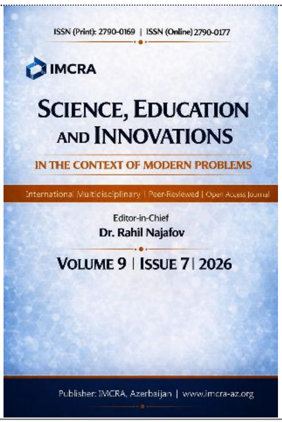

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RESEARCH ARTICLE

Transboundary PM10 and PM2.5 Pollution and Asthma Exacerbations: Implications for Population Health

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Abstract

Transboundary air pollution has emerged as one of the most pressing environmental determinants of global population health, with particulate matter measuring ≤10 µm (PM10) and ≤2.5 µm (PM2.5) representing the principal pollutants responsible for adverse respiratory outcomes. Unlike locally generated emissions, transboundary particulate matter can undergo long-range atmospheric transport, exposing populations located hundreds or even thousands of kilometers from the original emission sources. Although the association between ambient particulate matter and respiratory morbidity has been extensively documented, the specific contribution of transboundary PM episodes to asthma exacerbations remains insufficiently characterized within contemporary epidemiological research. This narrative review critically synthesizes current evidence regarding the relationship between transboundary PM10 and PM2.5 exposure and asthma exacerbations, integrating findings from environmental epidemiology, atmospheric science, toxicology, and public health. Particular emphasis is placed on the biological mechanisms underlying particulate matter-induced airway inflammation, oxidative stress, immune dysregulation, and epithelial injury, together with epidemiological evidence derived from time-series, case-crossover, and observational studies. Regional case studies from Europe, Southeast Asia, North America, and the Caucasus are examined to illustrate the health consequences of desert dust intrusions,

wildfire smoke transport, and cross-border industrial emissions. Available evidence consistently indicates that transboundary particulate matter episodes are associated with increased asthma-related emergency department visits, hospital admissions, medication use, and disease severity, particularly among children, older adults, and individuals with pre-existing respiratory disorders.
The review further evaluates the public health, socioeconomic, and policy implications of transboundary particulate matter exposure by critically assessing existing international governance frameworks, including the Convention on Long-Range Transboundary Air Pollution (CLRTAP), the ASEAN Agreement on Transboundary Haze Pollution, and the Stockholm Convention. Persistent deficiencies in monitoring infrastructure, exposure assessment, source attribution, and regulatory implementation, together with the accelerating influence of climate change on wildfire activity and desertification, underscore the urgent need for enhanced international collaboration, integrated environmental surveillance systems, and multidisciplinary research. Strengthening transboundary air quality governance and incorporating health-centered policy approaches are essential for reducing asthma-related morbidity and improving environmental health resilience under changing global climatic conditions.

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1. Introduction

Air pollution remains one of the most significant environmental determinants of global morbidity and premature mortality, contributing substantially to the worldwide burden of respiratory and cardiovascular diseases (WHO, 2018; Lelieveld et al., 2015). Among the diverse atmospheric pollutants, particulate matter (PM), particularly particles with aerodynamic diameters of ≤10 µm (PM10) and ≤2.5 µm (PM2.5), has attracted considerable scientific attention because of its strong association with adverse health outcomes. While extensive research has examined the health effects of locally generated air pollution, increasing evidence suggests that transboundary air pollution—the long-range atmospheric transport of pollutants across national borders—constitutes a distinct environmental health challenge that cannot be adequately addressed through national mitigation strategies alone.

Unlike local emissions, transboundary particulate matter is transported by large-scale meteorological processes, allowing pollutants to travel hundreds or even thousands of kilometers before deposition. Fine particulate matter, especially PM2.5, may remain suspended in the atmosphere for several days or weeks, enabling long-distance dispersion across continents (EEA, 2019). Consequently, populations located far from primary emission sources—including industrial regions, wildfire-prone landscapes, agricultural burning areas, and major desert systems—may experience significant particulate matter exposure despite relatively low domestic emissions. Such episodes illustrate the increasingly international nature of air pollution and emphasize the need for coordinated environmental governance.

Among the various health outcomes associated with particulate matter exposure, asthma represents one of the most sensitive indicators of environmental air quality. Affecting approximately 262 million people worldwide, asthma is a chronic inflammatory airway disease characterized by reversible airflow limitation, bronchial hyperresponsiveness, and recurrent episodes of wheezing, dyspnea, chest tightness, and coughing (GINA, 2024). Numerous epidemiological investigations have consistently demonstrated that both short-term and long-term exposure to PM10 and PM2.5 significantly increase the risk of asthma exacerbations, emergency department visits, hospital admissions, medication use, and deterioration of pulmonary function (Wong et al., 2008; Kelly & Fussell, 2011). However, despite this well-established relationship, most epidemiological studies have treated ambient particulate matter as a homogeneous exposure, rarely distinguishing between pollutants generated locally and those transported across national borders.

This distinction is scientifically important because the physicochemical characteristics of transboundary particulate matter frequently differ from those of local emissions. Transboundary pollution episodes are commonly associated with desert dust intrusions, wildfire smoke plumes, agricultural biomass burning, volcanic emissions, and cross-border industrial pollution. During atmospheric transport, particulate matter undergoes complex physical and chemical transformations, including oxidation, secondary aerosol formation, and interactions with biological materials and trace metals. Consequently, transported particles may exhibit different toxicological properties, exposure dynamics, and biological effects compared with locally generated PM, potentially resulting in unique patterns of respiratory morbidity, particularly among susceptible populations such as children, older adults, and individuals with pre-existing respiratory diseases.

Growing evidence indicates that episodic transboundary pollution events are associated with measurable increases in asthma-related emergency visits, hospitalizations, and respiratory symptoms across geographically diverse regions, including Europe, North America, East Asia, and the Mediterranean basin. Nevertheless, the available epidemiological evidence remains fragmented, and relatively few studies have specifically evaluated the independent contribution of transboundary particulate matter to asthma exacerbations after accounting for local pollution sources. This lack of source-specific epidemiological evidence represents a critical knowledge gap that limits both exposure assessment and the development of effective public health interventions.

The importance of this issue has become even more pronounced under the influence of climate change. Rising global temperatures, prolonged droughts, changing atmospheric circulation patterns, and increasing wildfire activity have substantially intensified the frequency, duration, and geographical extent of transboundary particulate matter episodes (Hajat et al., 2010; ERS, 2025). Desertification, large-scale biomass burning, and climate-driven alterations in atmospheric transport mechanisms are expected to further increase cross-border movement of airborne particles during the coming decades. Consequently, understanding the health consequences of transboundary PM has become an increasingly important priority for environmental epidemiology, climate adaptation strategies, and international public health policy.

