

Global Burden of Disease Attributable to Air and Water Pollution: A Systematic Review

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Abstract

Background: Air and water pollution are leading global health threats, with ambient PM_{2.5} causing 4.2 million deaths and 103 million disability-adjusted life years in 2015, and unsafe water contributing to 829,000 deaths annually. Vulnerable groups—including children under five, the elderly, pregnant women, and socioeconomically disadvantaged communities—face disproportionate risks. To guide interventions and policy, this review synthesizes quantitative and qualitative evidence on pollution-related health impacts, identifies at-risk populations, and highlights research gaps.

Methods: We searched PubMed, Embase, Scopus, Web of Science, and the WHO Global Health Library for human epidemiological studies and meta-analyses published January 2015–August 2025. Two reviewers independently screened studies, extracted data, and assessed quality. Findings were narratively synthesized by pollution type, health outcome, and vulnerable subgroup.

Results: From 3,488 records, 112 studies met inclusion criteria across 65 countries. Air pollution was linked to 9–11% increases in cardiovascular mortality and 18% increases in COPD incidence per 10 µg/m³ PM_{2.5}, and 8–14% increases in lung cancer risk. Water pollution exposures carried a 4.95-fold higher infant methemoglobinemia risk at nitrate >50 mg/L and 2.0–5.0 odds ratios for bladder cancer at arsenic ≥50 µg/L. Children under five and the elderly had markedly higher risks.

Conclusions: Air and water pollution are major, modifiable risk factors for global morbidity and mortality, with significant environmental justice implications. Key gaps include exposure misclassification, limited multi-pollutant studies, and underrepresentation of low- and middle-income countries. Innovations in exposure assessment, equitable policy frameworks, and climate adaptation integration are recommended to reduce pollution-related health disparities.

Keywords: Air Pollution; Water Pollution; Particulate Matter; Toxicity; Environmental epidemiology

Introduction:

Air and water pollution represent some of the gravest public health threats worldwide. Ambient fine particulate matter (PM_{2.5}) alone was estimated to cause 4.2 million deaths and contribute to 103 million disability-adjusted life years in 2015, making it the fifth leading risk factor for global mortality(1). Unsafe water, sanitation, and hygiene account for 8,29,000 deaths annually, primarily from diarrheal diseases, with young children disproportionately affected(2). These exposures exert their effects through cardiovascular, respiratory, oncologic, perinatal, and neurodevelopmental pathways, as documented by hundreds of cohort, case-control, time-series, and meta-analytic investigations(3,4). Vulnerable subpopulations—including children under five, the elderly, pregnant women, and socioeconomically disadvantaged communities—experience markedly higher risks, underscoring critical environmental justice concerns(5). Environmental epidemiology provides a robust evidence base for quantifying these associations and informing mitigation strategies. This systematic review is aimed to integrate quantitative and qualitative findings on the health consequences of air and water pollution, identify vulnerable groups, and highlight research gaps for policy and intervention.

Methods

Search Strategy

We conducted a comprehensive search of PubMed, Embase, Scopus, Web of Science, and the WHO Global Health Library for studies published between January 1, 2015, and August 1, 2025. Search terms combined MeSH and free-text keywords for “air pollution”, “PM_{2.5}”, “NO₂”, “ozone”, “water pollution”, “arsenic”, “nitrate”, “lead”, “epidemiology”, “cohort”, “case–control”, “time-series”, “meta-analysis”, and “systematic review”. Boolean operators (AND, OR) and truncation were applied to maximize retrieval. We supplemented database searches by hand-searching reference lists of pivotal systematic reviews and meta-analyses.

Inclusion criteria:

1. Human epidemiological studies or meta-analyses published between 2015 and 2025.
2. Quantitative assessments of associations between air or water pollution exposures and health outcomes.
3. Study designs including cohort, case–control, time-series, cross-sectional analyses, or meta-analyses with clearly defined exposure metrics and health endpoints.

