

## Article

# The Hot Topics, Frontiers and Trends about Research on the Relationship between Air Pollution and Public Health—Visual Analysis Based on Knowledge Map

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**Abstract:** It is of great practical significance to analyze the hot issues, research frontiers, and trends concerning the relationship between air pollution and public health and to adopt reasonable strategies to control air pollution and prevent health hazards for follow-up research in this field. Unlike traditional literature reviews, this paper adopts a visual, flexible, and scientifically systematic approach to the analysis, which makes these analysis results more intuitive and comprehensive. Based on the core collection of the Web of Science and CNKI databases, this paper uses CiteSpace software to draw and comment on the maps of Chinese and English keywords, publishing time, author, country, and research institutions in this field. The results show the following: (1) The number of studies on the relationship between air pollution and health has increased year by year; researchers have formed sub cooperation networks, and the trend of cooperation and exchange has become more and more obvious in recent years; the impact of air pollution on health is a hot topic in the world. (2) Research hot topics mainly focus on the selection of air pollutants, health economic consequences of air pollution and the global burden of disease it causes, health indicators, research samples, which are gradually being refined, the synergistic governance of air pollution, and climate change. (3) The analysis of research frontiers and trends reveals that, first, the study of air pollutants in the English literature has undergone a refinement from nitrogen dioxide to fine particulate matter, and the sources of air pollutants in the Chinese literature have undergone changes in the petrochemical industry, indoor formaldehyde pollution, and haze. Second, atmospheric pollution has a significant negative impact on health, increasing the incidence of respiratory and cardiovascular diseases, and even causing death. Third, sustained exposure to pollution then causes greater damage to health and will be a key direction for future research. Fourth, the literature not only studies the correlation but also emphasizes the causal inference between air pollution and health and measures the economic costs associated with health. Finally, air pollution and climate change need to be governed synergistically. The article points out that the three areas of sustained pollution exposure, indirect consequences of negative health effects of air pollution, and air pollution and climate change may be the future focus of the field.

**Keywords:** air pollutants; sustained exposure to pollution; respiratory and cardiovascular diseases; CiteSpace; co-occurrence keywords; burst words



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## 1. Introduction

Air pollution is a growing hazard to human health. It causes respiratory and other diseases, and is an important cause of morbidity and mortality. The London smog incident in December 1952, an air pollution disaster, caused more than 12,000 people to die of respiratory-related diseases [1]. The environmental disaster and a subsequent series of air pollution events have gradually attracted the attention of academia, world leaders, and the public on the relationship between air pollution and health.

Since the 1980s, the rapid urbanization and industrialization of developed countries have led to an increase in air pollutant emissions, which has intensified the urgency of studying and solving this problem. Based on a large random sample of data from developed countries, studies found that people living in cities with a high degree of urbanization and industrialization had significantly higher rates of respiratory cancer, atherosclerosis, and ischemic heart disease than in other areas, and that these risks increased over time [2–5]. In addition, air pollution also significantly increases infant mortality [6,7]. The above conclusions are drawn from the research based on the samples of developed countries such as the United States and Europe.

Developing countries, especially those that rely heavily on manufacturing and fossil energy for their development, are facing serious pollution challenges as their level of industrialization and urbanization increases. Some scholars have conducted a series of studies based on data from developing countries, considering that the health effects of air pollution in developing countries may differ in many ways from those in developed countries, such as differences in regulatory environment, public health services, education level, and initial level of pollution and health [8,9]. The OECD estimates that nearly 1.5 million people die each year from exposure to particulate matter, more than from malaria or water pollution. As pollution levels rise, the organization claims that this figure may exceed 3.5 million people per year by 2050, with most of deaths occurring in rapidly industrialized countries such as India and China.

China is typical in terms of air pollution research. There are three reasons for this. First, in recent years, China has experienced a significant decline in environmental quality with its high economic growth, which provides a direct case study for the field. At the same time, the Chinese government has taken various measures to increase its efforts to combat air pollution, and pollution concentrations have declined significantly, which provides scholars with good conditions for quasi-experimental research. In addition, the accuracy, availability and accessibility of pollution data in China have been qualitatively improved, which provides scholars with a good research basis. Considering that pollution levels and environmental policies in China vary greatly in space and time, as well as that the quality of pollution data has increased significantly, scholars have continued to pay attention to this issue, producing a large number of relevant representative studies. In view of this, this paper summarizes relevant research on CNKI in order to find the different impacts of air pollution on health in different periods and the research progress of the relationship between air pollution and health. At the same time, in view of the comprehensiveness and universality of the global research on the relationship between air pollution and health, this paper summarizes and compares the research results of air pollution and health in the web of science database and makes a more comprehensive analysis and supplement to the research on the relationship between air pollution and health. However, faced with a large number of studies, it is difficult to systematically and scientifically sort out and summarize the research results by simply reading and summarizing the literature. Based on this, this paper uses CiteSpace software to conduct atlas quantitative research on the literature related to the relationship between the two so as to master the research hot topics, frontiers and overall trends in this field. Unlike traditional literature reviews, the contribution of this paper is to identify the main areas of research activity on the relationship between air pollution and health, and the stages of evolution of the research topics involved, in a visual, flexible and scientifically systematic way, making the results of the analysis more intuitive and comprehensive.