Although several comprehensive reviews have examined the health effects of ambient particulate matter, relatively few have focused specifically on transboundary PM10 and PM2.5 as independent determinants of asthma morbidity. Furthermore, evidence derived from atmospheric sciences, toxicology, epidemiology, environmental health, and international environmental policy has rarely been synthesized within a single analytical framework. Integrating these multidisciplinary perspectives is essential for improving understanding of exposure pathways, biological mechanisms, and governance strategies aimed at reducing health risks associated with long-range transported air pollution.

Accordingly, this review aims to critically synthesize current scientific evidence regarding the relationship between transboundary PM10 and PM2.5 pollution and asthma exacerbations. Specifically, the review seeks to:

1. Describe the principal anthropogenic and natural sources of transboundary particulate matter and the atmospheric mechanisms responsible for its long-range transport;
2. Examine the biological and molecular mechanisms through which PM10 and PM2.5 contribute to asthma exacerbations;
3. Critically evaluate epidemiological evidence and regional case studies investigating the association between transboundary particulate matter episodes and asthma-related health outcomes; and
4. Assess the public health implications and international policy frameworks relevant to transboundary air pollution management, asthma prevention, and evidence-based environmental governance.

By explicitly distinguishing transboundary particulate matter from locally generated air pollution, this review provides a comprehensive and multidisciplinary perspective on an increasingly important environmental health issue. The synthesis presented herein aims to strengthen the evidence base supporting international air quality governance, inform public health policy, identify priorities for future epidemiological research, and contribute to the development of more effective strategies for reducing the global burden of asthma attributable to long-range transported particulate matter.

2. Literature Review

2.1 Transboundary Air Pollution as a Global Environmental Health Challenge

Transboundary air pollution has increasingly been recognized as one of the most complex environmental challenges affecting public health in the twenty-first century. Unlike locally generated air pollution, transboundary pollution is characterized by the long-range atmospheric transport of contaminants across political borders, making exposure largely independent of domestic emission sources. International organizations, including the World Health Organization (WHO) and the European Environment Agency (EEA), emphasize that particulate matter (PM10 and PM2.5) remains among the most harmful airborne pollutants because of its persistence in the atmosphere, ability to travel long distances, and well-established association with respiratory and cardiovascular diseases (WHO, 2018; EEA, 2019, 2022).

Lelieveld et al. (2015) estimated that a substantial proportion of premature deaths associated with ambient PM2.5 exposure originates from pollutants transported across national boundaries rather than from domestic emissions alone. Similarly, Rao et al. (2014) demonstrated that regional atmospheric circulation significantly influences particulate matter concentrations throughout Europe and

North America, highlighting that effective mitigation requires coordinated international environmental governance rather than isolated national interventions.

Natural sources such as Saharan dust storms, Central Asian desert dust, volcanic eruptions, and increasingly frequent wildfires contribute substantially to transboundary particulate matter transport. Anthropogenic emissions—including industrial combustion, agricultural biomass burning, power generation, and transportation—also represent major contributors to long-range particulate pollution (Ginoux et al., 2012; Hajat et al., 2010). Climate change has further intensified this phenomenon through increasing wildfire frequency, prolonged drought conditions, and altered atmospheric circulation patterns, thereby expanding both the geographical extent and duration of transboundary pollution episodes (WHO, 2021).

2.2 Characteristics and Long-Range Transport of PM10 and PM2.5

Particulate matter is generally classified according to aerodynamic diameter into coarse particles (PM10) and fine particles (PM2.5). PM10 primarily deposits within the upper respiratory tract, whereas PM2.5 penetrates deeply into terminal bronchioles and alveolar tissues, enabling systemic distribution through the bloodstream (WHO, 2018).

Particle size strongly determines atmospheric residence time and transport potential. PM2.5 particles may remain suspended for several days or even weeks, allowing transport over thousands of kilometers under favorable meteorological conditions, while PM10 particles, despite settling more rapidly, can also travel considerable distances during strong wind events and desert dust intrusions (EEA, 2019). Throughout atmospheric transport, particles undergo numerous physicochemical transformations, including oxidation, secondary aerosol formation, adsorption of heavy metals, and interaction with biological materials such as pollen, bacteria, and fungal spores. These transformations may substantially modify particle toxicity and consequently influence their biological effects following inhalation (Kelly & Fussell, 2011; Griffin, 2007).

Recent atmospheric modeling studies indicate that regional meteorological conditions—including wind direction, boundary layer dynamics, temperature inversions, and precipitation—play fundamental roles in determining transboundary PM transport and exposure intensity (EEA, 2022). Consequently, populations located far from major emission sources may periodically experience pollutant concentrations exceeding national air quality standards despite relatively low domestic emissions.

2.3 Biological Mechanisms Linking Particulate Matter to Asthma Exacerbations

The relationship between particulate matter exposure and asthma exacerbation has been extensively investigated over the past two decades. Experimental and epidemiological evidence consistently demonstrates that inhalation of PM10 and PM2.5 initiates multiple interconnected biological processes that contribute to airway dysfunction.

Fine particulate matter induces airway inflammation by activating epithelial cells and alveolar macrophages, resulting in increased production of pro-inflammatory cytokines including IL-6, IL-8, TNF-α, and other inflammatory mediators (Xing et al., 2016). Simultaneously, particulate matter generates oxidative stress through the production of reactive oxygen species (ROS), overwhelming endogenous antioxidant defenses and causing epithelial injury, mitochondrial dysfunction, and increased bronchial hyperresponsiveness (Kelly & Fussell, 2011; Kampa & Castanas, 2008).

In addition, PM exposure alters immune regulation by promoting Th2-mediated inflammatory responses and enhancing IgE production, thereby increasing allergic sensitization among susceptible individuals (Pavord et al., 2019). Long-term exposure has also been associated with epigenetic modifications affecting genes responsible for inflammatory regulation and immune responses, particularly among children exposed during early developmental stages (Xing et al., 2016). These biological mechanisms collectively explain why particulate matter exposure substantially increases asthma attacks, emergency healthcare utilization, and disease severity.

2.4 Epidemiological Evidence Linking Air Pollution and Asthma

Numerous epidemiological investigations have confirmed that exposure to ambient particulate matter significantly increases respiratory morbidity. Dominici et al. (2006) demonstrated that short-term increases in PM concentrations were associated with increased hospital admissions for respiratory and cardiovascular diseases across multiple U.S. cities. Similarly, Wong et al. (2008) reported positive associations between PM exposure and daily mortality and respiratory hospitalizations in Hong Kong.