Exclusion criteria:

1. Animal or in vitro studies.
2. Narrative reviews without systematic methodology.
3. Modelling studies lacking empirical health data.
4. Non–English language publications.

Study Selection and Data Extraction

Two reviewers independently screened titles and abstracts, followed by full-text review for eligibility. Discrepancies were resolved by consensus or third-party adjudication. Data extracted included study design, geographic location, population demographics, exposure assessment methods, health outcomes, effect estimates (with 95% confidence intervals), follow-up duration, and covariate adjustments.

Quality Assessment

Risk of bias in cohort and case–control studies was evaluated using the Newcastle–Ottawa Scale. Meta-analyses were appraised using the AMSTAR-2 tool. Studies scoring ≥ 7 on the Newcastle–Ottawa Scale and rated moderate to high quality on AMSTAR-2 were classified as high quality.

Data Synthesis

We performed a narrative synthesis, grouping findings by pollution type (air vs water), health outcome category (cardiovascular, respiratory, oncologic, perinatal, neurodevelopmental), and vulnerable subgroups (children <5 years, elderly ≥ 65 years, pregnant women, low socioeconomic status). Where available, pooled effect estimates per 10 $\mu\text{g}/\text{m}^3$ PM_{2.5} increase or per relevant contaminant concentration increment were reported. Synergistic effects of co-pollutant exposures were highlighted. Research gaps and policy implications were identified.

Results

Study Selection

Database and register searches yielded 3,488 records. After removal of 742 duplicates, 2,746 titles and abstracts were screened, of which 312 full-text articles were assessed for eligibility. A total of 112 studies met inclusion criteria and were included in the final synthesis, comprising 45 cohort studies, 28 case–control studies, 21 meta-analyses, 12 time-

series analyses, and 6 cross-sectional studies. The geographical distribution covered 65 countries across six continents, with sample sizes ranging from 1,200 to 8 million participants and follow-up durations from 1 to 30 years.

Air Pollution: Health Outcomes and Evidence

Cardiovascular Mortality and Morbidity

Long-term exposure to PM_{2.5} was associated with a 9–11% increase in cardiovascular mortality per 10 µg/m³ increment, as reported by multiple cohort and meta-analytic studies(6–8). Ischemic heart disease and stroke constituted 68% of ambient air pollution-related deaths globally, according to WHO estimates(9). Case-control and cohort analyses further demonstrated hazard ratios of 1.10 (95% CI: 1.05–1.15) for ischemic heart disease and 1.24 (95% CI: 1.18–1.31) for stroke per 10 µg/m³ PM_{2.5} (7,10).

Respiratory Disease

Cohort and time-series studies consistently reported an 18% increase in COPD incidence per 10 µg/m³ PM_{2.5} (HR: 1.18; 95% CI: 1.12–1.24) and 6–8% increases in respiratory mortality(8,11). Asthma exacerbations in both paediatric and elderly populations rose by 2–8% per 10 µg/m³ daily PM_{2.5} fluctuations(12).

Cancer

Particulate matter is classified as a Group 1 carcinogen. Meta-analyses of cohort and case-control studies showed an 8–14% increased lung cancer risk per 10 µg/m³ PM_{2.5} (RR: 1.11; 95% CI: 1.05–1.18)(13,14).

Perinatal and Child Health

Systematic reviews and cohort studies revealed a 5–7% increased risk of preterm birth and a 3–8% increased risk of low birth weight per 10 µg/m³ PM_{2.5} during pregnancy(15). Children under five experienced 2–3 times higher rates of acute lower respiratory infections and developmental delays in high-pollution areas(16).

Vulnerable Populations

Elderly individuals (≥ 65 years) had 1.5–2 times greater risk of cardiovascular and respiratory mortality from PM_{2.5} exposure(17). Pregnant women exhibited 1.3–1.8 times elevated risk for adverse birth outcomes(15). Socioeconomically disadvantaged communities faced 1.5–2.5 times higher pollution-related mortality, highlighting environmental justice disparities(5,18).

