

# Trends in the Use of Air Quality Indexes in Asthma Studies

Angie Daniela Barrera-Heredia <sup>1</sup>, Carlos Alfonso Zafra-Mejía <sup>2,\*</sup> , Alejandra Cañas Arboleda <sup>3,4</sup> ,  
María José Fernández Sánchez <sup>4,5</sup> , Liliana López-Kleine <sup>6</sup>  and Adriana Rojas Moreno <sup>7,8,9,10</sup> 

- <sup>1</sup> Maestría en Desarrollo Sustentable y Gestión Ambiental, Universidad Distrital Francisco José de Caldas, Bogotá E-110231, Colombia; adbarrerah@udistrital.edu.co
- <sup>2</sup> Grupo de Investigación en Ingeniería Ambiental—GIIAUD, Facultad del Medio Ambiente y Recursos Naturales, Universidad Distrital Francisco José de Caldas, Bogotá E-110231, Colombia
- <sup>3</sup> Departamento de Medicina Interna, Facultad de Medicina, Pontificia Universidad Javeriana, Bogotá E-110231, Colombia; alejandra.canas@javeriana.edu.co
- <sup>4</sup> Departamento de Medicina Interna, Hospital Universitario San Ignacio, Bogotá E-110231, Colombia; m.fernandez@javeriana.edu.co
- <sup>5</sup> Departamento de Ciencias Fisiológicas, Facultad de Medicina, Pontificia Universidad Javeriana, Bogotá E-110231, Colombia
- <sup>6</sup> Departamento de Estadística, Universidad Nacional de Colombia, Bogotá E-11001, Colombia; llopezk@unal.edu.co
- <sup>7</sup> Instituto de Genética Humana, Pontificia Universidad Javeriana, Bogotá E-110231, Colombia; rojas-adriana@javeriana.edu.co
- <sup>8</sup> Department of Genetics, University of Cordoba, E 14071 Córdoba, Spain
- <sup>9</sup> Maimónides Biomedical Research Institute of Córdoba (IMIBIC), E 14071 Córdoba, Spain
- <sup>10</sup> Reina Sofía University Hospital, E 14071 Córdoba, Spain
- \* Correspondence: czafra@udistrital.edu.co

**Abstract:** International air quality indexes (AQIs) are derived from air pollution and are essential global tools for mitigating diseases such as asthma, as they are used to reduce exposure to triggers. The aim of this article is to systematically review the global literature on the use of AQIs in asthma-related studies. To evaluate the importance of the variables considered, a citation frequency index (Q) was used. The results suggest that the most frequently reported air pollutants related to asthma are PM (Q3) > NO<sub>2</sub> (Q3) > O<sub>3</sub> (Q3) > CO (Q3) > NO (Q3) > SO<sub>2</sub> (Q3). In addition, climate variables play a relevant role in asthma research. Temperature (Q4) emerged as the most relevant climate variable, followed by atmospheric pressure (Q3) > wind direction (Q3) > solar radiation (Q3) > precipitation (Q3) > wind speed (Q3). AQIs, specifically the U.S.EPA Air Quality Index and the Air Quality Health Index, are directly associated with air pollution and the prevalence, severity and exacerbation of asthma. The findings also suggest that climate change presents additional challenges in relation to asthma by influencing the environmental conditions that affect the disease. Finally, this study provides a comprehensive view of the relationships among air quality, air pollutants and asthma and highlights the need for further research in this field to develop public health policies and environmental regulations.

**Keywords:** air pollution; air quality indexes; particulate matter; respiratory infections; public health; asthma; climate variables



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## 1. Introduction

Increasing urbanization has exacerbated public health problems related to air quality [1,2]. Urban dwellers are exposed to pollutants such as nitrogen dioxide (NO<sub>2</sub>), volatile organic compounds (VOCs), sulfur dioxide (SO<sub>2</sub>), carbon monoxide (CO), ozone (O<sub>3</sub>) and particulate matter (PM), which increase the risk of cardiovascular and respiratory diseases, causing premature death [3]. Air quality is a global problem since pollutants can be dispersed through wind and atmospheric conditions, affecting less polluted areas and causing harm to humans, plants and animals [4,5]. Factors such as population density

and health, environmental, economic and climatic characteristics also increase urban air pollution, generating adverse impacts on human health [6]. Since 2005, approximately 35 million people have died from chronic respiratory diseases, and an increase in the number of deaths associated with these diseases, especially asthma, is expected [7]. Undoubtedly, air pollution is a significant risk factor for human health and affects quality of life [8,9].

To mitigate diseases caused by air pollution and improve quality of life, international air quality indexes (AQIs) have been implemented globally [10]. AQIs, which are dimensionless values calculated from one or more criteria air pollutants, represent the atmospheric concentration and its possible effects on human health, facilitating community understanding of air quality in a specific place and time [11,12]. These indexes provide information on the permitted limits, which are distributed at different levels and represented by a color coding that can vary according to the country [13]. AQIs inform the community about air quality and offer recommendations for the general well-being of the population [14]. However, in developing countries, there is little information on the relationship between asthma health factors (AHFs) and medical exacerbations (e.g., respiratory and cardiovascular diseases) due to exposure to air pollution [15,16]. Current AQIs do not allow the prediction or detection of increases in emergency room admissions for asthma exacerbations, as they are based on concentrations measured in real time at automated monitoring stations [17,18]. According to Rosser et al. [19], given that these indexes are obtained by calculating the concentrations measured daily without considering the temporal and spatial variations in air pollution, it is likely that certain exposure will be incorrectly categorized. This situation could be the main reason for the lack of connection between AQIs and public health [20].