A comprehensive systematic review conducted by Orellano et al. (2017) concluded that both PM10 and PM2.5 consistently increase all-cause mortality and respiratory morbidity across diverse populations. Guarnieri and Balmes (2014) further reported that particulate matter exposure contributes to worsening asthma symptoms, increased medication use, and reduced pulmonary function among both children and adults.

Several investigations have specifically evaluated asthma outcomes. Kelly and Fussell (2011) emphasized that PM exposure increases airway inflammation and bronchial hyperresponsiveness, leading to more frequent asthma exacerbations. These findings are further supported by WHO (2021), which concluded that no completely safe threshold exists for particulate matter exposure, particularly for vulnerable populations.

2.5 Evidence Specifically Addressing Transboundary Pollution Episodes

Although the health impacts of ambient particulate matter are well documented, relatively fewer studies have specifically investigated transboundary pollution events. Nevertheless, the available evidence consistently indicates that long-range transported particulate matter significantly contributes to respiratory morbidity.

Desert dust episodes represent the most extensively studied transboundary pollution events. Pérez et al. (2008) demonstrated that Saharan dust intrusions significantly increased respiratory mortality in Barcelona, while Middleton et al. (2008) observed higher hospital admissions during prolonged Saharan dust exposure in Cyprus. Samoli et al. (2011) similarly reported increased respiratory mortality associated with Saharan dust episodes in Greece.

In East Asia, Kim et al. (2018) and Koo et al. (2020) documented substantial health impacts associated with PM2.5 transported from industrial regions of China into South Korea and Japan. These investigations identified increased hospital admissions and respiratory morbidity during documented transboundary pollution events.

Wildfire smoke has also emerged as an increasingly important transboundary pollution source. Reid et al. (2016) reviewed numerous studies demonstrating that wildfire smoke exposure consistently increases asthma exacerbations, respiratory symptoms, and emergency healthcare utilization. As climate change increases wildfire frequency worldwide, smoke transport is expected to become an increasingly significant contributor to transboundary PM exposure.

2.6 International Policy and Governance

Recognizing that transboundary pollution cannot be effectively controlled through national policies alone, several international agreements have been established to coordinate emission reduction efforts. The Convention on Long-Range Transboundary Air Pollution (CLRTAP), adopted under the United Nations Economic Commission for Europe, remains the principal international framework governing transboundary air pollution in Europe and North America (UNECE, 2022). Similarly, the ASEAN Agreement on Transboundary Haze Pollution addresses recurrent biomass burning and wildfire smoke affecting Southeast Asia (Varkkey et al., 2020).

Although these agreements have contributed substantially to emission reductions, numerous scholars argue that existing international policies continue to emphasize emission control rather than explicitly incorporating health-based outcomes, including asthma morbidity, into regulatory evaluation frameworks (WHO, 2018; UNEP, 2021). Furthermore, disparities in monitoring capacity, atmospheric modeling infrastructure, and health surveillance systems remain significant barriers to effective transboundary pollution management, particularly in low- and middle-income countries.

2.7 Research Gap

Despite considerable advances in understanding the health effects of particulate matter, several important research gaps remain. First, most epidemiological investigations evaluate ambient particulate matter as a homogeneous exposure without distinguishing between locally generated and transboundary pollution sources. Second, relatively limited evidence is available from regions such as the Caucasus, Central Asia, and parts of Eastern Europe, despite their frequent exposure to desert dust and long-range atmospheric transport. Third, relatively few multidisciplinary investigations integrate atmospheric transport modeling, satellite observations, chemical source apportionment, and epidemiological analyses within a unified analytical framework.

These limitations hinder accurate estimation of the independent contribution of transboundary PM10 and PM2.5 to asthma exacerbations and constrain evidence-based environmental policymaking. Consequently, there is a clear need for integrated, multidisciplinary research combining environmental monitoring, atmospheric sciences, epidemiology, and public health policy to better understand and mitigate the global health burden associated with transboundary particulate matter pollution.

3. Methodology

3.1 Study Design

This study was conducted as a comprehensive narrative review using a structured literature search and evidence synthesis approach to evaluate the relationship between transboundary particulate matter (PM10 and PM2.5) pollution and asthma exacerbations. The review integrates findings from environmental epidemiology, atmospheric sciences, toxicology, respiratory medicine, and environmental policy to provide a multidisciplinary understanding of the health impacts associated with long-range transported particulate matter. Although quantitative meta-analysis was beyond the scope of this study due to methodological heterogeneity among available publications, rigorous procedures were applied to ensure transparency, comprehensiveness, and reproducibility throughout the review process.

3.2 Literature Search Strategy

A comprehensive search of the scientific literature was conducted between January and April 2025 using five major electronic databases: PubMed/MEDLINE, Scopus, Web of Science Core Collection, ScienceDirect, and Google Scholar. To ensure comprehensive coverage of international environmental policies and technical reports, additional publications were retrieved from the websites of the World Health Organization (WHO), European Environment Agency (EEA), United Nations Environment Programme (UNEP), United Nations Economic Commission for Europe (UNECE), Global Initiative for Asthma (GINA), and the National Environment Agency of Georgia.

The search strategy employed combinations of Medical Subject Headings (MeSH) and free-text keywords connected through Boolean operators. Representative search terms included:

- *"transboundary air pollution"*
- *"long-range transport"*
- *"PM2.5"*
- *"PM10"*
- *"particulate matter"*
- *"asthma exacerbation"*
- *"environmental health"*
- *"wildfire smoke"*
- *"desert dust"*
- *"air quality governance"*

These keywords were combined using the operators AND and OR to maximize retrieval of relevant publications. Reference lists of eligible studies were also manually screened to identify additional articles not captured during the electronic database search.

3.3 Eligibility Criteria

Publications were selected according to predefined inclusion and exclusion criteria.

Studies were included if they:

- investigated transboundary or long-range transported PM10 and/or PM2.5;
- examined asthma exacerbations or other respiratory health outcomes associated with particulate matter exposure;
- evaluated biological mechanisms linking particulate matter exposure to respiratory disease;
- addressed atmospheric transport processes, exposure assessment, environmental monitoring, or public health implications;
- were published in peer-reviewed scientific journals or official reports issued by internationally recognized organizations;
- were available in English.

Studies were excluded if they:

- focused exclusively on locally generated air pollution without consideration of transboundary transport;
- investigated pollutants unrelated to particulate matter;
- consisted solely of conference abstracts, editorials, opinion papers, or unpublished reports lacking methodological detail;
- represented duplicate publications or overlapping datasets.

3.4 Study Selection Process

The study selection process consisted of two sequential stages. Initially, titles and abstracts identified through the database search were screened for relevance to the objectives of the review. Publications considered potentially eligible subsequently underwent full-text evaluation.

