD should be conditioned on the adoption of low-emission heating technologies; and EU-wide vehicle scrappage standards should accelerate fleet turnover to realise the health benefits of Euro 6 and Euro 7 within the current decade.

On health integration, three priorities stand out. Health authorities should be systematically embedded in air quality policy design at the Member State level, rather than confined to surveillance and communication roles. The EU burden-of-disease framework should be expanded to capture morbidity and economic impacts alongside mortality, so that the full scale of harm from particulate exposure is visible in the metrics that drive policy decisions. And equity should be an explicit, mandatory element of air quality plans and roadmaps, so that the communities bearing the highest exposure and the greatest health burden benefit the most from improvements in air quality.

Finland and Norway demonstrate that annual mean $PM_{2.5}$ concentrations at or approaching the WHO guideline of 5 µg/m^3 are attainable at scale in a European context, even in residential and industrial settings. The structural prerequisites are a clean electricity system, electrification of heating and transport, and sustained enforcement, which are conditions that are not necessarily unique to these two countries. The EU possesses the regulatory architecture, the institutional capacity, and the health evidence base to close the remaining gap between legal compliance and health-optimal exposure. What the evidence in this study shows is that doing so requires closing not the technical gap in emission standards, but the governance gaps in agricultural policy, implementation, enforcement, and cross-instrument coherence. These are the main barriers that currently prevent the EU framework from translating its regulatory ambition into health outcomes at the scale the scientific evidence demands.

ANNEX 1. METHODOLOGY

The following Annex briefly presents the methodology applied in this study.

Research design

The research design is structured around four tasks: (1) association between $PM_{2.5}$/PM_{10} and human health (RQ1); (2) trends across the EU; (3) legal and policy frameworks; and (4) policy recommendations. Given the complexity of the topic and the EP's focus on both scientific rigour and policy relevance, this study adopts a mixed-methods design that integrates quantitative analysis with qualitative insights. We combine a structured literature review, targeted desk research, stakeholder interviews, and comparative case studies. Throughout, we apply an explicit intersectional lens to identify how age, sex, socioeconomic status, education level, ethnicity and other social dimensions interact to shape exposure, vulnerability, and health outcomes.

Data sources

The study draws on the following data sources:

- **Desk research:** Analysis of EU and national policy documents and legislation relevant to $PM_{2.5}$/PM_{10}, including the Ambient Air Quality Directive (Directive (EU) 2024/2881), National Emission Ceilings Directive (2016/2284), Industrial Emissions Directive (2024/1785), Medium Combustion Plant Directive (2015/2193), Ecodesign (2024/1781), Energy Efficiency (2023/1791), Euro/fuel standards (98/70/EC), and related climate, energy, transport, agriculture and environmental noise instruments. We also consulted the EEA policies and measures database, WHO and OECD publications, Health Effects Institute reports, The Lancet Countdown, and national air quality plans and strategies. For trends and burden estimates, we harmonised indicators from EEA, Eurostat, WHO, and Global Burden of Disease (GBD) sources.
- **Umbrella review:** To ensure a comprehensive synthesis of current evidence, we systematically collated and analysed peer-reviewed systematic reviews published within the past ten years. Our literature search was conducted in PubMed, utilising pollutant-specific descriptors including “$PM_{2.5}$”, “PM_{10}”, and “particulate matter”.[427] After applying eligibility criteria (such as the study type and relevance to $PM_{2.5}$ or PM_{10} as the primary pollutant), **198 articles** were included in the final synthesis for the umbrella review.
- **Stakeholder interviews:** Semi-structured interviews with EU institutions and agencies, international organisations, national competent authorities, and experts at EU and Member State levels to gather implementation evidence, assess effectiveness and ambition, and identify policy gaps/enforcement challenges.
- **Case studies:** In-depth analysis of eight EU Member States and three non-EU countries. EU cases document sectoral measures (households/heating, transport, industry, agriculture), implementation/enforcement approaches, and linkages to air quality and health outcomes. Non-EU cases provide benchmarking against advanced or innovative frameworks and practices.