Water Pollution: Health Outcomes and Evidence

Infectious Diseases

Global surveillance data reported 214 drinking water outbreaks (2015–2020), resulting in 2,140 cases and 88 deaths, predominantly due to *Legionella* (786 cases; 86 deaths)(19). Meta-analyses indicated relative risks of 1.0–3.0 for diarrheal diseases in populations exposed to contaminated water versus controls(20).

Chemical Contaminants

- **Arsenic:** Dose-response meta-analyses demonstrated odds ratios of 2.0–5.0 for bladder cancer and 1.5–3.0 for lung cancer at water arsenic levels ≥ 50 µg/L (21,22).
- **Nitrate:** Studies found 4.95 times higher odds of infant methemoglobinemia at nitrate concentrations > 50 mg/L ($p < 0.001$) and ORs of 1.2–1.8 for neural tube defects per 10 mg/L nitrate increase(23,24).
- **Lead:** Systematic reviews reported a 6.9-point IQ decrement associated with blood lead increases from 2.4 to 30 µg/dL, with effects observed at levels < 5 µg/dL(25,26).

Combined Air and Water Pollution Exposure

A population-based study of 377 million people in China estimated 62,847 new cancer cases (7.4% of total) attributable to combined air and water pollution, demonstrating synergistic dose–response relationships(27).

Health Disparities and Environmental Justice

Children under five had 5–10 times greater risk from water pollution than adults(20,23). Rural and indigenous communities experienced 3–5 times higher exposure to arsenic and nitrate contamination (21,28). Low-income urban neighbourhoods encountered 2–4 times higher air pollution exposures, correlating with elevated disease burdens(18).

Disease Burden and Policy Implications

Air pollution was responsible for 8.1 million deaths and 11.3% of global mortality, while water pollution accounted for 1.5 million deaths and 2.5% of global mortality in 2021(9,29). Econometric analyses estimated annual healthcare and productivity losses exceeding US \$5 trillion for air pollution alone(30).

Research Gaps

Key gaps include underrepresentation of low- and middle-income countries, limited mixture-effect studies, exposure misclassification challenges, and insufficient mechanistic insights at low exposure levels(18,20,27,31).

Discussion

This systematic review comprehensively analyzed evidence from 112 studies spanning 45 cohort studies, 28 case-control studies, 21 meta-analyses, 12 time-series analyses, and 6 cross-sectional studies across 65 countries, revealing substantial disease burdens and persistent environmental justice concerns related to air and water pollution(32,33). The geographic breadth of this evidence base, covering six continents with sample sizes ranging from 1,200 to 8 million participants and follow-up durations from 1 to 30 years, provides robust foundations for understanding global pollution-health relationships while highlighting critical research gaps that must be addressed to strengthen future policy interventions.

Principal Findings and Public Health Significance

The review confirms that air and water pollution constitute major modifiable risk factors for global mortality and morbidity(32,34,35). The observed 9-11% increase in cardiovascular mortality per 10 $\mu\text{g}/\text{m}^3$ $\text{PM}_{2.5}$ exposure aligns with recent meta-analyses demonstrating consistent dose-response relationships across diverse populations(34,36). The documented 19% increased frailty risk from $\text{PM}_{2.5}$ exposure (hazard ratio 1.19; 95% CI 1.10-1.27) highlights emerging evidence of pollution effects on accelerated aging processes, particularly relevant for aging populations(36). The 18% increase in COPD incidence per 10 $\mu\text{g}/\text{m}^3$ $\text{PM}_{2.5}$ (HR: 1.18; 95% CI: 1.12-1.24) and 6-8% increases in respiratory mortality underscore the persistent respiratory burden from air pollution exposure(3,37).

These findings support the WHO estimate that environmental factors account for approximately 13 million deaths annually, representing nearly a quarter of the global disease burden(38,39). The documented 8-14% increased lung cancer risk per 10 $\mu\text{g}/\text{m}^3$ $\text{PM}_{2.5}$ (RR: 1.11; 95% CI: 1.05-1.18) reinforces the carcinogenic classification of particulate matter(40,41). The 5-7% increased risk of preterm birth and 3-8% increased risk of low birth weight per 10 $\mu\text{g}/\text{m}^3$ $\text{PM}_{2.5}$ during pregnancy demonstrate the intergenerational impacts of air pollution exposure(42).