Particular attention was given to studies providing evidence on:

- atmospheric transport mechanisms of particulate matter;
- epidemiological associations between transboundary PM exposure and asthma exacerbations;
- biological mechanisms of particulate matter toxicity;
- public health consequences of transboundary pollution; and
- international environmental governance and policy responses.

Only studies meeting all predefined eligibility criteria were included in the final synthesis.

3.5 Data Extraction

Data extraction was performed using a standardized review framework to ensure consistency across studies. The following information was extracted from each publication:

- authors and year of publication;
- country or study region;
- study design;
- characteristics of the study population;
- particulate matter type (PM10 and/or PM2.5);
- principal pollution source (desert dust, wildfire smoke, industrial emissions, biomass burning, or mixed sources);
- exposure assessment methodology;
- health outcomes evaluated;
- major findings; and
- study limitations.

For international reports, information regarding policy frameworks, monitoring systems, emission reduction strategies, and transboundary governance mechanisms was additionally extracted.

3.6 Quality Evaluation of Included Evidence

Although this review was not designed as a formal systematic review, the methodological quality and scientific credibility of the included literature were critically evaluated. Greater emphasis was placed on:

- systematic reviews and meta-analyses;
- prospective cohort studies;
- time-series and case-crossover investigations;
- multicenter epidemiological studies;
- atmospheric transport modeling studies;
- publications appearing in high-impact peer-reviewed journals; and
- official reports produced by internationally recognized organizations.

Preference was given to studies employing validated exposure assessment methods, robust statistical analyses, and clearly defined respiratory health outcomes.

3.7 Data Synthesis

Because of substantial heterogeneity in study designs, exposure assessment methodologies, geographical settings, and outcome definitions, quantitative meta-analysis was considered inappropriate. Therefore, a thematic narrative synthesis was adopted.

The evidence was synthesized across five principal thematic areas:

1. sources and atmospheric transport mechanisms of transboundary particulate matter;

2. biological mechanisms underlying particulate matter-induced asthma exacerbations;
3. epidemiological evidence from different geographical regions;
4. public health burden and socioeconomic implications; and
5. international environmental governance and future research priorities.

This thematic approach facilitated the integration of multidisciplinary evidence from environmental science, epidemiology, toxicology, and public health while identifying current scientific consensus, methodological limitations, and priority areas requiring further investigation.

3.8 Ethical Considerations

As this study is based exclusively on previously published scientific literature and publicly available institutional reports, ethical approval and informed consent were not required. All information included in this review was obtained from publicly accessible sources and appropriately cited in accordance with international standards for scholarly publishing.

4. Sources, Atmospheric Transport, and Biological Mechanisms of Transboundary Particulate Matter

4.1 Sources and Atmospheric Transport of Transboundary PM10 and PM2.5

Transboundary particulate matter (PM10 and PM2.5) originates from a diverse range of anthropogenic and natural emission sources capable of releasing airborne particles that remain suspended in the atmosphere long enough to be transported across regional and national boundaries. Unlike locally generated pollution, transboundary particulate matter contributes to episodic or prolonged air pollution events affecting populations located hundreds or even thousands of kilometers from the original emission source. Consequently, the health burden associated with particulate matter is no longer confined to the regions where emissions occur but has become an increasingly international public health concern requiring coordinated environmental governance.

Natural sources constitute a major component of long-range particulate matter transport. Large desert systems, including the Sahara Desert, the Arabian Peninsula, and the Central Asian deserts, generate enormous quantities of mineral dust that can be transported across continents through prevailing atmospheric circulation patterns. Saharan dust intrusions, for example, regularly influence air quality throughout Southern and Eastern Europe, producing substantial increases in PM10 concentrations and contributing to elevated respiratory morbidity and mortality during dust episodes (WHO, 2018; Lelieveld et al., 2015). In addition to mineral dust, volcanic eruptions and naturally occurring wildfires also contribute to regional and intercontinental particulate transport under favorable meteorological conditions.

Anthropogenic emissions represent another major source of transboundary particulate matter. Industrial activities, fossil fuel combustion, power generation, transportation, residential heating, and agricultural biomass burning collectively release large quantities of primary particulate matter together with precursor gases that contribute to secondary aerosol formation. Wildfires have emerged as one of the most significant contemporary sources of transboundary PM2.5 because combustion processes generate fine particles rich in organic carbon, black carbon, and numerous toxic combustion products. Smoke plumes frequently travel across neighboring countries and, in some cases, entire continents, substantially degrading regional air quality. Climate change has intensified this problem by increasing both the frequency and severity of large-scale wildfire events worldwide (Hajat et al., 2010; ERS, 2025).

Agricultural activities further contribute to transboundary particulate pollution through biomass burning and emissions of ammonia from fertilizer application and livestock production. During atmospheric transport, ammonia reacts with sulfur dioxide and nitrogen oxides to form secondary particulate matter, particularly ammonium sulfate and ammonium nitrate, thereby significantly increasing PM2.5 concentrations in receptor regions located far from the original emission sources (EEA, 2019).

Following emission, particulate matter undergoes complex atmospheric transport governed by meteorological and physicochemical processes. Particle size is one of the principal determinants of transport distance. PM2.5 particles may remain suspended in the atmosphere for several days or even weeks, allowing transport over thousands of kilometers, whereas PM10 particles generally settle more rapidly but may nevertheless travel substantial distances during intense wind events or desert dust intrusions (WHO, 2018). Atmospheric transport is strongly influenced by wind direction, wind velocity, planetary boundary layer dynamics, temperature inversions, humidity, and precipitation, all of which determine pollutant dispersion, transformation, and deposition (EEA, 2019).

During long-range transport, particulate matter undergoes continuous physical and chemical transformation. Oxidation reactions, condensation processes, and interactions with gaseous pollutants modify particle composition, while secondary aerosol formation substantially increases the PM2.5 fraction. Atmospheric aging may also alter the toxicity of particulate matter by enriching particles with sulfates, nitrates, heavy metals, organic compounds, and biological materials. Consequently, transboundary particulate matter often differs considerably from locally generated pollution in both chemical composition and biological activity, resulting in complex exposure profiles and potentially enhanced health risks (Kelly & Fussell, 2011).

4.2 Biological Mechanisms Linking Transboundary Particulate Matter to Asthma Exacerbations

Exposure to transboundary PM10 and PM2.5 contributes to asthma exacerbations through multiple interconnected biological pathways involving inflammatory, oxidative, immunological, and molecular mechanisms. Because transboundary particulate matter frequently differs from locally generated particles in chemical composition, particle size distribution, and oxidative potential, its biological effects may vary substantially depending on emission source, atmospheric aging, and transport history.