[427] The following search was conducted on 27 January 2026: ("particulate matter"[MeSH Terms] OR Particulate Matter [Title/Abstract] OR "airpollution"[MeSH Terms] OR Air Pollution [Title/Abstract] OR fine particulate [Title/Abstract]) AND (PM2.5 [Title/Abstract] OR PM10 [Title/Abstract]).

- **Stakeholder workshop:** A dedicated stakeholder workshop will be used to test the feasibility and relevance of policy recommendations.

Stakeholder consultation

12 in-depth interviews were conducted. Stakeholders were selected for their knowledge on fine particles and their representation across EU institutions and agencies, Member States, international organisations, and civil society. For the case studies, national competent authorities and experts were consulted. Backup contacts were identified to mitigate non-responsiveness. Interviews were tailored to each stakeholder's expertise and aligned with the study's research tasks. A full list of interviewed stakeholders is provided in Annex 2.

Case study selection and design

Eight Member States were selected for case studies: Poland, Bulgaria, Denmark, Finland, Germany, Italy, Spain, and France (Table 7). Selection criteria included geographical balance, population size, $PM_{2.5}$ exposure levels, and the burden of attributable deaths. Each case study examines national measures across key emitting sectors (such as households and heating, transport, industry, and agriculture), their implementation and enforcement, and their contribution to reducing exposure to $PM_{2.5}$/PM_{10} and associated health impacts. The case studies are supported by desk research and interviews with national competent authorities and experts. They contribute to the assessment of legal and policy frameworks and inform the formulation of evidence-based recommendations. All case studies follow a common template to ensure comparability.

Table 7: Overview of case study countries

Country	Region	Population size (million)	$PM_{2.5}$ exposure level (µg/m^3, annual mean)	Attributable deaths per 100,000 inhabitants
EU				
Poland	Central/Eastern	36.5	15	136
Bulgaria	Central/Eastern	6.4	15	180
Denmark	Northern	6.0	8	31
Finland	Northern	5.6	5	1
Spain	Southern	49.1	9	58
Italy	Southern	58.9	13	113
Germany	Western	83.6	8	55
France	Western	68.6	9	48
Non-EU				
United Kingdom	Western	69.3	7.5	12.5
Norway	Northern	5.6	7	9
China	N/A	1,409.0	35	104.4

Source: Authors' own elaboration.

ANNEX 2. LIST OF INTERVIEWED STAKEHOLDERS AND GUIDE

Table 8: List of interviewed stakeholders

#	Organisation	Number of interviewees	Stakeholdergroup	Interview date
1	DG ENV (C3 Unit)	1	EU institutions and agencies	26 March 2026
2	EEA	1	EU institutions and agencies	17 March 2026
3	European Respiratory Society	1	Experts at EU level	30 April 2026
4	European Environmental Bureau	1	Experts at EU level	02 April 2026
5	Health and Environment Alliance (HEAL)	1	Experts at EU level	31 March 2026
6	Institute of Environmental Assessment and Water Research	1	Experts at Member State level	17 April 2026
7	Respire -Association Nationale pour l'Amélioration de la Qualité de l'Air	1	Experts at Member State level	17 April 2026
8	HEAL Poland	1	Experts at Member State level	25 March 2026
9	Danish Centre for Environment and Energy, at Aarhus University	1	Experts at Member State level	27 March 2026
10	German Environment Agency	2	National competent authorities	23 April 2026
11	Finnish Ministry of Environment	2	National competent authorities	16 April 2016
12	Ministerio para la Transición Ecológica y el Reto Demográfico	1	National competent authorities	08 May 26

Source: Authors' own elaboration.

Questionnaire EU institutions and agencies

1) How effective is the current EU air quality acquis (particularly the Ambient Air Quality Directive) in reducing PM2.5 and PM10 exposure in practice?
2) What evidence do you rely on (e.g., compliance statistics, exceedance duration, attributable burden indicators), and what are the most appropriate success metrics to make this assessment?
3) Which provisions of the acquis are most important for protecting health, and which are currently the weakest?
4) How do you assess the gap between EU limit values and WHO Air Quality Guidelines in terms of health protection?
5) Where does legislation rely too heavily on Member State discretion, and what consequences do you observe?
6) Which implementation or enforcement challenges recur most consistently across Member States?