Air pollution, defined by the World Health Organization (WHO) as the presence of harmful substances in the atmosphere, has intensified with economic, social and political development; these changes thus affect air quality and human health [21]. This phenomenon, together with climate conditions, has emerged as a critical factor that can compromise public health, increasing the incidence of respiratory diseases [22]. AQIs play an important role in protecting public health, especially in regard to respiratory diseases such as asthma and chronic obstructive pulmonary disease. These indexes evaluate the levels of pollutants in the air, allowing the population and authorities to take informed preventive measures [23]. For conditions such as asthma, where air quality can trigger and aggravate symptoms, AQIs offer a useful guide for reducing exposure to triggers. By providing up-to-date and accurate information on air quality and its effects on human health, they allow communities to make conscious decisions about their health [24].

At the global level, AQIs have been established to assess air pollution and its possible impact on human health [13,14]. Among the most recognized AQIs are the World Health Organization Air Quality Index (WHO-AQI), the U.S.EPA Air Quality Index (U.S.EPA-AQI), the European Union Air Quality Index (EU-AQI) and the China Air Quality Index (CN-AQI) [25,26]. The widely used U.S.EPA-AQI considers parameters such as PM<sub>2.5</sub>, PM<sub>10</sub>, O<sub>3</sub>, NO<sub>2</sub>, SO<sub>2</sub> and CO. The WHO-AQI is based on the WHO guidelines and evaluates the same pollutants [27]. Although these indexes share the objective of providing understandable information on air quality, the differences in their thresholds and methodologies have prevented their total unification in the context of public health [28,29]. The variability of these indexes at the global level is due to factors such as heterogeneity in exposure to pollutants, epidemiological profiles and country-specific regulations, which makes it difficult to unify criteria in relation to risks to human health [30]. The most cited AQIs worldwide, such as the U.S.EPA-AQI and the WHO-AQI, have been used in various regions to assess and report on air pollution levels and their effects on public health [31]. In China, the CN-AQI has been used as part of government efforts to address serious air pollution in cities such as Beijing. This index has contributed to increasing awareness of the health risks associated with air quality and has promoted mitigation measures to reduce exposure to air pollutants [32].

In Europe, the European Union uses the EU-AQI to report on air quality in various regions, facilitating informed decisions by citizens about their outdoor activities [11]. In Canada, the AQHI has been effective in alerting people with respiratory problems to potential risks and promoting protective behaviors such as limiting outdoor exposure during periods of poor air quality [33]. These experiences highlight the usefulness of AQIs for generating public awareness and promoting preventive measures against air pollution [34]. However, they also emphasize the importance of adapting these indexes to local conditions and the needs of the population, recognizing the differences in pollutant profiles and risk levels in different parts of the world [30,35].

The main objective of this article is to systematically review the literature worldwide on the use of AQIs in asthma-related studies. The main air pollutants associated with asthma are identified based on their citation frequency in scientific databases. The climate variables most considered by the AQIs are also identified. Lastly, a worldwide spatiotemporal analysis is carried out based on the use of the different AQIs. In the context of air pollution and asthma, this study is relevant because of the following practical aspects: (1) it deepens the knowledge associated with the application of AQIs in asthma studies; (2) it considers critical air pollutants from mitigation and public health intervention perspectives; (3) it analyzes the relevance of climate variables to better understand their interactions with air pollution and their effects on public health; (4) it provides relevant information to visualize AQI optimization strategies in relation to asthma.

## 2. Materials and Methods

### 2.1. Bibliographic Search System

A systematic review of the literature was carried out to analyze the use of AQIs, air pollutants and climate variables in studies on asthma worldwide between 2011 and 2022. Various scientific databases, including Google Scholar, Science Direct, Springer Link and Taylor & Francis, were used. These databases were selected because of the significant number of documents detected according to the main objective of this study and because of their use in literature review studies on air pollution and asthma [36–38]. The review process was carried out following the methodology proposed by Zafra et al. [39]. During this review, the total content of the documents detected in the databases selected for this study was exhaustively considered.

### 2.2. Bibliographic Analysis System

The bibliographic analysis was structured in four phases: (I) a general search, (II) the detection of the most studied air pollutants in the context of asthma, (III) the identification of the main climate variables and (IV) the classification of the existing air quality indexes. These phases were based on a citation frequency index (Q) and were used to study the importance of the detected air quality and asthma variables [40]. The Q indexes were averaged, and the following four quartile ranges were established: Q1 = 0.00–0.24, Q2 = 0.25–0.49, Q3 = 0.50–0.74 and Q4 = 0.75–1.0. In this study, it was assumed that the relationship between air quality and asthma could depend on the frequency of citations in the databases consulted. That is, the Q1 quartile could be associated with less important air quality and asthma assessment methods, while the Q4 quartile could be linked to issues of greater relevance worldwide.

#### Phases of Bibliographic Analysis

Phase 1: In the initial phase of the bibliographic search, the following keywords were used: (I) index, (II) air pollution and (III) asthma. During this phase, the following information inclusion criteria were applied in line with the objectives of this study: (I) articles related to air quality and asthma, (II) articles related to air pollution, (III) articles related to asthma and (IV) articles related to AHFs and asthma. These information inclusion criteria were assumed based on the main objective of this study: air quality indexes and asthma. In this phase of analysis, 32,665 relevant documents were identified in all the

selected databases (information universe). The database that registered the largest number of documents was Google Scholar, with a total of 20,800 documents, which represented 63.7% of the total information (Table 1). The Science Direct database had 4859 documents (14.9%). The Springer scientific database contributed 4497 documents (13.8%), while Taylor & Francis contributed 2509 documents (7.68%).