One of the primary mechanisms involves airway inflammation. Following inhalation, PM2.5 penetrates deeply into the terminal bronchioles and alveolar regions, where it activates airway epithelial cells and alveolar macrophages. This activation stimulates the production of pro-inflammatory cytokines, including interleukin-6 (IL-6), interleukin-8 (IL-8), and tumor necrosis factor-alpha (TNF-α), initiating an inflammatory cascade characterized by airway edema, mucus hypersecretion, and bronchoconstriction. These pathological changes represent the fundamental biological processes underlying acute asthma exacerbations (Xing et al., 2016; Kampa & Castanas, 2008).

Another important mechanism is oxidative stress. Fine particulate matter carries reactive oxygen species together with transition metals and other redox-active compounds capable of overwhelming endogenous antioxidant defense systems. Excessive oxidative stress damages airway epithelial cells, disrupts epithelial barrier integrity, promotes mitochondrial dysfunction, and amplifies inflammatory signaling pathways. These processes collectively increase airway hyperresponsiveness and reduce pulmonary function, particularly among individuals with pre-existing asthma (Kelly & Fussell, 2011; WHO, 2018).

Particulate matter exposure also produces significant immunological alterations. Experimental and clinical studies have demonstrated that PM promotes T-helper type 2 (Th2)-mediated immune responses, enhances immunoglobulin E (IgE) production, and increases allergic sensitization. Consequently, susceptible individuals—especially children, atopic patients, and those with chronic respiratory disease—experience heightened vulnerability to asthma attacks during transboundary pollution episodes (Pavord et al., 2019).

In addition, particulate matter impairs the normal function of the mucociliary clearance system, which represents one of the respiratory tract's primary defense mechanisms. Damage to ciliated epithelial cells together with altered mucus rheology reduces the efficiency of particle and pathogen removal from the airways, thereby increasing susceptibility to respiratory infections that frequently precipitate asthma exacerbations (Kampa & Castanas, 2008).

Emerging research further indicates that chronic exposure to PM2.5 may induce epigenetic and molecular alterations affecting genes involved in inflammatory regulation, oxidative stress responses, and immune function. Such modifications may contribute not only to recurrent asthma exacerbations but also to disease progression, airway remodeling, and long-term deterioration of respiratory health. These epigenetic effects appear particularly important following exposure during early childhood, when respiratory and immune system development remains highly sensitive to environmental influences (Xing et al., 2016; WHO, 2018).

Collectively, these biological mechanisms demonstrate that transboundary particulate matter constitutes more than a passive environmental exposure. Instead, it acts as a multifactorial pathogenic agent capable of initiating complex inflammatory and immunological processes that substantially increase asthma morbidity, particularly among vulnerable populations exposed to recurrent long-range pollution events.

Table 1. Major Sources of Transboundary PM10 and PM2.5 and Their Characteristics

Source	**Type**	**Dominant PM Fraction**	**Major Pollutants**	**Geographic Examples**	**Public Health Relevance**
Desert dust storms	Natural	PM10 > PM2.5	Mineral dust, silica, metals, microorganisms	Sahara, Arabian Peninsula, Central Asia	Increased respiratory morbidity, asthma exacerbations
Wildfires	Natural/Climate-related	PM2.5	Organic carbon, black carbon, PAHs	North America, Australia, Southern Europe	Severe asthma attacks, hospital admissions
Industrial emissions	Anthropogenic	PM2.5	Sulfates, nitrates, heavy metals	China, Europe, North America	Chronic respiratory and cardiovascular diseases

Transportation	Anthropogenic	PM2.5	Black carbon, NOx-derived particles	Urban and metropolitan regions	Airway inflammation and reduced lung function
Agricultural biomass burning	Anthropogenic	PM2.5	Organic aerosols, ammonia-derived particles	Southeast Asia, South America	Regional haze and asthma exacerbations
Residential combustion	Anthropogenic	PM2.5	Carbonaceous particles, secondary aerosols	Eastern Europe, Central Asia	Long-term respiratory exposure

Table 2. Atmospheric Processes Governing Long-Range Transport of Particulate Matter

Atmospheric Process	Description	Influence on PM Transport	Public Health Implication
Wind circulation	Large-scale horizontal transport	Enables cross-border pollutant movement	Exposure far from emission sources
Atmospheric stability	Temperature inversions reduce vertical mixing	Pollutant accumulation	Higher PM concentrations
Boundary layer dynamics	Controls vertical dispersion	Determines exposure intensity	Increased population exposure
Chemical aging	Oxidation and secondary aerosol formation	Alters PM toxicity	Enhanced respiratory toxicity
Wet deposition	Removal by rainfall	Reduces atmospheric PM	Temporary improvement in air quality
Dry deposition	Gravitational settling of particles	Terminates transport	Surface contamination

Table 3. Biological Mechanisms Linking Transboundary PM Exposure to Asthma Exacerbations

Biological Mechanism	Principal Cellular Events	Clinical Consequences	Key References
Airway inflammation	Activation of epithelial cells and macrophages; release of IL-6, IL-8, TNF-α	Bronchoconstriction, airway edema, asthma attacks	Xing et al. (2016); Kampa & Castanas (2008)
Oxidative stress	Excess reactive oxygen species and oxidative injury	Epithelial damage and airway hyperresponsiveness	Kelly & Fussell (2011); WHO (2018)
Immune dysregulation	Enhanced Th2 response and IgE production	Increased allergic sensitization	Pavord et al. (2019)
Impaired mucociliary clearance	Dysfunction of ciliated epithelial cells	Increased respiratory infections and asthma exacerbations	Kampa & Castanas (2008)
Epigenetic alterations	DNA methylation and altered inflammatory gene expression	Long-term asthma progression	Xing et al. (2016); WHO (2018)

5. Epidemiological Evidence and Regional Case Studies of Transboundary Air Pollution

5.1 Epidemiological Evidence on the Health Effects of Transboundary Air Pollution

A substantial body of epidemiological research has established ambient air pollution as one of the leading environmental determinants of global morbidity and premature mortality. Exposure to particulate matter, particularly PM10 and PM2.5, has consistently been associated with increased risks of respiratory and cardiovascular diseases, hospital admissions, reduced pulmonary function, and premature death (Pope et al., 2002; Brook et al., 2010; WHO, 2021). While the adverse health effects of ambient particulate matter are well documented, comparatively fewer investigations have specifically quantified the independent contribution of transboundary air pollution, largely because distinguishing long-range transported particles from locally generated emissions requires sophisticated atmospheric transport models, satellite observations, and chemical source apportionment techniques.