7) Across Member States, where do you see the largest enforcement or implementation disparities, and what explains them?
8) How effective are current EU mechanisms for monitoring compliance and addressing exceedances?
9) To what extent are health outcomes explicitly considered when assessing effectiveness?
10) What part of the acquis is more realistically going to be open to revision to strengthen health protection?
11) What are feasible EU-level policy changes that would deliver the largest health gains within the coming (5 to 10) years?

Questionnaire EU-level experts, academics

1) How effective is the current EU air quality acquis (particularly the Ambient Air Quality Directive) in reducing PM2.5 and PM10 exposure in practice?
    a. What evidence do you rely on (e.g., compliance statistics, exceedance duration, attributable burden indicators), and what are the most appropriate success metrics to make this assessment?
    b. Does current EU air quality legislation adequately reflect the latest evidence on PM-related health impacts?
    c. How adequate are current PM2.5 and PM10 limit values for protecting public health?
2) Which design features most undermine health effectiveness (e.g. thresholds, timelines, averaging, exemptions, data granularity, enforcement mechanisms)?
3) Where do you see the biggest cross-Member State disparities in protection or outcomes?
    a. Where does compliance fail the most?
    b. What are the main drivers for such disparities?
4) Are vulnerable or high-exposure populations sufficiently protected under the acquis?
5) How does the EU's approach compare to international best practice from a health perspective?
    a. We are particularly interested in Norway, UK and China, but other examples are also useful.
6) Which provisions would benefit most from tighter alignment with WHO guidelines?
7) What evidence most strongly supports revising EU standards or obligations?
8) What risks should policymakers be aware of when strengthening the acquis?
9) What are feasible EU-level policy changes that would deliver the largest health gains within the coming (5 to 10) years?
    a. At which level (EU or Member State) must action be taken?

Questionnaire National competent authorities

1) Which EU air quality obligations are most challenging to implement at national or regional levels?
2) How workable are current monitoring and reporting requirements for PM2.5 and PM10?
3) Do your national air quality plans lead to concrete mitigation actions? How?
4) Which sectors pose the greatest difficulties for achieving compliance, and why?
5) How effective are existing enforcement tools in addressing exceedances?
6) Where does the acquis need more clarity (or flexibility?) from an implementation perspective?
7) How are health authorities involved in air quality policy implementation?
8) How do national standards and implementation practice compare to WHO guidelines, and what would tightening towards WHO imply in practice?
9) To what extent do political, economic, or social constraints limit ambition?
10) Which changes would most improve effectiveness (while being feasible)?
11) What lessons can you draw from national implementation should inform the EU-level?
    a. Best practices, blind spots…

ANNEX 3. BURDEN OF DISEASE BETWEEN 2021 AND 2023

The figures in the tables below are expressed in Disability-Adjusted Life Years (DALYs) per 100,000 inhabitants. A DALY represents one year of healthy life lost, combining years of life cut short by premature death with years lived in poor health or with disability. A higher number indicates a greater burden of disease.

Table 9: Disability Adjusted Life Years per 100k affected people 2021[428]

	Asthma - children and adolescents	Chronic obstructive pulmonary disease	Diabetes Mellitus	Ischemic heart disease	Lung cancer	Stroke	Total
Austria	30.5	82	124.5	166	85.6	88.2	576.8
Belgium	38.3	100.9	69.2	97.7	110.7	99.2	516
Bulgaria	49.9	85.1	182.4	495.6	131.7	733.1	1677.8
Croatia	57.3	137.2	544	386.3	200.9	329.9	1655.6
Cyprus	56.4	70.7	309.8	200.5	110.8	145.1	893.3
Czechia	44	96.3	263.3	360.4	116.5	172.6	1053.1
Denmark	23.4	78.6	64.6	51.1	64.4	60.3	342.4
Estonia	5.2	6.9	21.6	33.4	12.9	24.1	104.1
Finland	3.4	5.5	7.6	17.4	6.4	11.1	51.4
France	36.9	58.7	78.7	64.9	87.4	77.9	404.5
Germany	29.5	92.3	105.3	153.4	85.3	104.6	570.4
Greece	55.6	96.7	199.8	399.4	221.6	314.6	1287.7
Hungary	50.4	191.9	277.5	651.7	231.8	315.3	1718.6
Ireland	20.4	26.2	22	56.1	30.9	24.8	180.4
Italy	43.4	109.9	212.4	185.1	147.9	201.1	899.8
Latvia	32	49.6	153.8	460.6	81.1	341.5	1118.6

