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Review article

Influence of Outdoor Air Pollutants on Asthma: A Narrative Review

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ABSTRACT

Asthma is a chronic lung disease affecting individuals across all age groups, contributing to significant morbidity and mortality. Exposure to air pollutants is a major factor in both the development and exacerbation of asthma symptoms. This study reviewed the impact of key air pollutants, including nitrogen dioxide (NO_2), particulate matter with a diameter $\leq$2.5 μm ($PM_{2.5}$) or $\leq$10 μm (PM_{10}), and ozone (O_3), on asthma outcomes. Our analysis of 20 studies showed significant associations between exposure to these pollutants and increased asthma incidence and prevalence, particularly in children. Specifically, pollutants such as elemental carbon (EC), benzene, NO_2, PM_{10}, and sulfur dioxide (SO_2) were found to be significantly associated with asthma development in children, while NO_2 and $PM_{2.5}$ were linked to asthma exacerbations in both children and adults. Additionally, hospitalizations and emergency room visits were positively correlated with exposure to $PM_{2.5}$ and O_3 in both children and adults, and the elderly showed significant associations with O_3 exposure. Although asthma-related mortality was not directly linked to specific pollutants, a few studies indicated a broader association between exposure to pollutants like NO_2 and $PM_{2.5}$ and increased overall mortality. These findings highlight the importance of reducing exposure to outdoor air pollutants to mitigate asthma risk and improve public health outcomes, particularly in vulnerable populations like children and the elderly.

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Influencia de los contaminantes atmosféricos exteriores en el asma: una revisión narrativa

Palabras clave:
Asma
Contaminación del aire
Asma infantil
Exacerbación del asma
Sibilancias
Desarrollo del asma

RESUMEN

El asma es una enfermedad pulmonar crónica que afecta a personas de todas las edades, contribuyendo a una morbimortalidad significativa. La exposición a contaminantes atmosféricos es un factor clave tanto en el desarrollo como en la exacerbación de los síntomas del asma. Este estudio revisa el impacto de los principales contaminantes del aire, incluyendo dióxido de nitrógeno (NO_2), material particulado con un diámetro $\leq$ 2,5 μm ($PM_{2.5}$) o $\leq$ 10 μm (PM_{10}), y ozono (O_3), sobre los resultados del asma. Nuestro análisis de 20 estudios muestra asociaciones significativas entre la exposición a estos contaminantes y un aumento en la incidencia y prevalencia del asma, especialmente en niños. En particular, contaminantes como el carbono elemental (EC), el benceno, el NO_2, el PM_{10} y el dióxido de azufre (SO_2) se asociaron significativamente con el desarrollo del asma en niños, mientras que el NO_2 y el $PM_{2.5}$ se vinculaban con exacerbaciones del asma tanto en niños como en adultos. Además, se encontraron correlaciones positivas

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entre las hospitalizaciones y las visitas a urgencias con la exposición a $PM_{2,5}$ y O_3 en niños y adultos, y los ancianos mostraron asociaciones significativas con la exposición a O_3. Aunque la mortalidad relacionada con el asma no se vinculó directamente a contaminantes específicos, algunos estudios indicaron una asociación más amplia entre la exposición a contaminantes como NO_2 y $PM_{2,5}$ y un aumento en la mortalidad general. Estos hallazgos resaltan la importancia de reducir la exposición a contaminantes atmosféricos exteriores para mitigar el riesgo de asma y mejorar los resultados en salud pública, especialmente en poblaciones vulnerables como niños y ancianos.

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Introduction

Asthma is a chronic lung disease characterized by inflammation and narrowing of the airways, usually resulting from an allergic reaction or hypersensitivity. It is a global health issue that affects people of all ages representing a significant cause of mortality and morbidity. According to the Global Burden of Diseases, Injuries, and Risk Factors (GBD) study, approximately 260 million people suffer from asthma worldwide, with around 436,000 deaths attributed to asthma in 2021.[1]

The main clinical manifestations of asthma include wheezing, coughing, chest tightness, and shortness of breath, often triggered by a range of factors such as allergens, respiratory infections, exercise, or environmental pollutants. Asthma disease course and prognosis vary widely, from asthma symptoms resolving spontaneously (or in response to medication) to irreversible airway obstruction.[2] In addition, patients may suffer acute episodes of asthma exacerbations, which worsen quality of life and may be life-threatening.[3] External factors that increase the risk of exacerbation include, among others, viral infections, smoking and air.[4] In fact, short-term exposure to air pollutants is closely related not only to asthma, but also to other respiratory conditions such as chronic obstructive pulmonary disease (COPD), shortness of breath and wheezing, entailing high morbidity and mortality burden.[5]

Air pollutants may have a natural source (wildfire, volcanos, etc.) or an anthropogenic one (traffic and industrialization-related pollution). The major health-damaging air pollutants include particles of solid or liquid matter suspended in the air, known as particulate matter (PM), and gases such as ozone (O_3), nitrogen dioxide (NO_2) and sulfur dioxide (SO_2), among others. Particulate matter are commonly used for determining air quality and classified according to its diameters as $PM_{2.5}$ (particles with a diameter $\leq 2.5\,\mu m$), PM_{10} (particles with a diameter $\leq 10\,\mu m$) and ultrafine particles (UFP) (particles with a diameter $< 0.1\,\mu m$). Furthermore, a mix of pollutants with higher impact on respiratory system are those derived from traffic, the so-called traffic-related air pollution (TRAP).[5,6] Although there has been improvement in air quality over recent decades, more than 90% of the global population lives in areas exceeding the $PM_{2.5}$ air quality guidelines.[7,8]

There is growing body of evidence linking air pollution with asthma development and exacerbations, especially in children. In fact, asthma is the most prevalent chronic disease among children.[9] Studies have also reported that prenatal exposure to outdoor air pollution may increase the risk of asthma and wheezing in children later in life.[9] This impact of air pollution on asthma may be partly explained by the direct irritant and inflammatory effects of air pollutants on airways and airway hyper-responsiveness, both typical asthma features.[10] The level of exposure to pollutants could have an impact on asthma development and exacerbations, since the effects of air pollution exposure may accumulate over time.[11] Several meta-analyses associate outdoor air pollutants with negative impact on asthma outcomes: higher incidence and prevalence, worsening of asthma symptoms, and more hospitalizations and exacerbations.[12–17] Besides its clinical impact, asthma also represents an important socioeconomic burden, with high direct and indirect health-related costs arising from the management and the associated disability.[18,19]

Although the relationship between air quality and asthma development, exacerbations, and mortality has been previously studied, the specific contribution of each pollutant to individual health outcomes remains unclear. Understanding the complex relationship between asthma and various air pollutants is crucial for improving patients' quality of life and addressing public health challenges effectively. Therefore, the objective of this narrative review was to evaluate the evidence on the association between different ambient air pollutants and the incidence, exacerbation, and mortality of asthma across various age groups.