Time-series, cohort, and case-crossover studies have consistently demonstrated that short-term increases in PM10 and PM2.5 concentrations are associated with acute respiratory outcomes, including asthma exacerbations, emergency department visits, and hospital admissions (Dominici et al., 2006; Atkinson et al., 2014). These associations become particularly pronounced during documented long-range pollution episodes, such as desert dust intrusions, wildfire smoke transport, and cross-border industrial pollution events, suggesting that transboundary particulate matter contributes substantially to population exposure and adverse respiratory outcomes.

Large-scale international studies further emphasize the importance of cross-border pollutant transport. Using global atmospheric chemistry models, Lelieveld et al. (2015) estimated that a considerable proportion of premature mortality attributable to PM2.5 exposure originates from emissions transported across national borders. Likewise, Rao et al. (2014) demonstrated that regional atmospheric transport significantly influences particulate matter concentrations throughout Europe and North America, illustrating that air quality and its associated health consequences frequently depend not only on domestic emissions but also on regional emission patterns and meteorological conditions. These findings reinforce the concept that effective protection of population health requires coordinated international emission-control strategies rather than isolated national interventions.

5.2 Regional Evidence from Desert Dust Events, East Asia, Europe, and the Caucasus

Desert dust transport represents one of the most extensively investigated forms of transboundary air pollution and provides compelling evidence of the health consequences associated with long-range atmospheric transport. Dust storms originating from the Sahara, the Arabian Peninsula, and Central Asian deserts transport enormous quantities of coarse and fine particulate matter across Southern Europe, the Mediterranean Basin, the Middle East, and the Caucasus. These episodic events substantially elevate PM10 and PM2.5 concentrations over large geographical areas and frequently exceed international air-quality standards (Ginoux et al., 2012).

Several epidemiological investigations conducted in Mediterranean countries have consistently linked Saharan dust intrusions with increased respiratory morbidity and mortality. Pérez et al. (2008) reported significantly elevated respiratory mortality during Saharan dust episodes in Barcelona, whereas Samoli et al. (2011) observed increased cardiovascular and respiratory mortality associated with dust events in Athens. Similarly, Middleton et al. (2008) documented higher hospital admission rates during prolonged Saharan dust exposure in Cyprus, further demonstrating the public health significance of transboundary mineral dust transport.

The toxicity of transported dust extends beyond its mineral composition. During atmospheric transport, dust particles adsorb numerous biological and chemical contaminants, including bacteria, fungal spores, heavy metals, persistent organic pollutants, and anthropogenic aerosols (Griffin, 2007; Querol et al., 2019). Consequently, transboundary dust frequently exhibits greater biological complexity and potentially higher toxicity than locally generated particulate matter, thereby increasing the likelihood of airway inflammation, allergic sensitization, and asthma exacerbations.

East Asia represents another region where the health effects of transboundary air pollution have been extensively investigated. Long-range transport of industrial emissions from mainland China significantly influences air quality in South Korea and Japan, particularly during winter and spring. Atmospheric transport analyses combined with epidemiological investigations have demonstrated clear associations between transported PM2.5 episodes and increased respiratory hospitalizations, emergency healthcare utilization, and premature mortality (Kim et al., 2018; Koo et al., 2020). These studies illustrate how regional atmospheric circulation can substantially amplify public health risks beyond the original emission regions.

Evidence from Europe similarly highlights the continental nature of particulate matter transport. According to the European Environment Agency (EEA, 2022), large-scale pollution episodes frequently occur simultaneously across multiple European countries, reflecting the dominant influence of regional atmospheric circulation rather than localized emission sources. Such events disproportionately affect vulnerable populations, including children, older adults, and individuals with chronic respiratory or cardiovascular diseases, resulting in increased healthcare utilization and significant economic costs.

In contrast, epidemiological evidence from the Caucasus region remains comparatively limited despite recurrent exposure to long-range transported particulate matter. Georgia, in particular, experiences periodic desert dust intrusions originating from southern and southeastern source regions. National air-quality monitoring data indicate repeated exceedances of PM10 and PM2.5 concentrations during these episodes, especially in urban and industrial centers such as Rustavi. However, few studies have systematically examined the relationship between these pollution events and respiratory health outcomes, including asthma exacerbations. The scarcity of region-specific epidemiological evidence limits understanding of the true public health burden associated with transboundary particulate matter in the Caucasus and highlights an important area for future investigation.

.3 Asthma Exacerbations, Susceptible Populations, and Future Research Needs

Asthma represents one of the respiratory conditions most consistently associated with short-term exposure to particulate matter. Numerous epidemiological studies have demonstrated that increases in ambient PM10 and PM2.5 concentrations are accompanied by higher frequencies of asthma attacks, emergency department visits, hospital admissions, increased medication use, and deterioration in pulmonary function (Guarnieri & Balmes, 2014; Orellano et al., 2017). These adverse effects become particularly evident during episodes of transboundary pollution, when pollutant concentrations rise rapidly over large geographical regions.

Certain population groups demonstrate substantially greater susceptibility to particulate matter exposure. Children are especially vulnerable because of their developing respiratory and immune systems, higher ventilation rates relative to body size, and greater time spent outdoors. Older adults, individuals with chronic respiratory diseases, patients with cardiovascular disorders, and those with compromised immune function similarly exhibit increased sensitivity to elevated particulate matter concentrations. According to the World Health Organization (WHO, 2021), no threshold has been identified below which particulate matter exposure can be considered entirely safe, emphasizing that even relatively short-term increases in PM concentrations may trigger clinically significant asthma exacerbations among susceptible individuals.

Although the scientific evidence supporting the adverse health effects of transboundary particulate matter has expanded considerably, important knowledge gaps remain. Existing epidemiological studies are geographically concentrated in Europe, North America, and East Asia, whereas evidence from the Caucasus, Central Asia, the Middle East, and other understudied regions remains scarce. Furthermore, relatively few investigations have specifically quantified asthma outcomes attributable to long-range transported particulate matter independently of locally generated emissions.

Addressing these limitations will require multidisciplinary research integrating atmospheric transport modeling, satellite remote sensing, chemical source apportionment, ground-based air-quality monitoring, and comprehensive epidemiological surveillance. Such integrated approaches would improve source attribution, strengthen causal inference, and provide more robust evidence for environmental policy development. Expanding region-specific epidemiological research, particularly in countries experiencing recurrent transboundary pollution episodes, will be essential for developing effective public health interventions and internationally coordinated strategies to mitigate the growing health burden associated with transboundary particulate matter.