Phase 2: From the keywords selected during phase 1, the search filters (keywords) of the Springer, Science Direct and Taylor & Francis databases were used. This approach was used to detect additional keywords in the context of the main air pollutants reported in asthma studies. The keywords detected were as follows (Table 1): nitrogen dioxide, ozone, nitric oxide, particulate matter, sulfur dioxide and carbon monoxide. In addition, in this phase, a stratified sample was selected from the total number of documents detected in phase 1 for each database considered. The sample size assumed was 50 documents in total. Thus, 63.7% (31 documents), 14.9% (7 documents), 13.8% (7 documents) and 7.68% (4 documents) of the first 50 documents detected according to their relevance in the Google Scholar, Science Direct, Springer Link and Taylor & Francis databases, respectively, were selected. The final sample size established then corresponded to 49 documents. Based on these documents, the main air pollutants in asthma studies were analyzed again (Table S1).

Phase 3: The third phase of the review was carried out to organize the subcategories of analyses related to climate variables in studies on asthma and, thus, to establish their relationships with the detected AQIs. Once again, the citation frequency index (Q) was used [39]. During this phase, the following additional keywords were detected and incorporated (Table 1): precipitation, wind speed, wind direction, temperature, atmospheric pressure and solar radiation. The information inclusion criterion during this phase was based on studies that addressed the climate variables used in AQIs. During this phase, the 49 documents selected in phase 2 were again analyzed (Table S1).

Phase 4: During this phase, an analysis was carried out on the spatiotemporal trends of the detected variables [41]. This trend analysis considered the citation frequency index (Q) and the classification obtained for the AQIs in studies on asthma on a global scale. This trend analysis was performed from the 49 documents selected (sample size according to its relevance) from the databases considered (Table S1).

### 2.3. Statistical Analysis

Statistical tests were carried out to study the main variables of interest in the context of air pollution and asthma. A database was built in Microsoft Excel (V.2017) to analyze the spatiotemporal distribution of the documents detected (Table S1) [42]. Descriptive statistics and reasons were used to establish an order of hierarchy in the AQIs and to study their spatiotemporal trend [43]. Finally, a cluster analysis [44] was performed by using SPSS V.25 software [45] to group the variables considered in the context of this study (construction of a dendrogram).

**Table 1.** Order of world importance for air pollutants, variables used and air quality indexes detected.

Phase	Keywords	Science Direct		Springer Link		Google Scholar		Taylor & Francis		Total Documents Detected	Average Q Index	Mean Quartile	Quartile Variation
		Detected Documents	Q Index	Detected Documents	Q Index	Detected Documents	Q Index	Detected Documents	Q Index				
Information universe	Index, Air Pollution and Asthma	4859	1.00	4497	1.00	20,800	1.00	2509	1.00	32,665	1.00	Q4	Q4,Q4,Q4,Q4
Air pollutants	Index, air pollution, asthma and nitrogen dioxide	1602	0.33	1469	0.33	17,900	0.86	748	0.30	21,719	0.66	Q3	Q2,Q2,Q4,Q2
	Index, air pollution, asthma and ozone	1651	0.34	1503	0.33	16,500	0.79	809	0.32	20,463	0.63	Q3	Q2,Q2,Q4,Q2
	Index, air pollution, asthma and nitric oxide	892	0.18	785	0.17	17,600	0.85	479	0.19	19,756	0.60	Q3	Q1,Q1,Q4,Q1
	Index, air pollution, asthma and particulate matter	2636	0.54	2001	0.44	17,200	0.83	1021	0.41	22,858	0.70	Q3	Q3,Q2,Q4,Q2
	Index, air pollution, asthma and sulfur dioxide	1206	0.25	1159	0.26	15,700	0.75	651	0.26	18,716	0.57	Q3	Q2,Q2,Q4,Q2
	Index, air pollution, asthma and carbon monoxide	1191	0.25	1070	0.24	17,100	0.82	627	0.25	19,988	0.61	Q3	Q2,Q1,Q4,Q2
Climate variables	Index, air pollution, asthma and precipitation	782	0.16	1007	0.22	15,200	0.73	494	0.20	17,483	0.54	Q3	Q1,Q1,Q3,Q2
	Index, air pollution, asthma and wind speed	898	0.18	1233	0.27	14,900	0.72	320	0.13	17,351	0.53	Q3	Q1,Q2,Q3,Q1
	Index, air pollution, asthma and wind direction	681	0.14	1181	0.26	16,800	0.81	195	0.08	18,857	0.58	Q3	Q1,Q2,Q4,Q1
	Index, air pollution, asthma and temperature	2806	0.58	2812	0.63	17,100	0.82	1275	0.51	23,993	0.73	Q4	Q3,Q3,Q4,Q3
	Index, air pollution, asthma and atmospheric pressure	931	0.19	1218	0.27	17,900	0.86	651	0.26	20,700	0.63	Q3	Q1,Q2,Q4,Q2
	Index, air pollution, asthma and solar radiation	498	0.10	710	0.16	17,600	0.85	172	0.07	18,980	0.58	Q3	Q1,Q1,Q4,Q1
Air quality indexes	Index, air pollution, asthma and Common Air Quality Index	2672	0.55	3167	0.70	18,300	0.88	1286	0.51	25,425	0.78	Q4	Q3,Q3,Q4,Q3
	Index, air pollution, asthma and Air Quality Index	3899	0.80	3926	0.87	19,000	0.91	1831	0.73	28,656	0.88	Q4	Q4,Q4,Q4,Q3
	Index, air pollution, asthma and Air Quality Health Index	3805	0.78	3873	0.86	9010	0.43	1273	0.51	17,961	0.55	Q3	Q4,Q4,Q2,Q3
	Index, air pollution, asthma and Air Pollution Tolerance Index	743	0.15	1067	0.24	15,400	0.74	266	0.11	17,476	0.54	Q1	Q1,Q1,Q4,Q1
	Index, air pollution, asthma and Arithmetically Aggregated Pollutant Index	25	0.01	13	0.00	88	0.00	1	0.00	127	0.00	Q1	Q1,Q1,Q1,Q1

### 3. Results and Discussion

#### 3.1. AQIs, Air Pollutants and Asthma

During the initial phase of the bibliographic review, 32,665 relevant documents were identified. These documents were linked to the following keywords: (I) index (38.8%), (II) air pollution (36.7%) and (III) asthma (24.5%). The search was carried out in four selected databases: (I) Science Direct, (II) Springer Link, (III) Google Academic and (IV) Taylor & Francis. Google Scholar provided the highest volume of documents, with a total of 20,800 (63.7%). It was followed by Science Direct, which contributed 4859 papers (14.9%). Springer Link and Taylor & Francis contributed 4497 (13.8%) and 2509 documents (7.68%), respectively (Table 1).