The water pollution burden, while numerically smaller than air pollution, disproportionately affects vulnerable populations in low- and middle-income countries(33,35). The documented 4.95-fold increased risk of infant methemoglobinemia at nitrate concentrations $> 50 \text{ mg}/\text{L}$ ($p < 0.001$) and substantial cancer risks from arsenic contamination (odds ratios of 2.0-5.0 for bladder cancer and 1.5-3.0 for lung cancer at water arsenic levels $\geq 50 \mu\text{g}/\text{L}$) demonstrate the persistent threat of chemical contaminants in drinking water supplies(43,44). The systematic review revealed a 6.9-point IQ decrement associated with blood lead increases from 2.4 to 30 $\mu\text{g}/\text{dL}$, with effects observed at levels $< 5 \mu\text{g}/\text{dL}$, highlighting the neurodevelopmental impacts of water contamination(38,45). The global surveillance data revealing 214 drinking water outbreaks between 2015-2020, resulting in 2,140 cases and 88 deaths, underscores ongoing challenges in water safety infrastructure(35,46).

Environmental Justice and Health Equity Implications

The review reveals profound environmental inequities that exacerbate existing health disparities (47–49). The 1.5-2.5 times higher pollution-related mortality in socioeconomically disadvantaged communities reflects structural inequalities in exposure distribution and access to healthcare(47,50). Children under five experience 5-10 times greater water pollution risks than adults, while elderly populations face 1.5-2 times elevated risks from air pollution exposure(33,51). These differential impacts align with emerging evidence that marginalized communities—including racial/ethnic minorities and low-income populations—bear disproportionate environmental burdens due to proximity to pollution sources and limited political power to influence siting decisions(48,49).

Recent research confirms that vulnerable populations experience cumulative exposures through multiple pathways, including poor housing conditions, proximity to industrial facilities, and limited access to clean environments(49). Participants in qualitative studies report that vulnerable populations can be exposed to pollution through various means including poor infrastructure, waste dumps and landfills, high traffic areas such as highways and ports, in-home contamination from poor housing, fossil fuel extraction sites, and pesticide runoff from farms(49). The "not in my backyard" syndrome continues to concentrate pollution sources in disadvantaged communities, creating environmental racism that perpetuates health inequalities(47,48). This necessitates environmental justice frameworks that prioritize targeted interventions and community engagement in pollution control strategies, as evidenced by the National Air Quality Programme's integration of environmental justice principles and adoption of targeted monitoring and mitigation strategies(44,47).

Methodological Limitations and Research Gaps

Despite the substantial evidence base from this diverse collection of study designs, several methodological limitations constrain the interpretation and generalizability of findings(3,41).

Exposure misclassification represents a fundamental challenge in environmental epidemiology, with measurement error potentially biasing effect estimates toward the null and undermining the validity of risk assessments. Bias due to exposure measurement error is likely the major limitation to the validity of environmental health studies. Many studies rely on ambient monitoring data that may poorly represent individual exposure levels, particularly for populations spending significant time indoors or in microenvironments with distinct pollution profiles. This is particularly problematic given that occupational and environmental exposure data are measured with error, often substantial error (43).

The systematic review methodology reveals important gaps in study design and reporting quality. Most methodologies were adapted from clinical epidemiology and have not been adequately modified to evaluate and integrate evidence from observational epidemiology studies assessing environmental and occupational hazards, especially in evaluating the quality of exposure assessments. Many reviews inadequately address exposure heterogeneity and fail to systematically evaluate potential confounders across diverse populations and study settings(3,41). The predominant focus on single-pollutant models overlooks the reality of multi-pollutant exposures and potential synergistic effects. Limited mixture-effect studies represent a critical knowledge gap, as real-world exposures involve complex combinations of chemical, biological, and physical stressors. Cumulative risk assessment is currently hampered by inadequate knowledge about interactive mechanisms of toxicity among mixture constituents(52).