6. Public Health Implications and Policy Responses to Transboundary Air Pollution

6.1 Public Health Burden and Health System Challenges

Transboundary particulate matter (PM10 and PM2.5) represents one of the most significant contemporary environmental threats to global public health. Unlike locally generated pollution, long-range transported particulate matter affects populations irrespective of national emission inventories, creating complex cross-border exposure patterns that challenge conventional public health management. According to the World Health Organization (WHO), ambient air pollution contributes to approximately 4.2 million premature deaths annually, with fine particulate matter (PM2.5) accounting for the largest proportion of adverse health outcomes because of its ability to penetrate deeply into the pulmonary alveoli and subsequently enter systemic circulation (WHO, 2021).

From a respiratory health perspective, transboundary pollution episodes frequently produce abrupt increases in particulate matter concentrations that exceed national air-quality standards despite relatively low domestic emissions. Such episodes have repeatedly been associated with increased asthma exacerbations, emergency department visits, hospital admissions, and excess mortality, particularly during prolonged desert dust intrusions, wildfire smoke transport, and regional industrial pollution events (Middleton et al., 2008; Zhang et al., 2021). Because these pollution episodes often occur simultaneously across multiple countries, their cumulative burden extends beyond individual healthcare systems and represents a regional public health challenge requiring coordinated international responses.

The health impacts of transboundary particulate matter are not distributed equally across populations. Children remain particularly vulnerable owing to the immaturity of their respiratory and immune systems, higher ventilation rates relative to body size, and longer lifetime exposure potential. Older adults, individuals with chronic respiratory or cardiovascular diseases, pregnant women, and socioeconomically disadvantaged populations similarly demonstrate increased susceptibility to particulate matter exposure (WHO, 2018; Kelly & Fussell, 2011). Repeated exposure to elevated PM concentrations may accelerate disease progression, increase healthcare utilization, and contribute to long-term reductions in quality of life.

Beyond its direct clinical consequences, transboundary particulate matter imposes substantial socioeconomic costs. Asthma exacerbations attributable to particulate pollution result in increased healthcare expenditures, reduced workforce productivity, school absenteeism, medication costs, and broader economic losses associated with disability and premature mortality (Nurmagambetov et al., 2018). Importantly, these economic burdens are frequently borne by countries located downwind of major emission sources, despite their limited capacity to influence the originating emissions. Consequently, transboundary air pollution raises important issues of environmental justice, health equity, and shared international responsibility, emphasizing the need for cooperative environmental governance.

Current national public health systems remain inadequately equipped to address many aspects of transboundary pollution. Air-quality management strategies traditionally focus on controlling domestic emission sources such as transportation, industrial activities, and residential heating. However, long-range atmospheric transport introduces external determinants of exposure that remain beyond national regulatory control (EEA, 2019). Furthermore, respiratory health surveillance systems rarely integrate atmospheric transport modeling, satellite observations, chemical source apportionment, and epidemiological monitoring, thereby limiting the ability to attribute asthma exacerbations directly to transboundary pollution episodes (Anenberg et al., 2014).

These challenges are particularly evident in low- and middle-income countries, where monitoring infrastructure, particulate composition analysis, and exposure assessment remain limited. In many regions affected by recurrent desert dust intrusions or wildfire smoke transport, sparse monitoring networks may substantially underestimate population exposure, thereby reducing the effectiveness of both public health surveillance and environmental policy interventions (UNEP, 2021).

6.2 International Policy Responses and Future Directions

Recognizing that transboundary air pollution cannot be effectively managed through national legislation alone, numerous international agreements have been established to facilitate regional cooperation in emission reduction and environmental monitoring. Among these, the Convention on Long-Range Transboundary Air Pollution (CLRTAP), adopted under the auspices of the United Nations Economic Commission for Europe in 1979, remains the most comprehensive legally binding framework addressing long-range atmospheric pollution. Through successive protocols regulating sulfur dioxide, nitrogen oxides, volatile organic compounds, ammonia, and particulate matter precursors, CLRTAP has contributed substantially to improving air quality across Europe and North America (UNECE, 2022).

Despite these achievements, existing international frameworks exhibit several important limitations. Their primary emphasis has historically focused on emission reduction and ecosystem protection rather than explicitly incorporating measurable public health outcomes, including asthma morbidity, respiratory hospitalizations, or premature mortality, into regulatory evaluation. Moreover, the geographical coverage of CLRTAP remains limited, while rapidly industrializing regions experiencing severe transboundary pollution often lack similarly comprehensive multilateral agreements.

At the global level, organizations such as the World Health Organization (WHO) and the United Nations Environment Programme (UNEP) have strengthened international awareness of the health consequences associated with ambient air pollution by promoting evidence-based air-quality guidelines, global monitoring initiatives, and integrated environmental health policies. Nevertheless, particulate matter regulation frequently remains indirect, with relatively limited attention devoted to the specific health implications of recurrent transboundary pollution episodes (WHO, 2018).

Reducing the burden of asthma associated with transboundary particulate matter requires a multidisciplinary and internationally coordinated public health strategy. Future policy should strengthen cross-border emission reduction initiatives, expand regional air-quality monitoring networks, improve atmospheric transport forecasting, and develop integrated early-warning systems capable of identifying high-risk pollution episodes before population exposure occurs. Combining satellite remote sensing, chemical transport modeling, and ground-based monitoring would substantially improve exposure assessment and facilitate timely public health interventions.

Equally important is the integration of environmental and healthcare information systems. Linking air-quality monitoring with hospital admissions, emergency department records, pharmaceutical utilization, and respiratory disease surveillance would enhance the capacity to quantify the health burden attributable to transboundary pollution and improve evidence-based policymaking. Such integrated surveillance systems would also facilitate evaluation of intervention effectiveness and strengthen preparedness for future pollution events.

Public health communication represents another critical component of effective asthma prevention. Early-warning systems should provide timely information to healthcare providers and vulnerable populations regarding anticipated transboundary pollution episodes, enabling implementation of protective measures such as limiting outdoor exposure, optimizing controller medication use, and reducing strenuous physical activity during periods of elevated particulate concentrations.

Finally, future environmental policies should explicitly recognize asthma exacerbations as a sensitive and measurable health indicator of transboundary particulate matter exposure. Incorporating standardized respiratory health indicators into international air-quality governance would improve evaluation of policy effectiveness while strengthening collaboration among environmental scientists, atmospheric modelers, epidemiologists, clinicians, and public health authorities. Such an integrated approach is essential for reducing the growing global health burden associated with transboundary air pollution under changing climatic and environmental conditions.