Material and methods

PECO question

The aim of this study was to synthesize information on outdoor air pollutants and their impact on asthma following the PECO (Population, Exposure, Comparison, Outcome) approach. The target population included individuals of all ages diagnosed with asthma. Exposure was defined by the presence of common environmental air pollutants (specific details in Supplementary Table 1). In terms of comparison, scenarios with significant environmental air pollution exposure were contrasted against those without such exposure. Finally, the outcomes measured encompassed the prevalence and incidence of asthma and other respiratory diseases, the asthma development, exacerbations of asthma or other respiratory conditions, including hospitalizations and emergency room (ER) visits, and all-cause mortality.

This review aimed to evaluate the evidence supporting an association between air pollution and the asthma development in the general population, as well as its association with the exacerbation of asthma symptoms and asthma-related mortality in affected individuals.

Search strategy

A systematic search of all published studies from April 2010 to November 2023 was performed in PubMed and The Cochrane Library. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines were followed.[20] In the search, key words, medical subject headings (MeSH) titles, and free-text terms for the following concepts: "pollution AND asthma AND (incidence OR mortality OR exacerbation)" were used.

Inclusion and exclusion criteria

In this review only published systematic reviews or meta-analysis providing summarized quantitative data about the impact of air pollutants on the development or exacerbation of asthma were included. Only publications in English or Spanish with accessible abstracts were considered.

Study selection

After an initial screening by the scientific committee, potentially eligible studies were included. Then, the titles and the abstracts of all the identified studies were assessed for their eligibility, and articles satisfying the aforementioned inclusion criteria were selected. Two primary reviewers (C.A. and I.M.) thoroughly read the papers to accurately discern whether they met the inclusion/exclusion criteria and were relevant for the review.

Data extraction

Subsequently, data from the selected articles were extracted by two independent reviewers (C.A and I.M.) using a standardized data collection sheet. The data extraction form was created *ad hoc* for this project (Supplementary Table 2).

Data analysis

All articles that incorporated statistical values from a diverse array of studies were included. In the present study, a vote-counting systematic approach was adopted, where the *p*-values or statistical outcomes from comparisons of multiple studies within a single review, based on relative risk (RR) or odds ratio (OR) statistics were recorded. These statistical data points served as the primary units of analysis, each representing an individual item or discrete entry in the data extraction table. Each item captures the strength of evidence for the specific comparison under investigation.

When the data extracted were not providing a specific significance *p*-value, but RR or OR together with an associated confidence interval was given, these were converted into approximate *p*-values based on the confidence provided (commonly 95%, meaning a $p < 0.05$) to indicate the significance.

The populations from each study were grouped into predetermined age intervals: children (0–18 years), adults (19–64 years), and elderly individuals (> 65 years). Additionally, the results were also analyzed in the whole population (without age-grouping). Details of pollutants and pollutants thresholds were also collected although they were considered as the same pollutant (Supplementary Table 1).

The outcomes measured in relation to asthma collected are shown in Supplementary Table 3. The outcomes were classified from the most general to the most specific to facilitate subsequent sub-analysis.

All these outcomes and sub-outcomes were classified into three broad categories: incidence of asthma, asthma exacerbation and mortality. The items were classified into two categories using the vote-counting approach, "statistically significant" (based on a *p*-value < 0.05 or a 95% confidence interval 95% not capturing the neutral value) and "non-statistically significant" (based on a *p*-value > 0.05 or a 95% confidence interval capturing the neutral value). Thereafter, these sub-analyses were rigorously scrutinized to explore potential influential factors affecting asthma.

Finally, these multiple evaluations were conducted for each age group (children, adults, elderly), as well as for unspecified age groups, and for the overall population.

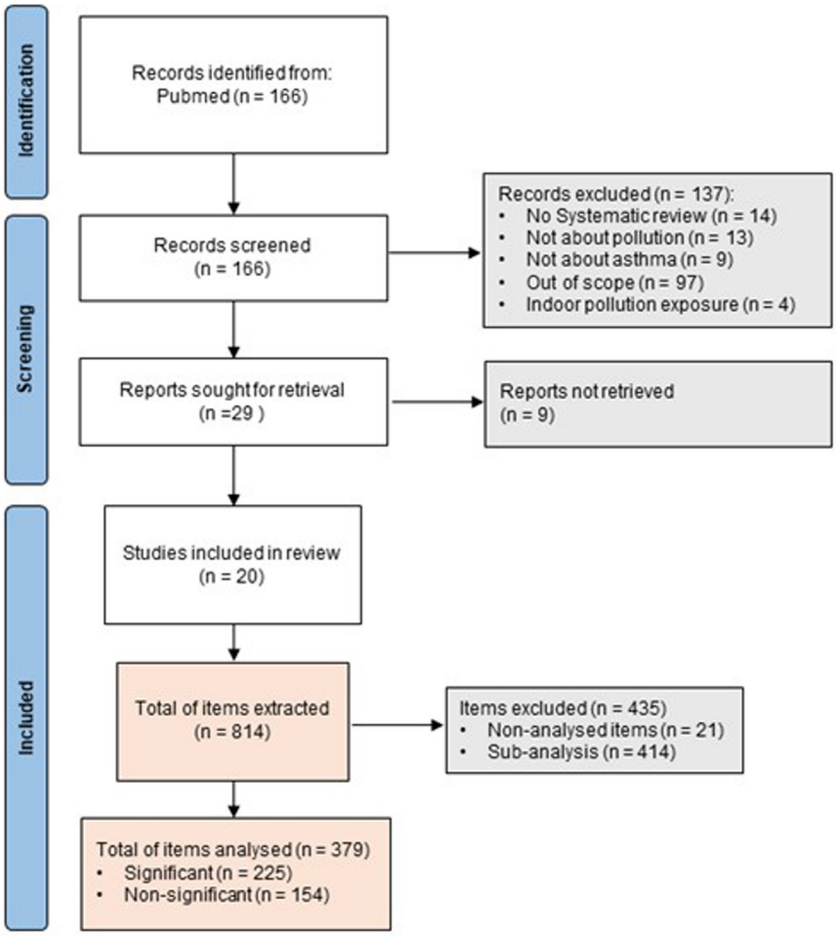


Fig. 1. Flow diagram of selection of the publications, according to PRISMA.