Geographic representation bias remains problematic, with substantial underrepresentation of low- and middle-income countries in the evidence base(3,32). This limitation is particularly concerning given that these populations often experience the highest pollution levels and may have different susceptibility patterns due to nutritional status, co-morbidities, and healthcare access(32,33). The lack of standardized exposure assessment methods across studies further complicates evidence synthesis and limits the ability to establish universal exposure-response relationships(3,43). The evidence base reveals gaps for certain chemicals and health outcomes (e.g., endocrine disruptors, some metals, and persistent organic pollutants) and populations (e.g., low- and middle-income countries for exposures different from indoor air pollution)(3).

Economic Burden and Policy Implications

The economic analysis reveals staggering costs associated with pollution-related health impacts, with air pollution alone accounting for USD 2.9-5 trillion in annual global economic losses, corresponding to 3.3% of the world's GDP(40,46). The healthcare expenditure burden represents only a portion of total costs, which include productivity losses, premature mortality, and ecosystem service degradation. Research demonstrates that pollution disproportionately affects economically productive populations, with India experiencing an estimated USD 95 billion loss (3% of GDP) in 2019 from air pollution-related productivity impacts (40,53). In 2018, unhealthy air quality caused 1.8 billion days of work absences worldwide, highlighting the substantial economic impact beyond healthcare costs(40).

Importantly, the evidence strongly supports the economic case for pollution control interventions. The demonstrated 30:1 benefit-to-cost ratio for Clean Air Act implementation in the United States provides compelling evidence that environmental protection generates substantial economic returns. Recent analysis suggests that a 10 $\mu\text{g}/\text{m}^3$ PM_{2.5} reduction could save over USD 9.2 billion annually in healthcare costs in China alone, representing about 1.5% of China's annual healthcare expenditure(40). These findings support arguments for pollution taxes and regulatory frameworks that internalize environmental externalities. As research indicates, pollution represents a substantial burden on societies, imposing direct and indirect costs that manifest in compromised health outcomes, damaged ecosystems, and reduced productivity(46).

The documented 62,847 new cancer cases (7.4% of total) attributable to combined air and water pollution in a population-based study of 377 million people in China demonstrates the synergistic economic burden of multiple pollution exposures(54). Air pollution was responsible for 8.1 million deaths and 11.3% of global mortality, while water pollution accounted for 1.5 million deaths and 2.5% of global mortality in 2021, with annual healthcare and productivity losses exceeding US \$5 trillion for air pollution alone(49,55,56).

Emerging Research Priorities and Future Directions

Several critical research priorities emerge from this systematic review(45,57). **Mechanistic understanding** of pollution effects remains limited, particularly for low-level chronic exposures and vulnerable populations(45,52). Systems biology approaches offer promising avenues for elucidating complex exposure-disease pathways and identifying biomarkers of early effects(52). The interaction between environmental exposures and genetic susceptibility requires further investigation to enable precision public health approaches. Research is needed to comprehensively understand the biological effects and genetic risk associated with air pollution(57).

Mixture toxicology represents an urgent research need, as populations experience simultaneous exposures to multiple pollutants with potentially synergistic effects(50,52). The documented synergistic dose-response relationships in combined air and water pollution exposure demonstrate the importance of cumulative risk assessment(54). Future studies must develop methodologies for characterizing multi-pollutant exposures and their combined health effects(52). There is a crucial need for systematic review methods adapted to assess observational studies in environmental and occupational health, as most current methodologies were adapted from clinical epidemiology(41). New evidence has been documented on the adverse health effects of air pollution at lower exposure levels, indicating ongoing challenges in risk assessment(57).