7. Discussion and Conclusions

7.1 Discussion

This review synthesized multidisciplinary evidence from atmospheric sciences, environmental epidemiology, toxicology, respiratory medicine, and public health policy to examine the relationship between transboundary particulate matter (PM10 and PM2.5) and asthma exacerbations. The available evidence consistently indicates that long-range transported particulate matter constitutes a significant environmental health hazard capable of triggering acute respiratory events across geographically diverse populations. Although the adverse effects of ambient particulate matter have been extensively documented, this review demonstrates that transboundary pollution possesses distinct exposure characteristics that warrant separate consideration within both epidemiological research and environmental policy.

One of the principal findings emerging from the reviewed literature is that transboundary particulate matter differs substantially from locally generated pollution in terms of emission source, physicochemical composition, atmospheric aging, transport dynamics, and exposure duration. During long-range atmospheric transport, particulate matter undergoes continuous chemical transformation through oxidation, condensation, and interaction with gaseous pollutants and biological materials. Consequently, transported particles frequently contain complex mixtures of mineral dust, secondary aerosols, heavy metals, organic compounds, and microorganisms, potentially increasing their biological reactivity and respiratory toxicity. These findings suggest that evaluating particulate matter solely according to particle size may underestimate the importance of source-specific characteristics in determining health outcomes.

The epidemiological evidence reviewed further demonstrates consistent associations between transboundary pollution episodes and increased respiratory morbidity. Desert dust intrusions throughout the Mediterranean Basin, wildfire smoke transport across North America and Australia, and industrial emissions transported throughout East Asia have all been associated with increases in asthma exacerbations, emergency department visits, respiratory hospitalizations, and medication use. Importantly, many of these associations persist even after adjustment for locally generated particulate matter, indicating that transboundary pollution independently contributes to respiratory health risks. Collectively, these findings support the hypothesis that asthma exacerbations represent a sensitive clinical indicator of acute exposure to long-range transported particulate matter.

The biological evidence reviewed provides plausible mechanistic support for these epidemiological observations. Airway inflammation, oxidative stress, immune dysregulation, impaired mucociliary clearance, and epigenetic modifications represent interconnected biological pathways through which PM10 and PM2.5 contribute to asthma exacerbations. The convergence of mechanistic and epidemiological evidence strengthens causal inference and reinforces the importance of transboundary particulate matter as an independent determinant of respiratory disease.

Despite these advances, the current body of evidence remains subject to several important methodological limitations. Most epidemiological studies continue to rely primarily on ambient monitoring stations that cannot adequately distinguish locally generated pollution from long-range transported particulate matter. Although recent developments in atmospheric transport modeling, satellite remote sensing, and chemical source apportionment have substantially improved exposure assessment, these approaches remain insufficiently integrated into routine epidemiological investigations. Consequently, accurately quantifying the independent contribution of transboundary particulate matter to asthma morbidity remains challenging.

Another limitation concerns the geographical distribution of existing evidence. Most published studies originate from Europe, North America, and East Asia, whereas comparatively little research has been conducted in regions such as the Caucasus, Central Asia, the Middle East, and parts of Africa. These regions frequently experience recurrent desert dust intrusions and increasing wildfire activity but often lack comprehensive environmental monitoring infrastructure and long-term epidemiological surveillance. As a result, the global health burden attributable to transboundary particulate matter is likely underestimated.

The findings of this review also have important implications for environmental governance. Existing international agreements have achieved considerable progress in reducing atmospheric emissions; however, policy evaluation continues to focus predominantly on emission inventories rather than measurable health outcomes. Incorporating standardized indicators such as asthma-related emergency visits, hospital admissions, and respiratory morbidity into international air-quality governance would provide a more comprehensive assessment of policy effectiveness while strengthening collaboration between environmental agencies and public health institutions.

Future research should adopt increasingly multidisciplinary approaches that integrate atmospheric chemistry, satellite remote sensing, ground-based monitoring, epidemiological surveillance, and clinical outcome assessment. Longitudinal cohort studies examining repeated exposure to transboundary particulate matter, particularly among vulnerable populations, would substantially improve understanding of cumulative respiratory health effects. Furthermore, advances in chemical source apportionment and machine-learning–based exposure assessment offer promising opportunities for improving source attribution and strengthening causal inference in future epidemiological investigations.

7.2 Conclusions

Transboundary particulate matter pollution has emerged as a major environmental health challenge with significant implications for asthma morbidity worldwide. The evidence synthesized in this review demonstrates that long-range transported PM10 and PM2.5 originating from desert dust, wildfire smoke, industrial activities, transportation, and biomass burning contribute substantially to respiratory health risks beyond national borders. Through interconnected biological mechanisms involving airway inflammation, oxidative stress, immune dysregulation, impaired mucociliary clearance, and molecular alterations, these pollutants increase the frequency and severity of asthma exacerbations, particularly among children, older adults, and individuals with pre-existing respiratory disease.

Although considerable progress has been made in understanding the health consequences of ambient particulate matter, important knowledge gaps remain regarding the specific contribution of transboundary pollution. Limitations in exposure assessment, source attribution, and regional epidemiological evidence continue to constrain precise estimation of its public health burden. Addressing these challenges will require stronger integration of atmospheric transport modeling, satellite observations, chemical characterization of particulate matter, and comprehensive health surveillance systems.

From a policy perspective, effective mitigation of transboundary air pollution cannot be achieved through national interventions alone. Strengthening international cooperation, expanding regional monitoring networks, improving early-warning systems, and incorporating health-based indicators into international environmental agreements are essential for reducing the adverse effects of long-range transported particulate matter. As climate change continues to intensify desertification, wildfire activity, and atmospheric instability, the frequency and magnitude of transboundary pollution episodes are expected to increase. Consequently, recognizing transboundary particulate matter as a critical determinant of asthma exacerbations should become a priority within future environmental health research, international air-quality governance, and evidence-based public health policy.

Declarations

Ethics Approval and Consent to Participate

Ethical approval was not required for this study because it is based exclusively on previously published scientific literature, publicly available reports, and environmental monitoring data. No human participants, animals, or identifiable personal data were involved.

Consent for Publication

Not applicable.

Availability of Data and Materials

No new datasets were generated or analyzed during the current study. All information supporting the findings of this review is available in the cited references and publicly accessible reports.

Competing Interests

The authors declare that they have no competing financial or non-financial interests related to this work.

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Authors' Contributions

Nana Meparishvili: Conceptualization, literature review, data collection, manuscript drafting, and revision.

Robizon Tsiklauri: Study design, methodological guidance, critical revision of the manuscript, and supervision.

Stefanie Ebelt: Scientific supervision, interpretation of findings, critical review of the manuscript, and editorial revisions.

Elina Bakradze: Scientific consultation, validation of environmental health content, and manuscript review.

Marine Arabidze: Environmental monitoring expertise, interpretation of air quality data, and manuscript review.

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