The results show that the most frequently reported atmospheric pollutants related to asthma were suspended particles ( $PM_{2.5}$  and  $PM_{10}$ ),  $NO_2$ ,  $O_3$ ,  $SO_2$ , CO and  $NO_x$  (Table 2). PM, which originate from various sources, such as the burning of fuels and vehicular traffic, was associated with lung irritation and the induction of asthma attacks [46].  $O_3$ , formed by the reaction of nitrogen oxides and volatile organic compounds, was associated with irritation of the respiratory tract and reduced lung function [47].  $SO_2$ , whose generation is attributed mainly to the combustion of fossil fuels such as oil and coal, was identified as a potential irritant of the respiratory tract, exacerbating asthma symptoms [48,49].  $NO_x$ , which is produced by the combustion of fossil fuels in vehicles and power plants, was identified as a contributor to the formation of tropospheric ozone and fine particles, which aggravate asthma symptoms [4]. Finally, CO, which results from the incomplete combustion of fossil fuels, although not identified as a main trigger of asthma, was associated with the worsening of respiratory symptoms in individuals with preexisting asthma who were exposed to high levels of it [50].

**Table 2.** Air pollutants, climate variables and air quality indexes in asthma studies.

Categories	Frequency of Occurrence (Selected Documents, $n = 49$ )	Subcategories	Quartile
Air pollutants	85.7%	Index, air pollution, asthma and particulate matter	Q3
	75.5%	Index, air pollution, asthma and nitrogen dioxide	Q4
	73.5%	Index, air pollution, asthma and ozone	Q3
	63.3%	Index, air pollution, asthma and sulfur dioxide	Q3
	30.6%	Index, air pollution, asthma and carbon monoxide	Q3
	14.3%	Index, air pollution, asthma and nitric oxide	Q3
Climate variables and AQIs	53.1%	Index, air pollution, asthma and temperature	Q3
	24.5%	Index, air pollution, asthma and precipitation	Q3
	24.5%	Index, air pollution, asthma and wind speed	Q3
	16.3%	Index, air pollution, asthma and wind direction	Q3
	16.3%	Index, air pollution, asthma and solar radiation	Q3
	12.2%	Index, air pollution, asthma and atmospheric pressure	Q4



Table 2. Cont.

Categories	Frequency of Occurrence (Selected Documents, <i>n</i> = 49)	Subcategories	Quartile
Classification of AQIs	46.9%	Index, air pollution, asthma and Air Quality Index (U.S.EPA-AQI)	Q4
	46.9%	Index, air pollution, asthma and Air Quality Health Index (AQHI)	Q4
	10.2%	Index, air pollution, asthma and Common Air Quality Index (CAQI)	Q3
	4.1%	Index, air pollution, asthma and Arithmetically Aggregated Pollutant Index (AAPI)	Q1
	4.1%	Index, air pollution, asthma and Air Pollution Tolerance Index (APTI)	Q3

The results show that PM and O<sub>3</sub> were reported in 85.7% and 73.5% of the studies, respectively (Table 2). PM is a significant risk factor for people with asthma, as it can exacerbate symptoms, increase the frequency of asthma attacks and contribute to airway inflammation and damage [2]. O<sub>3</sub>, known for its irritant capacity in the respiratory tract, has various effects on human health depending on the concentration and duration of exposure [14]. NO<sub>2</sub>, which was mentioned in 75.5% of the studies, emerged as the main pollutant associated with asthma. This primary pollutant, emitted mainly by the combustion of gasoline in motor vehicles, was associated with irritation of the respiratory tract, causing symptoms such as coughing, chest pain and bronchitis [51]. SO<sub>2</sub>, present in 63.3% of the studies, was identified as an irritating gas for the respiratory tract that decreases lung function in patients with asthma [52], triggering symptoms such as shortness of breath and persistent cough. NO, reported in 14.3% of the studies, was related to shortness of breath, chest tightness, cough and wheezing [14]. Lastly, CO, a product of the incomplete combustion of organic material in oxygen-deficient environments, was also addressed in the reviewed literature [53]. Although it was not identified as a major trigger for asthma, it contributes to the disease by reducing the body's ability to transport oxygen to tissues.

The results show the following order of importance for the air pollutants in the asthma studies: PM (85.7%) > NO<sub>2</sub> (75.5%) > O<sub>3</sub> (73.5%) > SO<sub>2</sub> (63.3%) > CO (30.6%) > NO (14.3%). These data were obtained from the selected documents (Table 2). Regarding the climate variables, the following order of importance was observed: temperature (53.1%) > precipitation (24.5%) > wind speed (24.5%) > wind direction (16.3%) > solar radiation (16.3%) > atmospheric pressure (12.2%). Regarding the classification of AQIs, the order of importance detected was as follows: Air Quality Index (U.S.EPA-AQI; 46.9%), Air Quality Health Index (AQHI; 46.9%), Common Air Quality Index (CAQI; 10.2%), Arithmetically Aggregated Pollutant Index (AAPI; 4.1%) and Air Pollution Tolerance Index (APTI; 4.1%). Thus, these orders of importance offer a perspective on the most relevant air pollutants in relation to asthma and on the climate variables and the AQIs most used in research. This information can be used to guide future research and public health policies.