Table 1
Articles included in the data extraction step for the review.

Reference	Study design	Geographical area	No. of studies encompassed	Age group	Number of analyzed items
21	Systematic review	Europe	60	Children	12
14	Meta-analysis	Worldwide	19	Children	17
22	Meta-analysis	Worldwide	110	Any age	5
13	Meta-analysis		19	Children	7
23	Meta-analysis	Worldwide	87	Children, adults and elderly	35
24	Meta-analysis		16	Children and adults	4
25	Meta-analysis	Worldwide	30	Children, adults and elderly	66
26	Meta-analysis		41	Children	10
27	Review	Worldwide	22	Children	12
28	Systematic review		18	Children	9
29	Meta-analysis	East Asia	16	Children	5
30	Meta-analysis	Worldwide	8	Children	6
31	Meta-analysis	Worldwide	47	Children, adults and elderly	24
32	Systematic review	Worldwide	4	Any age	1
33	Meta-analysis	Latin and Central America	27	Children	10
34	Meta-analysis	Worldwide	67	Any age	6
35	Meta-analysis	Europe and North America	6	Children	5
17	Meta-analysis	Worldwide	84	Children and adults	106
36	Systematic review	Worldwide	343	Children and adults	32
9	Meta-analysis		13	Children	7
Total			1037		379

Results

Characteristics of the included studies

The systematic search retrieved 166 potential studies. After an initial screening of title and abstract, 137 records were excluded. The remaining 29 articles were fully assessed for eligibility through a complete reading of the text, and among these, 9 articles were excluded. Finally, 20 studies were included in the review (Fig. 1).[9,13,14,17,21–36] The list of all excluded studies along with the reasons for exclusion is included as Supplementary Table 4.

Information of the selected publications regarding the number of included studies, the number of analyzed items and age group considered is summarized in Table 1. Overall, the 20 articles encompassed 1037 studies and 814 items of information, but only 379 were considered in this analysis. The remaining items were excluded because they were not the aim of this study, did not met the PECO question or were sub-analyses exploring external factors (Supplementary Table 5).

Development of asthma

Children

The association between air pollutants and asthma development in children was analyzed for each outcome and pollutant (Table 2). Statistically significant associations were identified between the asthma development in children and exposure to the following air pollutants: elemental carbon (EC), benzene, nitrogen dioxide (NO_2), nitrogen oxides (NO_x), particulate matter $\leq$10 μm (PM_{10}), particulate matter $\leq$2.5 μm ($PM_{2.5}$) and sulfur dioxide (SO_2). In contrast, no associations were found between carbon monoxide (CO) and ozone (O_3) and the asthma development. Additionally, significant associations were noted between asthma prevalence and industrialization-related pollution (IRP), NO_2, traffic-related air pollution (TRAP), SO_2, O_3, and PM_{10}.

When considering asthma incidence, positive associations were found between EC and $PM_{2.5}$, but no association was reported between NO_2 and asthma incidence in children. Finally, associations were found between the development of asthma symptoms and NO_2, PM_{10} and total volatile organic compounds (TVOC), but no association was found with ultrafine particles (UFP, particles <0.1 μm). Specifically, NO_2 exposure was positively associated to the development of wheezing in children, although no associations were found with polycyclic aromatic hydrocarbons (PAH), PM_{10} and $PM_{2.5}$ (Table 2).

Adults

In this population, only NO_2 showed statistically significant association with asthma incidence in one systematic review. Moreover, no association was found between asthma prevalence and $PM_{2.5}$ in one study (Table 3).

Elderly

No information about air pollutants and asthma incidence or development in the elderly was reported in either study (Table 4).

Asthma and mortality

Subsequently, an analysis was conducted on the association between air pollutants and respiratory mortality across various age groups. However, none of the studies reviewed provided data on asthma-specific respiratory mortality across these age categories. Nonetheless, within the studies that did not specify age ranges, two review articles identified a significant association between exposure to certain pollutants – including elemental EC, NO_2, and $PM_{2.5}$ – and an increase in overall mortality (irrespective of the cause of death) (Supplementary Table 6).

Asthma morbidity and exacerbation

Children

When evaluating asthma morbidity in children, statistically significant associations between air quality index (AQI), CO, NO_2, O_3, PM_{10}, $PM_{2.5}$, SO_2 and UFP and exacerbations of asthma were identified. Similarly, statistically significant associations between CO, NO_2, O_3, particulate matter $\leq$1 μm (PM_1), PM_{10}, $PM_{2.5}$, SO_2 and UFP and hospitalizations. Additionally, statistically significant associations between NO_2, $PM_{2.5}$ and UFP exposure and emergency room (ER) visits were observed.

Finally, regarding respiratory infection incidence, a positive association with NO_2 was found, but no association between EC and respiratory infection incidence was observed (Table 2).

Adults

Regarding asthma morbidity in adults, $PM_{2.5}$ and O_3 showed statistically significant associations with asthma exacerbation, while

Table 2
Association between air pollutants and asthma development and exacerbation in children. Vote-counting of the number of statistically significant/not statistically significant items are shown for each outcome and pollutant.