Climate change impacts on pollution-health relationships require immediate attention(38,45,57)(55,57). Rising temperatures may exacerbate air pollution effects, while changing precipitation patterns could alter water contamination risks. Climate change is exacerbating health risks by increasing the frequency and severity of extreme weather events, including deadly heatwaves(38)(55). The health co-benefits of climate mitigation strategies, such as reduced air pollution from renewable energy transitions, represent important policy synergies that merit systematic evaluation(34,45). Meteorological pattern changes in the last 60 years have been linked to a climate penalty for ozone, meaning strategies to reduce air pollution may be less effective or take longer to achieve than expected(57).

Health systems adaptation requires evidence on effective interventions for pollution-related health impacts(38,44). The development of early warning systems, clinical management protocols, and community health worker training programs represents priority areas for implementation research. The National Programme on Climate Change and

Human Health has developed comprehensive health adaptation plans to minimize and control the burden of disease, disability and mortality associated with air pollution, demonstrating systematic approaches to health system preparedness(44). Integration of environmental health considerations into universal health coverage frameworks is essential for achieving health equity goals(38,39).

Technology and Innovation Opportunities

Advances in exposure assessment technologies offer opportunities to address historical limitations in environmental epidemiology(43,57). Personal monitoring devices, satellite-based exposure estimation, and biomarker development could substantially improve exposure characterization and reduce misclassification bias(43). Machine learning approaches for analyzing complex environmental datasets may reveal previously undetected exposure-health relationships and enable more precise risk prediction. The emergence of low-cost sensors offers opportunities to gather more data on exposure to combined exposures of air pollutants, especially indoors(57).

Digital health interventions, including mobile health applications for pollution exposure awareness and behavioral modification, represent promising approaches for population-level risk reduction. Integration of real-time air quality data with health advisory systems could enable individuals to make informed decisions about outdoor activities and protective behaviors(44). Web applications that allow targeted and individual recommendations can increase public awareness regarding the health risks associated with air pollution and climate change(57).

Global Governance and Policy Integration

The transboundary nature of pollution requires coordinated international responses that transcend traditional sectoral boundaries(38,39). The WHO Global Strategy on Health, Environment and Climate Change provides a framework for integrated action, emphasizing primary prevention and multi-sectoral collaboration through effective and equitable action on the drivers of environmental risks to health. The strategy calls for massively expanded primary prevention requiring substantial and sustained investment of resources towards addressing major risks to health, with resources funded by pricing, tax and subsidy reforms that reflect the true costs to society(39). However, implementation remains challenging due to competing priorities and limited resources in many countries.

Health in All Policies approaches offer mechanisms for ensuring that health considerations are integrated into environmental, transportation, energy, and urban planning decisions(38,39). Recent evidence suggests that co-benefits approaches, highlighting the health gains from environmental protection measures, may generate broader political support for pollution control policies(40,50). The transition to renewables and electric vehicles offers reductions in air pollutants related to ill health as well as greenhouse gases(57).

Conclusion

This systematic review provides compelling evidence that air and water pollution represent major threats to global public health, with disproportionate impacts on vulnerable populations. The substantial economic burden of pollution-related health effects, combined with demonstrated cost-effectiveness of control measures, supports urgent policy action. However, critical research gaps in mixture effects, low-level exposures, and mechanistic understanding limit the precision of risk assessments and the development of targeted interventions.

Future research must prioritize methodological innovations that address exposure misclassification, enhance geographic representation, and elucidate complex exposure-disease relationships. The development of consensus statements for environmental health systematic reviews that are published, well-disseminated, and adopted by journals as guidance would strengthen evidence synthesis. Policy implementation should emphasize environmental justice principles, ensuring that pollution control efforts do not exacerbate existing health inequalities. The integration of environmental health considerations into climate change adaptation and sustainable development frameworks represents an essential step toward achieving health equity and environmental sustainability.

The evidence synthesized in this review underscores the urgent need for transformative changes in how societies approach pollution control and environmental health protection. Only through coordinated action across research, policy, and practice domains can we address the substantial and persistent burden of pollution-related disease affecting

populations worldwide. Several populations, such as older people and children, face increased harm from air pollution and should become priority groups for action.

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