The results show that air pollution worldwide has had a significant impact on public health, exacerbating respiratory diseases such as asthma [54]. This problem has been intensified by social inequalities, with the most vulnerable populations being exposed to high levels of air pollutants [55]. This exposure increases the economic burden of asthma, representing a challenge for health systems and national economies [56]. However, air pollution mitigation faces political and regulatory challenges [57]. This situation elucidates the need for concerted political action and a collective commitment to promote stricter environmental regulations [58]. Addressing these challenges requires a global and collaborative response involving multiple stakeholders [59]. For example, in Latin America, the dynamics of air pollutants and their relationships with asthma are complex and influenced

by factors such as accelerated urbanization, ongoing industrialization and limitations in environmental regulation [60]. Latin American cities face increases in air pollution due to the concentration of emissions from vehicular traffic, industry and residential heating [61]. Continuous industrialization has increased the emissions of pollutants such as SO<sub>2</sub>, NO<sub>x</sub> and PM [62]. Limitations in environmental regulation in some developing countries have resulted in high levels of air pollution in urban and industrial areas, increasing the exposure of the population to the risk of asthma and other respiratory diseases [50].

The results suggest that the socioeconomic vulnerability of certain groups, such as low-income groups, contributes to increased risks of exposure to air pollution, thus increasing the prevalence and severity of asthma [63]. Climate change influences the distribution and concentration of atmospheric pollutants in Latin America, affecting the formation of tropospheric ozone and other polluting particles, which has impacted the respiratory health of the population and the prevalence of asthma in the region [54]. Understanding the relationship between air pollutants and asthma is critical to addressing public health challenges on a global scale. The need to analyze both the spatial and temporal trends of these pollutants was highlighted. Such analyses can offer a comprehensive view of how air pollution affects the prevalence and severity of asthma in different regions of the world. Table 3 presents a detailed summary of the main spatiotemporal trends observed worldwide, elucidating the influence of various factors on air quality and respiratory health.

**Table 3.** Spatiotemporal trend of air pollutants in the context of asthma.

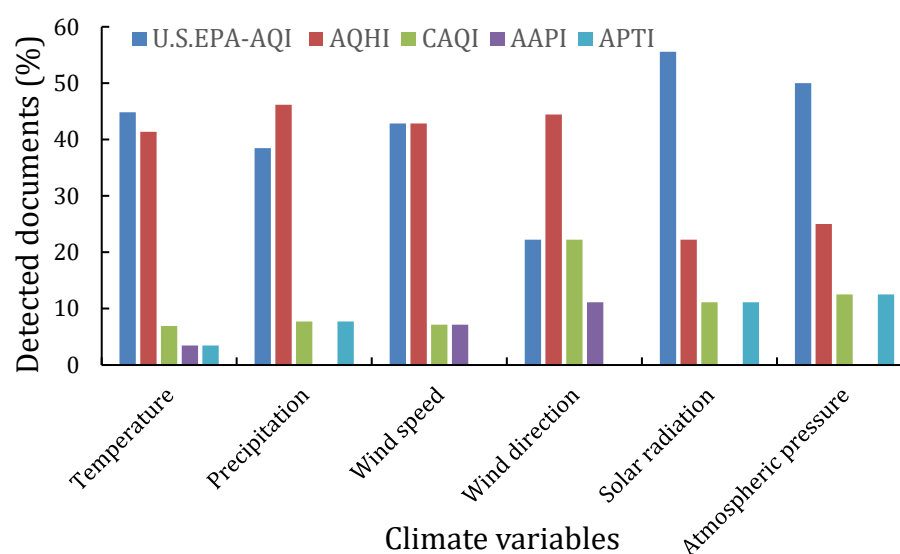
Factors	Spatial Trends	Temporal Trends
Urbanization	Urban areas experience higher levels of air pollution due to the concentration of pollutant sources such as vehicular traffic and industries [64].	Efforts have been made to reduce air pollutant emissions in urban areas through stricter regulations [65].
Industrialization	Highly industrialized regions face significant challenges in terms of air quality due to industrial emissions [66].	Industrial growth in developing areas has contributed to increased air pollution, especially in densely populated areas [67].
Developing regions	Developing regions experience rapid industrial and urban growth, leading to an increase in air pollution [68].	Climate change influences the distribution of pollutants and may exacerbate asthma symptoms in developing areas due to the lack of effective regulations [69].
Climate change	Climate change can influence the distribution of air pollutants and affect the prevalence and severity of asthma [70].	Climate changes can affect the formation of air pollutants and the prevalence of asthma, especially in vulnerable areas [54].

The identification and understanding of the main air pollutants associated with asthma are fundamental for the effective management of this respiratory disease [71]. Exposure to pollutants such as SO<sub>2</sub>, PM<sub>2.5</sub> and PM<sub>10</sub> was associated with an increased risk of developing or worsening asthma [72]. This information has enabled the implementation of adequate preventive measures, such as stricter environmental policies and air quality monitoring programs [73]. Furthermore, it is essential to tailor asthma treatment according to environmental conditions, improve disease management and reduce the burden of symptoms for patients [74]. Public awareness of the health risks associated with air pollution can promote changes in individual behavior and more effective public health policies [75]. Lastly, the identification of air pollutants related to asthma has prompted ongoing research to develop more effective interventions and reduce the global burden of the disease [76].