Pollutants	AQI	Benzene	CO	EC	IRP	NO_2	NO_x	O_3	PAH	PM_1	PM_{10}	$PM_{2.5}$	SO_2	TRAP	TVOC	UFP	PM_{10}, NO_2, SO_2, O_3	Total
Development of asthma																		
Asthma incidence	–	–	–	1/1 [13]/[36]	–	–/2 –/[13,36]	–	–	–	–	–	1/1 [13]/[36]	–	–		–	–	2/4
Asthma prevalence		–	–	–/2 –/[36]	1/– [29]/–	2/– [36]/–	–	–	–	–	–	–/1 –/[36]	–	1/– [29]/–		–	3/– [29]/–	7/3
Development of asthma	–	1/– [33]/–	–/1 –/[28]	2/– [26]/–	–	7/1 [26,28,33]/[9]	1/1 (Khreis et al., 2017)(Khreis et al., 2017)/(Khreis et al., 2017)(Khreis et al., 2017)	–/1 –/(Hehua et al., 2017)(Hehua et al., 2017)	–	–	3/1 (Hehua et al., 2017; Khreis et al., 2017)(Hehua et al., 2017; Khreis et al., 2017)/(Hua et al., 2023)(Hua et al., 2023)	4/4 (Han et al., 2021; Khreis et al., 2017)(Han et al., 2021; Khreis et al., 2017)/(Han et al., 2021; Hehua et al., 2017; Hua et al., 2023)(Han et al., 2021; Hehua et al., 2017; Hua et al., 2023)	1/1 (Hua et al., 2023)(Hua et al., 2023)/(Hehua et al., 2017)(Hehua et al., 2017)	–		–	–	19/10
Development of asthma symptoms	–	–	–	–	–	4/2 (Weinmayr et al., 2010)(Weinmayr et al., 2010)/(Weinmayr et al., 2010)(Weinmayr et al., 2010)	–	–	–	–	5/1 (Weinmayr et al., 2010)(Weinmayr et al., 2010)/(Weinmayr et al., 2010)(Weinmayr et al., 2010)	–	–	–	1/– (Han et al., 2021)(Han et al., 2021)/–	–/1 –/(Q. Li et al., 2019)(Q. Li et al., 2019)	–	10/4
Development of wheezing	–	–	–	–	–	1/1 (Hehua et al., 2017)(Hehua et al., 2017)/(Hua et al., 2023)(Hua et al., 2023)	–	–	–/1 –/(Hehua et al., 2017)(Hehua et al., 2017)	–	–/1 –/(Hua et al., 2023)(Hua et al., 2023)	–/2 –/(Hehua et al., 2017; Hua et al., 2023)(Hehua et al., 2017; Hua et al., 2023)	–	–		–	–	1/5
Total	–	1/–	–/1	3/3	1/–	14/6	1/1	–/1	–/1	–	8/3	5/8	1/1	1/–	1/–	–/1	3/–	39/26
Asthma morbidity and mortality																		
Exacerbation of asthma	2/– (Huang et al., 2022)(Huang et al., 2022)/–	–	2/1 (Huang et al., 2022)(Huang et al., 2022)/(Orellano et al., 2017)(Orellano et al., 2017)	–	–	2/1 (Huang et al., 2022; Orellano et al., 2017)(Huang et al., 2022; Orellano et al., 2017)/(Huang et al., 2022)(Huang et al., 2022)	–	2/4 (X. Li et al., 2019)(X. Li et al., 2019)/(Huang et al., 2022; X. Li et al., 2019; Orellano et al., 2017)(Huang et al., 2022; X. Li et al., 2019; Orellano et al., 2017)(Huang et al., 2022; X. Li et al., 2019; Orellano et al., 2017)	–	–	2/1 (Huang et al., 2022)(Huang et al., 2022)(Huang et al., 2022)/(Orellano et al., 2017)(Orellano et al., 2017)(Orellano et al., 2017)	3/– (Huang et al., 2022; Orellano et al., 2017)(Huang et al., 2022; Orellano et al., 2017)(Huang et al., 2022; Orellano et al., 2017)/–	3/– (Huang et al., 2022; Orellano et al., 2017)(Huang et al., 2022; Orellano et al., 2017)(Huang et al., 2022; Orellano et al., 2017)/–	–		2/1 (Q. Li et al., 2019)(Q. Li et al., 2019)(Q. Li et al., 2019)/(Q. Li et al., 2019)(Q. Li et al., 2019)(Q. Li et al., 2019)	–	18/8

Table 2
(*Continued*)

Pollutants	AQI	Benzene	CO	EC	IRP	NO_2	NO_x	O_3	PAH	PM_1	PM_{10}	$PM_{2.5}$	SO_2	TRAP	TVOC	UFP	PM_{10}, NO_2, SO_2, O_3	Total
ER visits	–	–	–	–	–	1/– (Zhang et al., 2016)(Zhang et al., 2016)(Zhang et al., 2016)/–	–	–	–	–	–	2/– (Fan et al., 2016; Zhang et al., 2016)(Fan et al., 2016; Zhang et al., 2016)(Fan et al., 2016; Zhang et al., 2016)/–	–	–		1/– (Q. Li et al., 2019)(Q. Li et al., 2019)(Q. Li et al., 2019)/–	–	4/–
Hospitalizations	–	–	3/– (Zhang et al., 2016; Zheng et al., 2015)(Zhang et al., 2016; Zheng et al., 2015)(Zhang et al., 2016; Zheng et al., 2015)/–	–	–	3/– (Zhang et al., 2016; Zheng et al., 2015)(Zhang et al., 2016; Zheng et al., 2015)(Zhang et al., 2016; Zheng et al., 2015)/–	–	3/– (Zhang et al., 2016; Zheng et al., 2015)(Zhang et al., 2016; Zheng et al., 2015)(Zhang et al., 2016; Zheng et al., 2015)/–	–	1/– (Hu et al., 2022)(Hu et al., 2022)(Hu et al., 2022)/–	2/1 (Zhang et al., 2016; Zheng et al., 2015)(Zhang et al., 2016; Zheng et al., 2015)(Zhang et al., 2016; Zheng et al., 2015)/(Zhang et al., 2016)(Zhang et al., 2016)(Zhang et al., 2016)	2/1 (Zhang et al., 2016; Zheng et al., 2015)(Zhang et al., 2016; Zheng et al., 2015)(Zhang et al., 2016; Zheng et al., 2015)/(Zhang et al., 2016)(Zhang et al., 2016)(Zhang et al., 2016)	2/1 (Zhang et al., 2016; Zheng et al., 2015)(Zhang et al., 2016; Zheng et al., 2015)(Zhang et al., 2016; Zheng et al., 2015)/(Zhang et al., 2016)(Zhang et al., 2016)	–		1/– (Q. Li et al., 2019)(Q. Li et al., 2019)	–	17/3
Respiratory infection incidence	–	–	–	–/1 –/(Boogaard et al., 2022)(Boogaard et al., 2022)	–	1/– (Boogaard et al., 2022)(Boogaard et al., 2022)/–	–	–	–	–	–	–	–	–		–	–	1/1
Sensitization to allergen	–	–	–	–	–	–/2 –/(Bowatte et al., 2015)(Bowatte et al., 2015)	–	–	–	–	–	–/2 –/(Bowatte et al., 2015)(Bowatte et al., 2015)	–	–		–	–	–/4
Total	2/–	–	5/1	–/1	–	7/3	–	5/5	–	1/–	4/2	7/3	5/1	–		4/1	–	40/16

AQI: air quality index; EC: elemental carbon; ER: emergency room; IRP: industrial-related pollution; PAH: polycyclic aromatic hydrocarbons; PM: particulate matter; TRAP: traffic-related pollution; TVOC: total volatile organic compounds; UFP: ultrafine particles.