428 European Environment Agency, 2022, *Air quality data viewer (countries and NUTS)*. Available at: https://discomap.eea.europa.eu/App/AQViewer/index.html?fqn=Airquality_Dissem.ebd.countries_and_nuts&ScenarioDescription=Baseline%20from%20WHO%202021%20AQG&UrbanisationDegree=All%20Areas%20(incl.unclassified)&Year=2022&Sex=Total.

	Asthma – children and adolescents	Chronic obstructive pulmonary disease	Diabetes Mellitus	Ischemic heart disease	Lung cancer	Stroke	Total
Lithuania	30	74.9	129.9	600.7	70.9	307.7	1214.1
Luxembourg	22.3	40.1	27.3	35.3	30.9	31.9	187.8
Malta	52	44.4	238.2	243.4	91.3	82.9	752.2
Netherlands	37.1	87.4	74.1	67.5	103.7	91.1	460.9
Poland	195.5	91.9	270	535	218.4	347.8	1658.6
Portugal	27.8	33.4	66.6	51.8	41.2	77.1	297.9
Romania	56	84.4	154	609.1	125	489.7	1518.2
Slovakia	48.5	79.9	152.1	642.8	110	291.3	1324.6
Slovenia	58.7	61.6	129.5	187.3	138.8	184.5	760.4
Spain	28	45.5	78.4	83.9	84.8	80.3	400.9
Sweden	10.2	10.2	18.9	24.5	11.7	16.5	92

Source: Authors' own elaboration.

Table 10: Disability Adjusted Life Years per 100k affected people 2022[429]

	Asthma – children and adolescents	Chronic obstructive pulmonary disease	Diabetes Mellitus	Ischemic heart disease	Lung cancer	Stroke	Total
Austria	31.5	87	133.1	173.4	86.8	90.8	602.6
Belgium	34.2	97.6	58.2	84.1	98.9	85.7	458.7
Bulgaria	49.6	88.5	151.9	482.8	133.7	726.6	1633.1
Croatia	58	145.7	551.5	375.3	215.2	307.3	1653
Cyprus	61.6	85.6	339.8	231.2	125.6	151.8	995.6
Czechia	42.7	106.8	249.6	337.1	121	170.6	1027.8
Denmark	22.1	71.8	57.9	44.7	57.1	56.7	310.3
Estonia	4.3	6.4	20.1	28.3	9.9	18.5	87.5
Finland	1.3	2.1	3	6.4	2.3	4.2	19.3
France	38.2	63.1	79.3	64.5	88.7	78.7	412.5
Germany	28.9	96.4	102.9	148.8	82.1	102.5	561.6
Greece	54.4	88.2	203.7	341.1	213.4	285.3	1186.1
Hungary	48	201.4	251.8	634	230	311.2	1676.4
Ireland	21.8	31.9	24.7	62.3	33	28.4	202.1
Italy	49.3	129.1	228.9	202.2	166.9	224.4	1000.8
Latvia	21.6	35.2	95.4	325.5	53.1	228.5	759.3
Lithuania	23.1	61.7	91.6	465.4	60.1	247.7	949.6
Luxembourg	22	39.7	26.3	31.6	29.8	31.7	181.1
Malta	45.4	48.8	162.5	208.8	69.8	73.9	609.2

429 European Environment Agency, 2022, *Air quality data viewer (countries and NUTS)*. Available at: https://discomap.eea.europa.eu/App/AQViewer/index.html?fqn=Airquality_Dissem.ebd.countries_and_nuts&ScenarioDescription=Baseline%20from%20WHO%202021%20AQG&UrbanisationDegree=All%20Areas%20(incl.unclassified)&Year=2022&Sex=Total.