### 3.2. AQIs, Climate Variables and Asthma

The results reveal the following six key climate variables in studies on asthma: precipitation (Q3), wind speed and direction (Q3), temperature (Q3), atmospheric pressure (Q4) and solar radiation (Q3). These climate variables are considered by the following AQIs: Common Air Quality index—CAQI (Q3); Air Quality Index—U.S.EPA-AQI (Q4); Air Quality Health Index—AQHI (Q4); Air Pollution Tolerance Index—APTI (Q3); and Arithmetically Aggregated Pollutant Index—AAPI (Q3) (Figure 1). Thus, temperature was the most frequently cited climate variable (Q3). It was followed, in order of importance, by precipitation (Q3) and wind speed (Q3) (Table 2). Solar radiation (Q3) was also mentioned with a significant frequency, while atmospheric pressure (Q4) was the least mentioned variable. These findings support the importance of considering a variety of climate variables in asthma studies to better understand their relationships with environmental and public health factors.



**Figure 1.** Climate variables associated with air quality indexes in asthma studies (selected documents,  $n = 50$ ). U.S.EPA-AQI = Air Quality Index, AQHI = Air Quality Health Index, CAQI = Common Air Quality Index, AAPI = Arithmetically Aggregated Pollutant Index and APTI = Air Pollution Tolerance Index.

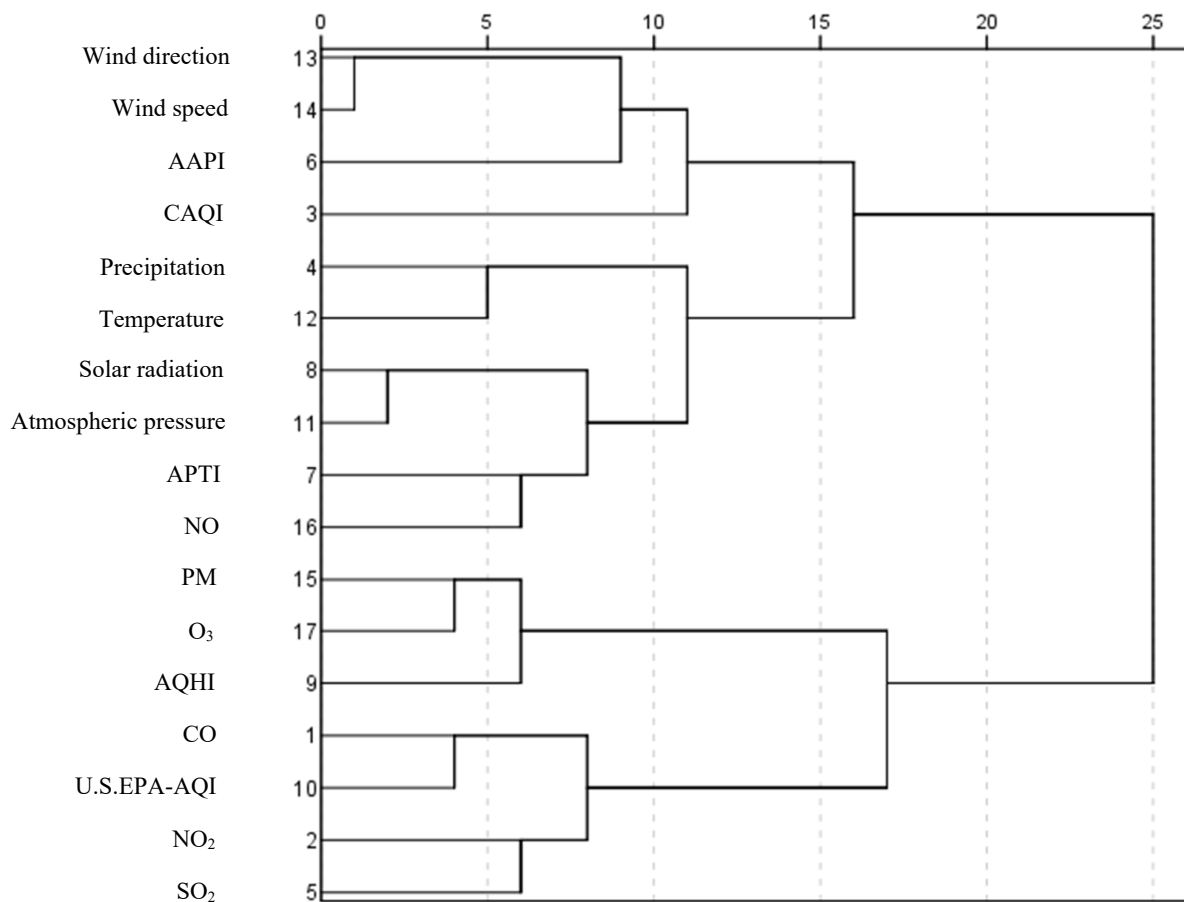
The findings show that in asthma studies, it is relevant to consider various climate variables that influence the prevalence, severity and exacerbation of asthma (Figure 1) [77]. Temperature plays a significant role in the development and exacerbation of asthma, with extreme temperatures triggering symptoms in some people [78]. Air humidity in seasons of increased precipitation also influences asthma, as high humidity increases the concentration of allergens in the air. Conversely, in seasons of low precipitation and air humidity, airways tend to dry out [79]. Precipitation is able to wash pollen out of the air, benefiting some people with allergic asthma, but thunderstorms trigger symptoms in some people due to changes in atmospheric pressure and the release of allergens into the air [80]. Changes in atmospheric pressure, such as those that occur before a storm, trigger asthma attacks in some people [81]. Wind-transported allergens such as pollen or air pollution influence the appearance of asthma symptoms [82]. Exposure to air pollutants such as  $\text{NO}_2$ ,  $\text{O}_3$  and  $\text{PM}_{2.5}$  worsen asthma symptoms and increase the risk of exacerbations [72]. The relationships between these climate variables and asthma are complex and varied according to the person and their individual sensitivity [83]. Other factors, such as geography, season and exposure patterns, also influence how these climate variables affect people with asthma [84].