Table 3
Association between air pollutants and asthma development and exacerbation in adults. Vote-counting of the number of statistically significant/not statistically significant items are shown for each outcome and pollutant.

Pollutants	CO	NO_2	O_3	PM_{10}	$PM_{2.5}$	SO_2	Total
Development of asthma							
Asthma incidence	–	1/– (Boogaard et al., 2022)(Boogaard et al., 2022)/–	–	–	–	–	1/–
Asthma prevalence	–	–/2 –/(Boogaard et al., 2022)(Boogaard et al., 2022)	–	–	–/1 –/(Boogaard et al., 2022)(Boogaard et al., 2022)	–	–/3
Total	–	1/2	–	–	–/1	–	1/3
Asthma morbidity and mortality							
Exacerbation of asthma	–/2 –/(Huang et al., 2022)(Huang et al., 2022)	1/1 (Huang et al., 2022)(Huang et al., 2022)/(Huang et al., 2022)(Huang et al., 2022)	3/2 (Huang et al., 2022; X. Li et al., 2019)(Huang et al., 2022; X. Li et al., 2019)(Huang et al., 2022; X. Li et al., 2019)/(Huang et al., 2022; X. Li et al., 2019)(Huang et al., 2022; X. Li et al., 2019)(Huang et al., 2022; X. Li et al., 2019)(Huang et al., 2022; X. Li et al., 2019)	1/1 (Huang et al., 2022)(Huang et al., 2022)(Huang et al., 2022)(Huang et al., 2022)/(Huang et al., 2022)(Huang et al., 2022)(Huang et al., 2022)(Huang et al., 2022)	2/– (Huang et al., 2022)(Huang et al., 2022)(Huang et al., 2022)(Huang et al., 2022)/–	–/2 –/(Huang et al., 2022)(Huang et al., 2022)(Huang et al., 2022)(Huang et al., 2022)	7/8
ER visits	–	–/1 –/(Zhang et al., 2016)(Zhang et al., 2016)(Zhang et al., 2016)(Zhang et al., 2016)	–/1 –/(Zhang et al., 2016)(Zhang et al., 2016)(Zhang et al., 2016)(Zhang et al., 2016)	–/1 –/(Zhang et al., 2016)(Zhang et al., 2016)(Zhang et al., 2016)(Zhang et al., 2016)	1/– (Fan et al., 2016)(Fan et al., 2016)(Fan et al., 2016)(Fan et al., 2016)/–	–/1 –/(Zhang et al., 2016)(Zhang et al., 2016)(Zhang et al., 2016)(Zhang et al., 2016)	1/4
Hospitalizations	–/1 –/(Zheng et al., 2015)(Zheng et al., 2015)(Zheng et al., 2015)(Zheng et al., 2015)	1/1 (Zheng et al., 2015)(Zheng et al., 2015)(Zheng et al., 2015)(Zheng et al., 2015)/(Zhang et al., 2016)(Zhang et al., 2016)(Zhang et al., 2016)(Zhang et al., 2016)	1/1 (Zheng et al., 2015)(Zheng et al., 2015)(Zheng et al., 2015)(Zheng et al., 2015)/(Zhang et al., 2016)(Zhang et al., 2016)(Zhang et al., 2016)(Zhang et al., 2016)	1/1 (Zheng et al., 2015)(Zheng et al., 2015)(Zheng et al., 2015)(Zheng et al., 2015)/(Zhang et al., 2016)(Zhang et al., 2016)(Zhang et al., 2016)(Zhang et al., 2016)	1/- (Zheng et al., 2015)(Zheng et al., 2015)(Zheng et al., 2015)(Zheng et al., 2015)/–	–/2 –/(Zhang et al., 2016; Zheng et al., 2015)(Zhang et al., 2016; Zheng et al., 2015)(Zhang et al., 2016; Zheng et al., 2015)(Zhang et al., 2016; Zheng et al., 2015)	4/6
Total	–/3	2/3	4/4	2/3	4/–	–/5	12/18

ER: emergency room; PM: particulate matter.

no associations were reported between SO_2 and CO and exacerbations (Table 3).

Regarding ER visits, only $PM_{2.5}$ showed a positive association among adults, while no association between ER visits and NO_2, O_3, PM_{10}, and SO_2 were observed. Finally, a statistically significant association between NO_2, O_3, $PM_{2.5}$, PM_{10} and hospitalizations was identified (Table 3).

Elderly

The only significant association between air pollutants and asthma exacerbation was found for O_3 in one systematic review.[31] Additionally, CO, NO_2, O_3, PM_{10}, $PM_{2.5}$ and SO_2 showed statistically significant associations with hospitalization related to asthma exacerbations (Table 4).

Table 4
Association between air pollutants and asthma development and exacerbation in the elderly. Vote-counting of the number of statistically significant/not statistically significant items are shown for each outcome and pollutant.

Pollutants	CO	NO_2	O_3	PM_{10}	$PM_{2.5}$	SO_2	Total
Asthma morbidity and mortality							
Exacerbation of asthma	–	–	3/– (X. Li et al., 2019)(X. Li et al., 2019)(X. Li et al., 2019)(X. Li et al., 2019)/–	–	–	–	3/–
Hospitalizations	1/– (Zheng et al., 2015)(Zheng et al., 2015)(Zheng et al., 2015)(Zheng et al., 2015)/–	4/– (Zhang et al., 2016; Zheng et al., 2015)(Zhang et al., 2016; Zheng et al., 2015)(Zhang et al., 2016; Zheng et al., 2015)/–	1/2 (Zheng et al., 2015)(Zheng et al., 2015)(Zheng et al., 2015)(Zheng et al., 2015)/(Zhang et al., 2016)(Zhang et al., 2016)(Zhang et al., 2016)(Zhang et al., 2016)	3/1 (Zhang et al., 2016)(Zhang et al., 2016)(Zhang et al., 2016)(Zhang et al., 2016)/(Zhang et al., 2016)(Zhang et al., 2016)(Zhang et al., 2016)(Zhang et al., 2016)	1/2 (Zheng et al., 2015)(Zheng et al., 2015)(Zheng et al., 2015)(Zheng et al., 2015)/(Zhang et al., 2016)(Zhang et al., 2016)(Zhang et al., 2016)(Zhang et al., 2016)	1/2 (Zheng et al., 2015)(Zheng et al., 2015)(Zheng et al., 2015)(Zheng et al., 2015)/(Zhang et al., 2016)(Zhang et al., 2016)(Zhang et al., 2016)(Zhang et al., 2016)	11/7
Total	1/–	4/–	4/2	3/1	1/2	1/2	14/7

PM: particulate matter.