	Asthma - children and adolescents	Chronic obstructive pulmonary disease	Diabetes Mellitus	Ischemic heart disease	Lung cancer	Stroke	Total
Netherlands	34.2	90.8	70.3	63.7	95.7	85.5	440.2
Poland	170.2	89.5	255.1	444.9	204.8	327.3	1491.8
Portugal	48	59	114.8	91.9	69.9	126.5	510.1
Romania	56.1	86.2	137.7	578.9	143.3	471.9	1474.1
Slovakia	42.8	73.5	127.7	574.5	108.6	268	1195.1
Slovenia	68	72.7	115.9	214.7	156.5	203	830.8
Spain	35.4	60.5	98.6	106.2	108.1	99.8	508.6
Sweden	7.7	8.5	14.5	17.7	8.4	11.8	68.6

Source: Authors' own elaboration.

Table 11: Disability Adjusted Life Years per 100k affected people 2023[430]

Row Labels	Asthma – children and adolescents	Chronic obstructive pulmonary disease	Diabetes Mellitus	Ischemic heart disease	Lung cancer	Stroke	Total
Austria	26.4	73.7	112.4	140.5	71.7	75.6	500.3
Belgium	26	76.2	45.8	66.1	77.2	67.5	358.8
Bulgaria	47.3	89	171.2	482.7	149.7	708.9	1648.8
Croatia	51.4	138.2	477.1	315.8	202.8	245	1430.3
Cyprus	61.5	86.1	279.2	164.4	104.8	149.2	845.2
Czechia	31.7	81.4	193.9	242.8	90.1	127.3	767.2
Denmark	13.6	45.3	36.9	28.3	35.7	35.8	195.6
Estonia	2.4	3.8	11.7	15.8	6	10.7	50.4
Finland	0.7	1.1	1.5	3.2	1.1	2.1	9.7
France	29.5	50.5	63.1	50.9	71.3	63	328.3
Germany	20.4	71.7	73.3	104.4	58.6	72.8	401.2
Greece	58.4	102.8	232.9	398.3	246.3	336.1	1374.8
Hungary	41.3	187.6	199	534.2	207.3	260.4	1429.8
Ireland	13.6	20	15.5	38.9	20.7	17.7	126.4
Italy	45	124.2	224.3	197.7	160	218.6	969.8
Latvia	17.2	29.2	81.8	282	45.2	199.9	655.3
Lithuania	15.6	42	70.6	313.5	42.4	158	642.1
Luxembourg	19.9	33.3	27.3	32.4	25	25.3	163.2
Malta	47.9	52.9	173.9	225.9	75.1	80.2	655.9

430 European Environment Agency, 2022, *Air quality data viewer (countries and NUTS)*. Available at:. https://discomap.eea.europa.eu/App/AQViewer/index.html?fqn=Airquality_Dissem.ebd.countries_and_nuts&ScenarioDescription=Baseline%20from%20WHO%202021%20AQG&UrbanisationDegree=All%20Areas%20(incl.unclassified)&Year=2022&Sex=Total.

Row Labels	Asthma – children and adolescents	Chronic obstructive pulmonary disease	Diabetes Mellitus	Ischemic heart disease	Lung cancer	Stroke	Total
Netherlands	26.4	69.8	51.2	46.9	70	65.8	330.1
Poland	141	75.8	205.8	370.7	184.5	279	1256.8
Portugal	31	39.3	78.5	61.9	46.8	85.8	343.3
Romania	49.8	83.8	133.8	574.3	138	468.3	1448
Slovakia	37	55.1	94.9	472.5	99.9	203.7	963.1
Slovenia	57.4	63.2	107.9	203.3	144.3	201.3	777.4
Spain	27.5	50.9	78.7	83.2	86	78.9	405.2
Sweden	3.3	3.8	6.5	7.8	3.7	5.2	30.3

Source: Authors' own elaboration.

ANNEX 4. BIBLIOGRAPHY

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This study examines the health effects of fine particulate matter (PM2.5 and PM10), trends in exposure, and the effectiveness of EU legal and policy frameworks. It draws on an umbrella review of 198 systematic reviews, quantitative analysis of exposure trends, stakeholder interviews, and comparative case studies across EU Member States. The study shows consistent health effects of PM2.5 exposure across multiple disease categories and identifies persistent inequalities in exposure across populations and regions, with no safe threshold for PM2.5 exposure identified. It proposes evidence-based policy recommendations to reduce health impacts across the EU.

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