The asthma studies chosen considered climate variables due to their relevance in understanding this disease [85]. These variables, along with other asthma triggers, such as environmental allergens, air pollutants and respiratory infections, interact with and affect

respiratory health [86]. The temporal and geographic variabilities in climate conditions play important roles in the manifestation of asthma [87]. Numerous epidemiological studies have demonstrated associations between climate variables and the incidence, prevalence and severity of asthma [88]. The findings revealed the pathophysiological mechanisms by which climate variables influence the development and exacerbation of asthma [89]. The consideration of climate variables in asthma studies was based on a combination of epidemiological evidence, pathophysiological knowledge and the need to understand and mitigate the risks associated with the disease to improve respiratory health and the quality of life of affected people [90].

The dendrogram based on the cluster analysis is a visual representation that groups the climate variables and air pollutants, showing complex patterns of interactions among the variables considered (Figure 2). A tendency to cluster in the direction and speed of wind was observed, which suggests an association with the dispersion of pollutants, where the wind could influence the direction and speed of propagation of atmospheric pollutants [91]. Similarly, a close grouping was observed among air pollutants, such as CO, NO<sub>2</sub> and SO<sub>2</sub>, and PM and O<sub>3</sub>, which could have common emission sources or be influenced by similar climate factors. In addition, climate variables such as temperature, solar radiation, atmospheric pressure and precipitation showed a close association with air pollutants in the dendrogram, suggesting that climate could play a significant role in the dispersion and concentration of atmospheric pollutants, where factors such as temperature and solar radiation could affect chemical reactions and the formation of pollutants [92]. Additionally, a close grouping was observed between AQIs such as the U.S.EPA-AQI and the AQHI and air pollutants, indicating their direct association with air quality and its impact on public health [93]. Taken together, this cluster analysis provided a deeper understanding of the complex interactions between climate variables and air pollutants, elucidating the importance of considering multiple factors in assessing air quality and its impact on human health [94].

The results suggest that climate change presents additional challenges in relation to asthma by influencing the environmental conditions that affect the disease. Climate change was associated with an increase in the occurrence of phenomena such as heat waves, electrical storms and episodes of air pollution, which can trigger asthma exacerbations and increase the burden of the disease [95]. In addition, climate change can influence the distribution and season of environmental allergens such as pollen and mold, increasing the exposure of people with asthma to allergic triggers and potentially the prevalence and severity of the disease [96]. Likewise, climate change can affect air quality by influencing the formation of atmospheric pollutants such as ozone and fine particles, thus increasing the risk of asthma exacerbations and possibly contributing to the development of the disease in some people [97]. Global temperature rise and urbanization also play important roles in creating warmer urban environments and increasing exposure to heat and air pollution in urban areas, which could have negative consequences for people with asthma, especially those who live in disadvantaged environments or who have limited access to health care [95]. In terms of public health, climate change could increase the burden of respiratory diseases, including asthma, posing additional challenges for health care systems and public health in general [98]. Therefore, it is essential to develop adaptation and mitigation strategies to protect vulnerable populations and reduce the risks associated with asthma and other climate-related health problems [99].



**Figure 2.** Dendrogram of climate variables, air pollutants and AQIs in asthma studies. Dendrogram using a Ward linkage. Combination of rescaled distance clusters. U.S.EPA-AQI = Air Quality Index, AQHI = Air Quality Health Index, CAQI = Common Air Quality Index, AAPI = Arithmetically Aggregated Pollutant Index and APTI = Air Pollution Tolerance Index.

The results show that the complex interaction among urban heterogeneity, climate conditions and air quality configures a challenging scenario for the study of asthma, especially in densely populated urban environments [100,101]. Thus, detailed characterization of urban heterogeneity, including land use typology, population density and urban infrastructure, is critical to understanding the spatial distribution of emission sources (anthropogenic and natural) and the dispersion patterns of air pollutants [102]. Natural and urban landscapes vary significantly in their ability to mitigate or exacerbate pollution. Green areas, such as parks and forests, are able to act as sinks for pollutants, while industrial and heavily trafficked areas contribute to their accumulation [103]. Climatic factors cannot be overlooked. The analysis of climate conditions, including weather patterns, primary pollutant concentrations and secondary pollutant formation, is instrumental in determining their influence on the transport, transformation and persistence of pollutants in the urban atmosphere. For example, thermal inversion episodes, which trap pollutants close to the ground, can aggravate air quality in densely populated urban areas [2,104]. Therefore, continuous air quality monitoring and calculation of AQIs, using standardized methodologies and considering relevant pollutants to understand and mitigate risks associated with asthma, provide essential information on air pollution exposure [14,105].

### 3.3. Spatiotemporal Trends

The research findings reveal that the most frequently examined AQIs, which comprised 46.9% of cases, considered both air pollution and asthma and included the U.S.EPA-AQI (Table 2). This index was placed in the fourth quartile (Q4), which indicated high relevance

and frequency in research. Another AQI that also examines the relationship between air pollution and asthma was found, the AQHI. This index was found in the fourth quartile (Q4), covering the same percentage as the previous quartile (46.9%). However, other less common AQIs were detected but had equal relevance. One of them, the CAQI, which accounted for 10.2% of the cases, was linked to asthma and air pollution and was classified in the third quartile (Q3). This indicated that despite being less studied, it still holds considerable importance in research. In addition, less frequent AHFs were identified, each representing 4.1% of the cases. One of them, the AAPI, examined the relationships among air pollution and asthma, while the other focused on asthma and air pollution tolerance (the APTI). Both were classified in the first (Q1) and third quartiles (Q3). This analysis revealed the diversity of approaches to investigating the relationship between air quality and asthma, highlighting the importance of considering multiple dimensions in this field of study.