Additionally, the results were also analyzed in the overall population. Statistically significant associations between ER visits and CO, NO_2, O_3, PM_{10}, $PM_{2.5}$ and SO_2 were observed. In a similar way, it was reported statistically significant associations between asthma exacerbation and AQI, CO, NO_2, O_3, PM_1, PM_{10}, $PM_{2.5}$. Finally, positive associations between asthma-related hospitalizations and AQI, CO, NO_2, O_3, PM_{10}, $PM_{2.5}$, SO_2 were observed (Supplementary Table 6).

Discussion

This narrative review synthesizes 379 data points from 20 studies published between April 2010 and November 2023. Each data point corresponds to a statistical measure representing the association between specific air pollutants and asthma-related outcomes. We conducted both overall and age-specific analyses to provide new insights into the association between outdoor air pollutants and the risk of developing asthma, as well as asthma-related morbidity and mortality.

This review strengthens the evidence for a positive association between exposure to pollutants – including elemental carbon (EC), benzene, nitrogen dioxide (NO_2), nitrogen oxides (NO_x), coarse (PM_{10}) and particulate matter $\leq$2.5 μm ($PM_{2.5}$), and sulfur dioxide (SO_2) – and asthma development in children. Previous studies have also highlighted the negative impact of air pollution on asthma onset and clinical outcomes in both adults and children.[6] According to the 2024 GINA Report,[4] up to 13% of global childhood asthma incidence could be attributable to traffic-related air pollution (TRAP), which primarily consists of particulate matter (PM) known to have harmful effects on the respiratory system.[4] In contrast, no significant associations were found between specific air pollutants and asthma development in adults and the elderly. Children are particularly vulnerable to air pollutants due to their underdeveloped respiratory and immune systems, higher ventilation rates, and reduced efficiency in filtering inhaled particles.[26,37,38] Therefore, reducing exposure to pollutants during early life stages is crucial.

Our findings reinforce evidence for a positive association between air quality index (AQI) and components such as carbon monoxide (CO), NO_2, ozone (O_3), PM_{10}, $PM_{2.5}$, SO_2, and ultrafine particles (UFP)with asthma exacerbations in children; $PM_{2.5}$ and O_3 with exacerbations in adults; and O_3 with exacerbations in the elderly. Although the exact mechanisms by which air pollution aggravates asthma are not fully understood, pollutants are known to induce oxidative stress, sensitize individuals to aeroallergens, and promote airway inflammation, all of which can trigger asthma exacerbations.[27,39] Specifically, exposure to PM, O_3, NO_2, and SO_2 has been shown to cause airway inflammation and hyperresponsiveness.[10] These mechanisms may lead to increased exacerbations, worse clinical outcomes, and a higher healthcare burden. Our study further supports the association between $PM_{2.5}$ and increased hospitalizations and ER visits across all age groups. Similarly, Anenberg et al. estimated that O_3 and $PM_{2.5}$ were responsible for 9–23 million and 5–10 million annual asthma-related ER visits globally in 2015, representing 8–20% and 4–9% of total visits, respectively.[40]

Although asthma was responsible for approximately 436,000 deaths in 2021, its relationship with mortality is complicated by the presence of comorbidities, making it difficult to establish direct causality. Due to the lack of studies specifically investigating the link between air pollution and asthma-related mortality, current data are insufficient to provide a clear explanation for asthma-attributed deaths. In this review, two studies demonstrated a significant association between EC, NO_2, and $PM_{2.5}$ and mortality in the general population.[22,36] Another study reported a 2.8% increase in PM-related mortality for every 10 $\mu g/m^3$ rise in $PM_{2.5}$ exposure.[41] Naess et al. found that chronic exposure to NO_2, PM_{10}, and $PM_{2.5}$ was consistently linked to an increased risk of mortality from all causes, with the effects being more pronounced at NO_2 levels above 40 $\mu g/m^3$ in younger populations and in the 20–60 $\mu g/m^3$ range for older individuals.[42] Although asthma is most prevalent in children, the highest asthma-related mortality rates are seen in the elderly.[1]

Notably, between 1990 and 2015, asthma-related mortality decreased by 58.5%, though reductions in years lived with disability (YLDs) were far smaller.[1] This suggests that interventions have reduced asthma's fatality, but not its incidence, making it more of a

chronic condition. Asthma can be effectively managed with preventive treatment and rescue medications during flare-ups. In low- and middle-income countries, where access to healthcare and treatments may be limited, asthma-related mortality rates remain high, underscoring the impact of sociodemographic factors on asthma mortality.[1]

Reducing exposure to outdoor pollutants is critical for improving asthma incidence and morbidity. This requires policy actions and a strong commitment to reduction of emissions. Emissions from human activities account for approximately 37% of the impact of O_3-related respiratory effects and 73% of the contribution to $PM_{2.5}$-related respiratory effects, including exacerbation of asthma symptoms and increased asthma-related morbidity.[40] Therefore, reducing outdoor pollution should be a priority for minimizing asthma risk factors and associated burdens. The improvements in air quality observed during COVID-19 lockdowns, which coincided with a significant reduction in acute asthma exacerbations, further support this need, although the effect may have been temporary.[43]

Moreover, since daily exposure to multiple pollutants has been associated with increased use of asthma rescue medication, reliable air pollution forecasts could serve as valuable predictors of exacerbations.[44]

Future studies

The association between air pollution and asthma has been extensively studied, but its significance compared to other causes of asthma exacerbation, such as viral infections, requires further investigation. Additionally, a more accurate understanding of PM composition could help clarify its effects on the body and, consequently, its role in asthma development and exacerbation. Therefore, continued research in this area is essential. Lastly, studies examining the use of digital systems to monitor the impact of specific pollutants on asthma outcomes are still limited. These systems could prove valuable not only in predicting a patient's need for additional resources, such as medication, but also in anticipating the demands on healthcare facilities.

Strengths and limitations

This study has several strengths, such as the inclusion of data from meta-analyses and derived from a systematic literature search. Meta-analyses provide more robust data than other sources of information implying higher quality data. Furthermore, two independent reviewers examined the eligible studies based on the inclusion and exclusion criteria, and data extraction was performed using a standardized form previously and *ad hoc* defined for this project.

A notable limitation of this study lies in the heterogeneity of the systematic reviews included. Data included was heterogeneous and proceeded from different regions all over the world. The geographical characteristics, weather, climate and industrialization of each region also affect air quality and its potential impact on the results cannot be ruled out. Additionally, while the study encompasses a comprehensive set of literature, it acknowledges the absence of data from densely populated regions such as India and Africa, which limits the applicability of the findings to these areas.