The structure of the rest of this paper is arranged as follows: the second part shows the data and methods, the third part discusses the general overview of air pollution and health research, the fourth part includes the analysis of research progress in the field of air pollution and health, the fifth part is the conclusions draw from our research, and the sixth part represents a discussion of our findings.

## 2. Data, Methods and Descriptions of Indicators

### 2.1. Data Sources

This paper takes the Chinese core journals in CNKI and the core collection of Science Citation retrieval Web of Science as the data source to conduct general measurement and statistics on the research on the relationship between air pollution and public health; we visualize and analyze the dataset with CiteSpace. Since there are few relevant documents in each year before 1991, which has little statistical significance, the retrieval time area of Chinese and English studies are uniformly set from 1991 to 2021. In the CNKI core journal database, the search strategy is set as the theme “atmosphere pollution” or “air pollution” and “health”. The search condition of the Web of Science core collection is TS = (air pollution and health). A total of 1111 Chinese documents and 29,422 English documents meet the search strategy.

### 2.2. Research Methods and Descriptions of Indicators

This paper uses CiteSpace visualization software for bibliometric analysis and literature knowledge mapping. The CiteSpace software was developed by Dr. Chaomei Chen, which combines social network analysis, association rule analysis and other methods to analyze the development dynamics of research fields through knowledge mapping, and explore the evolution trends, research hot topics, and research frontiers of research fields.

Based on the bibliometric method, 1111 Chinese studies and 29,422 English studies were retrieved as the research database of the relationship between air pollution and health, and the literature database was imported into CiteSpace software for the analysis of publication time, authors, issuing institutions, issuing countries, research hot topics, and research frontiers. Among them, the selection of evaluation indexes about research hot topics and research frontiers are explained as follows.

First, there is the issue of research hot topics. Keywords are a high condensation of the research content of the literature, and high-frequency keyword co-occurrence analysis, keyword clustering analysis, keyword centrality, and research content of highly cited literature can be used as the analysis indicators of research hot topics. Keyword co-occurrence analysis is a bibliometric method to identify research hot topics in the field by revealing or expressing how frequently keywords at the core of the literature appear in that research field. Based on the co-occurrence keyword spectrum, it can be found that the keyword co-occurrence network clusters into irregular regions, each of which corresponds to a label. The order is from zero to large, and the smaller the number, the more keywords are contained in the clusters; each cluster is composed of multiple closely related words. Centrality indicates the amount of information flow between keywords and the degree of control over the literature network, which can reflect the importance and connectivity of the relative position of the keyword nodes in a research field and is used to test whether the high-frequency keywords are in the core position and reflect the position of the nodes in the overall network. In addition, this paper also selects the highly cited literature in this field in both the English and Chinese literature as an auxiliary analysis, and the highly cited literature can also reflect the research hot topics in this field.

Second, there is the issue of research frontiers. The identification and tracking of research frontiers can provide the evolutionary dynamics of the research field, identify the research progress in each stage of the field and predict the development trend, mainly through the analysis results of the burst keywords for judgment. Among them, burst keywords are keywords with a sudden increase in frequency in a certain time period, emphasizing sudden change, which can reflect the research hot topics and trends in a specific time period. By identifying and tracking research frontiers, we can detect the sudden growth of research interest in a certain subject area and can predict the development trend of the field and identify the direction of further development.

### 3. General Situation of Air Pollution and Health Research

#### 3.1. Chronological Distribution

The publication of the research on the relationship between air pollution and health published in Chinese core journals is shown in Figure 1. The overall number of published papers shows an upward trend. The number of papers published before 2002 was less than 20, and the number began to increase significantly after 2002. The number of papers published in 2018 reached 99. The impact of air pollution on health has attracted extensive attention in the academic community.