In relation to the temporal trend, the findings show a variation in the number of documents published annually, with peaks occurring in 2020 and 2021. In 2011, 2013 and 2016, 8% of the documents were published, while in 2012, 2014 and 2015, only 2% of the documents were published. These data were obtained from the documents selected in this study (Table S1). In 2017, an upward trend was observed; a total of 4% of the documents were published in 2017 and 2018, followed by a significant increase in 2019, when 14% of the documents were published. However, the most notable increases were recorded in 2020 and 2021, when 18% and 28% of the documents, respectively, were published. This increase in the last two selected years suggests a growing interest in the subject and greater research activity in this field. In relation to the spatial trend, a diversity of countries and continental areas were represented in the studies, with greater concentrations in North America (36%) and Asia (38%). When analyzing how the variables temporarily changed, an increase in the frequency of citations of certain air pollutants and climate variables was observed in recent years. For example, nitrogen dioxide (NO<sub>2</sub>), particulate matter (PM) and ozone (O<sub>3</sub>) have been increasingly studied, as evidenced by reports published in 2020 and 2021. In addition, variables such as wind speed and temperature have become relevant in recent research, as evidenced by published studies.

The results show that the continents with the greatest number of documents related to AQIs in the context of asthma were Asia > North America > Europe > Africa (Table S1). The Asian continent ranked first, with 57.1% of the documents, which were distributed mainly in countries such as China and India. It was followed by North America with a total of 36.7% of the documents, associated mainly with the United States. Europe and Africa made smaller contributions, 16.3% and 2% of the documents, respectively. This disparity in the production of documents possibly suggests differences in care and research on air quality and asthma in different regions of the world.

The findings suggest that air quality assessment is essential to understanding the impact of air quality on human health [106]. AQIs, which consider a variety of atmospheric pollutants, such as O<sub>3</sub>, NO<sub>2</sub>, SO<sub>2</sub>, PM<sub>2.5</sub>, PM<sub>10</sub> and CO (Table S1), play essential roles in this process [107]. These pollutants were selected for their known adverse effects on respiratory health, including their ability to trigger or aggravate diseases such as asthma [108]. The indexes provide information on the concentration levels of these pollutants, which can be compared with air quality standards established by regulatory agencies to evaluate air quality and its possible impact on health [14]. The calculation methods used by the indexes are varied and specific; they combine information on different pollutants to generate a composite measure of air quality [26]. The results are interpreted and communicated in an understandable way for the public by classifying air quality into categories such as “good”, “moderate”, “bad” or “dangerous for health” [109].

The results suggest that data availability and access are essential for air quality indexes to be effective. These data are based on monitoring data provided by networks of government monitoring stations or other sources [110]. These indexes are essential for the evaluation and understanding of air pollution and its impact on human health [13].

Considering the variety of technical criteria, they provide an accurate measure of air quality and are valuable for the research and development of public health policies [106]. The accessibility of these data is relevant for their generation, updating and application in research and public health policies [111]. Lastly, they are essential to ensuring a healthy and sustainable environment for present and future generations [112].

Air pollution is a serious public health problem worldwide and has a great impact on the morbidity and mortality of the population. The most effective measures for reducing the impact of air pollution on the development of asthma and its burden of morbidity and mortality are those related to reducing emissions [46]. The expansion of public transport and the use of cleaner fuels in vehicles, industries and homes are feasible and necessary measures for reducing global warming and its direct effects on human health [113]. It is estimated that reducing emission levels to those recommended by the WHO can lead to an annual decrease of up to 60% in pollution-related deaths [114].

#### 4. Conclusions

The findings of this study allowed us to draw the following conclusions.

The results show that the most frequently reported air pollutants related to asthma are PM (Q3) > NO<sub>2</sub> (Q3) > O<sub>3</sub> (Q3) > CO (Q3) > NO (Q3) > SO<sub>2</sub> (Q3). These pollutants, generated mainly by the combustion of fossil fuels and vehicular traffic, are possibly associated with irritation of the respiratory tract and exacerbation of asthma symptoms. The findings suggest that this order of importance changes slightly when considering the use of AQIs in asthma studies: PM > NO<sub>2</sub> > O<sub>3</sub> > SO<sub>2</sub> > CO > NO.

These findings suggest that climate variables and AQIs play relevant roles in asthma research. Temperature (Q4) was the most relevant climate variable, followed by atmospheric pressure (Q3), wind direction (Q3), solar radiation (Q3), precipitation (Q3) and wind speed (Q3). The influence of the concentration and dispersion of air pollutants and, therefore, the prevalence and severity of asthma are relevant to asthma research.

The results suggest a complex interaction between climate variables and air pollutants. Factors such as temperature and solar radiation can affect chemical reactions and pollutant formation, while the direction and speed of wind can influence pollutant dispersion. AQIs such as the U.S.EPA-AQI and the AQHI are directly associated with air quality and the incidence, severity and exacerbation of asthma.

The findings suggest that climate change presents additional challenges in relation to asthma by influencing the environmental conditions that affect the disease. Phenomena such as heat waves, electrical storms and episodes of air pollution can trigger asthma exacerbations and increase the burden of the disease. Climate change can also influence the distribution and season of environmental allergens, as well as the formation of air pollutants, affecting the prevalence and severity of asthma.

Finally, these conclusions provide a comprehensive view of the relationships among AQIs, air pollutants and asthma and highlight the need for continued research in this field to develop public health policies and environmental regulations. Importantly, these findings should be interpreted in the context of the literature and the inherent limitations of observational studies. Indeed, more research is required to deepen our understanding of the mechanisms that link exposure to air pollution with asthma and to develop effective mitigation strategies.

**Supplementary Materials:** The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/atmos15070847/s1>, Table S1: Spatiotemporal trends for air pollutants, climate variables and AQIs in asthma studies [115–154].

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