Furthermore, it is important to highlight that potential overlaps between studies included in different meta-analyses were not excluded in this review, which could lead to some degree of overestimation in the results. However, based on the nature of the studies reviewed, the magnitude of this potential overestimation is not anticipated to be substantial.

Lastly, the systematic reviews analyzed may not have accounted for all potential confounding factors that may have had an influence on asthma incidence and exacerbation outcomes, such as socioeconomic factors, race or occupational risks.

Conclusions

In conclusion, a significant association between air pollutants and asthma development was observed in children but not in adults. Additionally, air pollutants were associated with increased morbidity (such as exacerbations and hospitalizations) in both children and adults, and with increased mortality among children and the elderly. These findings underscore the serious health impacts of air pollution and emphasize the need for policymakers to prioritize environmental policies aimed at preventing asthma development and mitigating related health outcomes.

Further cumulative meta-analyses are needed to clarify the specific associations between air pollutants and distinct asthma-related outcomes to enable more reliable conclusions.

Declaration of generative AI and AI-assisted technologies in the writing process

No generative artificial intelligence (AI) or AI-assisted technologies were used in the writing, editing, or creation of this manuscript. All content was produced by the authors.

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Authors' contributions

All authors made substantial contributions to the conception and design of the work as well as the acquisition, analysis and interpretation of the data. All authors contributed to the drafting of the work and undertook critical review for important intellectual content and approved the final version to be published. All authors agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

Conflicts of interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

DE has received fees as a speaker from AstraZeneca. VP in the last three years received honoraria for speaking at sponsored meetings from AstraZeneca, Boehringer-Ingelheim, Chiesi, Gebro, GSK, Luminova-Medwell and Sanofi, received help assistance to meeting travel from AstraZeneca and Chiesi and acted as a consultant for AstraZeneca, Chiesi, GSK and Menarini.

SQ has been on advisory boards for and has received speaker's honoraria from Allergy Therapeutics, AstraZeneca, Chiesi, GlaxoSmithKline, Gebro, Novartis and Sanofi.

JAT in the last three years has received fees as speaker, scientific advisor or participant of clinical studies of: AstraZeneca, Bial, Chiesi, GlaxoSmithKline, Menarini, Teva.

XM has received fees as a speaker, scientific advisor or participant of clinical studies of (in alphabetical order): AstraZeneca,

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Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version available at https://doi.org/10.1016/j.opresp.2025.100448.

References

1. Global Burden of Disease: GBD cause and risk summaries [Internet]; 2021. Available from: https://www.thelancet.com/gbd/summaries [cited 26 March 2024].
2. Reed CE. The natural history of asthma. J Allergy Clin Immunol. 2006;118:543–8.
3. National Asthma Education. Expert Panel Report 3 (EPR-3): guidelines for the diagnosis and management of asthma-summary report. J Allergy Clin Immunol. 2007;120 Suppl.:S94–138.
4. Global Initiative for Asthma – GINA. Global strategy for asthma management and prevention; 2024.
5. Manisalidis I, Stavropoulou E, Stavropoulos A, Bezirtzoglou E. Environmental and health impacts of air pollution: a review. Front Public Health. 2020;8:14.
6. Tiotiu AI, Novakova P, Nedeva D, Chong-Neto HJ, Novakova S, Steiropoulos P, et al. Impact of air pollution on asthma outcomes. Int J Environ Res Public Health. 2020;17:6212.
7. Evangelopoulos D, Perez-Velasco R, Walton H, Gumy S, Williams M, Kelly FJ, et al. The role of burden of disease assessment in tracking progress towards achieving WHO global air quality guidelines. Int J Public Health [Internet]. 2020;65:1455–65, http://dx.doi.org/10.1007/s00038-020-01479-z [cited 26 March 2024].
8. World Health Organization (WHO). Ambient air pollution [Internet]; 2022. Available from: https://www.who.int/news-room/fact-sheets/detail/ambient-(outdoor)-air-quality-and-health [cited 28 January 2025].
9. Hua L, Ju L, Xu H, Li C, Sun S, Zhang Q, et al. Outdoor air pollution exposure and the risk of asthma and wheezing in the offspring. Environ Sci Pollut Res. 2023;30:14165–89.
10. Guarnieri M, Balmes JR. Outdoor air pollution and asthma. Lancet. 2014;383:1581–92.
11. Zhou X, Sampath V, Nadeau KC. Effect of air pollution on asthma. Ann Allergy Asthma Immunol. 2024;132:426–32. Available from: http://www.annallergy.org/article/S1081120624000188/fulltext [cited 26 November 2024].
12. Barone-Adesi F, Dent JE, Dajnak D, Beevers S, Anderson HR, Kelly FJ, et al. Long-term exposure to primary traffic pollutants and lung function in children: cross-sectional study and meta-analysis. PLoS One. 2015;10:e0142565, http://dx.doi.org/10.1371/journal.pone.0142565 [cited 3 April 2024].
13. Bowatte G, Lodge C, Lowe AJ, Erbas B, Perret J, Abramson MJ, et al. The influence of childhood traffic-related air pollution exposure on asthma, allergy and sensitization: a systematic review and a meta-analysis of birth cohort studies. Allergy. 2015;70:245–56. Available from: https://onlinelibrary.wiley.com/doi/full/10.1111/all.12561 [cited 3 April 2024].
14. Gasana J, Dillikar D, Mendy A, Forno E, Ramos Vieira E. Motor vehicle air pollution and asthma in children: a meta-analysis. Environ Res. 2012;117:36–45.
15. Spann K, Snape N, Baturcam E, Fantino E. The impact of early-life exposure to airborne environmental insults on the function of the airway epithelium in asthma. Ann Glob Health. 2016;82:28–40, http://dx.doi.org/10.1016/j.aogh.2016.01.007 [cited 3 April 2024].
16. Peng W, Liu X, Taghizadeh-Hesary F. Carbon monoxide emission and air quality analysis based on an improved double-weight fuzzy comprehensive evaluation. Front Public Health. 2022;9:790383. Available from: https://pubmed.ncbi.nlm.nih.gov/35096743/ [cited 26 March 2024].
17. Huang J, Yang X, Fan F, Hu Y, Wang X, Zhu S, et al. Outdoor air pollution and the risk of asthma exacerbations in single lag0 and lag1 exposure patterns: a systematic review and meta-analysis. J Asthma. 2022;59:2322–39.
18. Melero Moreno C, Quirce S, Huerta A, Uría E, Cuesta M. Economic impact of severe asthma in Spain: multicentre observational longitudinal study. J Asthma. 2019;56:861–71.
19. Blasco Bravo AJ, Pérez-Yarza EG, De Mercado PLY, Perales AB, Díaz Vazquez CA, Moreno Galdó A. Coste del asma en pediatría en España: un modelo de evaluación de costes basado en la prevalencia. An Pediatr (Engl Ed). 2011;74:145–53.
20. Moher D, Liberati A, Tetzlaff J, Altman DG. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. PLoS Med. 2009;6:e1000097.
21. Weinmayr G, Romeo E, de Sario M, Weiland SK, Forastiere F. Short-term effects of PM10 and NO_2 on respiratory health among children with asthma or asthma-like symptoms: a systematic review and meta-analysis. Environ Health Perspect. 2010;118:449–57.
22. Atkinson RW, Kang S, Anderson HR, Mills IC, Walton HA. Epidemiological time series studies of PM2.5 and daily mortality and hospital admissions: a systematic review and meta-analysis. Thorax. 2014;69:660–5.
23. Zheng XY, Ding H, Jiang LN, Chen SW, Zheng JP, Qiu M, et al. Association between air pollutants and asthma emergency room visits and hospital admissions in time series studies: a systematic review and meta-analysis. PLoS One. 2015;10:e0138146.
24. Fan J, Li S, Fan C, Bai Z, Yang K. The impact of PM2.5 on asthma emergency department visits: a systematic review and meta-analysis. Environ Sci Pollut Res. 2016;23:843–50.
25. Zhang S, Li G, Tian L, Guo Q, Pan X. Short-term exposure to air pollution and morbidity of COPD and asthma in East Asian area: a systematic review and meta-analysis. Environ Res. 2016;148:15–23.
26. Khreis H, Kelly C, Tate J, Parslow R, Lucas K, Nieuwenhuijsen M. Exposure to traffic-related air pollution and risk of development of childhood asthma: a systematic review and meta-analysis. Environ Int. 2017;100:1–31.
27. Orellano P, Quaranta N, Reynoso J, Balbi B, Vasquez J. Effect of outdoor air pollution on asthma exacerbations in children and adults: systematic review and multilevel meta-analysis. PLoS One. 2017;12:e0174050.
28. Hehua Z, Qing C, Shanyan G, Qijun W, Yuhong Z. The impact of prenatal exposure to air pollution on childhood wheezing and asthma: a systematic review. Environ Res. 2017;159:519–30.
29. Orellano P, Quaranta N, Reynoso J, Balbi B, Vasquez J. Association of outdoor air pollution with the prevalence of asthma in children of Latin America and the Caribbean: a systematic review and meta-analysis. J Asthma. 2018;55:1174–86.
30. Li Q, Yi Q, Tang L, Luo S, Tang Y, Zhang G, et al. Influence of ultrafine particles exposure on asthma exacerbation in children: a meta-analysis. Curr Drug Targets. 2019;20:412–20. Available from: https://pubmed.ncbi.nlm.nih.gov/30156156/ [cited 26 March 2024].
31. Li X, Chen Q, Zheng X, Li Y, Han M, Liu T, et al. Effects of ambient ozone concentrations with different averaging times on asthma exacerbations: a meta-analysis. Sci Total Environ. 2019;691:549–61.
32. Qibin L, Yacan L, Minli J, Meixi Z, Chengye L, Yuping L, et al. The impact of PM2.5 on lung function in adults with asthma. Int J Tuberc Lung Dis. 2020;24:570–6.
33. Han K, Ran Z, Wang X, Wu Q, Zhan N, Yi Z, et al. Traffic-related organic and inorganic air pollution and risk of development of childhood asthma: a meta-analysis. Environ Res. 2021;194:110493.
34. Zheng X-Y, Orellano P, Lin H-L, Jiang M, Guan W-J. Short-term exposure to ozone, nitrogen dioxide, and sulphur dioxide and emergency department visits and hospital admissions due to asthma: a systematic review and meta-analysis. Environ Int. 2021;150:106435.
35. Hu Y, Wu M, Li Y, Liu X. Influence of PM1 exposure on total and cause-specific respiratory diseases: a systematic review and meta-analysis. Environ Sci Pollut Res Int. 2022;29:15117–26. Available from: https://pubmed.ncbi.nlm.nih.gov/34628607/ [cited 26 March 2024].
36. Boogaard H, Patton AP, Atkinson RW, Brook JR, Chang HH, Crouse DL, et al. Long-term exposure to traffic-related air pollution and selected health outcomes: a systematic review and meta-analysis. Environ Int. 2022;164:107262.
37. Bennett WD, Zeman KL, Jarabek AM. Nasal contribution to breathing and fine particle deposition in children versus adults. J Toxicol Environ Health A. 2008;71:227–37.
38. Wright RJ, Brunst KJ. Programming of respiratory health in childhood: influence of outdoor air pollution. Curr Opin Pediatr. 2013;25:232–9.
39. Esposito S, Tenconi R, Lelii M, Preti V, Nazzari E, Consolo S, et al. Possible molecular mechanisms linking air pollution and asthma in children. BMC Pulm Med. 2014;14:31.
40. Anenberg SC, Henze DK, Tinney V, Kinney PL, Raich W, Fann N, et al. Estimates of the global burden of ambient PM2:5, ozone, and NO_2 on asthma incidence and emergency room visits. Environ Health Perspect. 2018;126:107004.
41. Kloog I, Ridgway B, Koutrakis P, Coull BA, Schwartz JD. Long- and short-term exposure to PM2.5 and mortality. Epidemiology. 2013;24:555–61.
42. Næss Ø, Nafstad P, Aamodt G, Claussen B, Rosland P. Relation between concentration of air pollution and cause-specific mortality: four-year exposures to nitrogen dioxide and particulate matter pollutants in 470 neighborhoods in Oslo, Norway. Am J Epidemiol. 2007;165:435–43.
43. Singh A, Morley GL, Coignet C, Leach F, Pope FD, Neil Thomas G, et al. Impacts of ambient air quality on acute asthma hospital admissions during the COVID-19 pandemic in Oxford City, UK: a time-series study. BMJ Open. 2024;14:e070704.
44. Su JG, Barrett MA, Combs V, Henderson K, Van Sickle D, Hogg C, et al. Identifying impacts of air pollution on subacute asthma symptoms using digital medication sensors. Int J Epidemiol. 2022;51:213–24.