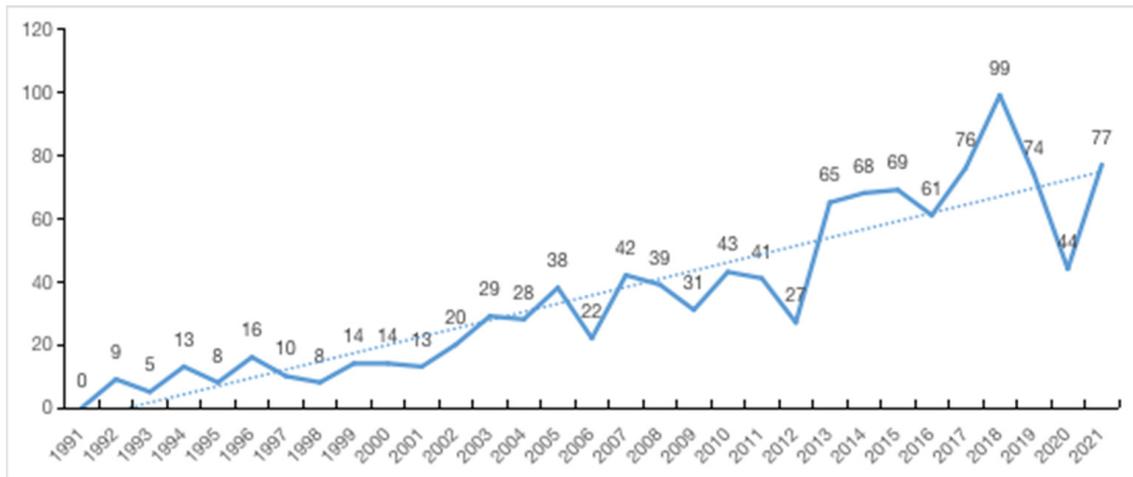


Figure 1. The number of Chinese studies with time.

According to the statistical analysis results of 29,422 English documents received in the core collection of Web of Science, the number of documents on the relationship between air pollution and public health is on the rise, especially after 1999, from 212 in 1999 to 4061 in 2021, as shown in Figure 2.

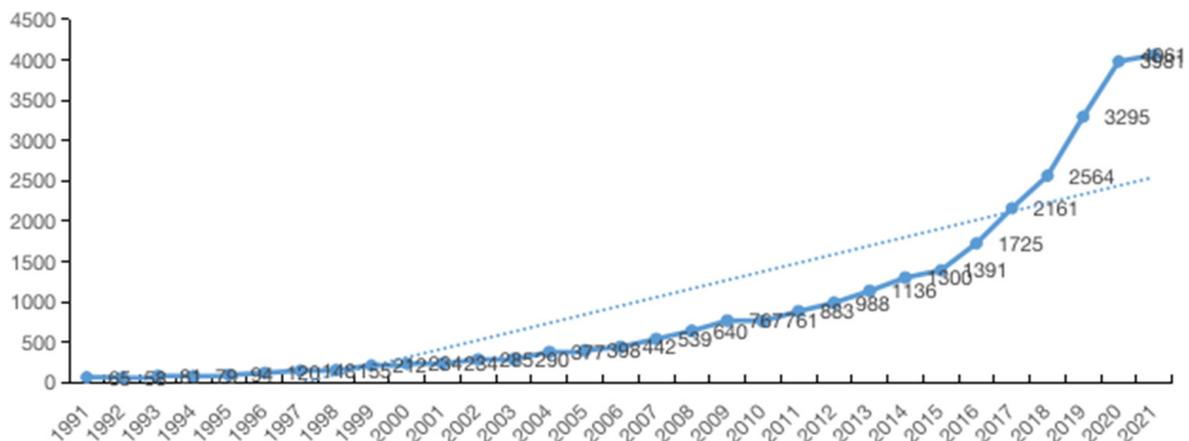


Figure 2. The number of English studies with time.

#### 3.2. Analysis of Author Collaboration Network

Figures 3 and 4 show the author collaboration network of the Chinese and English literature. The number of nodes, the number of links and the network density of the network can be seen by the parameters in the upper left corner. The number of nodes is the number of authors in the graph, and the number of links is the number of author collaborations; as long as the authors have appeared in the same document, there will be a link between them. The network density measures whether the authors collaborate closely with each other. In addition, the size of the circles of the nodes in the graph represents the

number of articles published by the authors, and the more articles published, the larger the circles. The color of the line corresponds to the color bar at the top of the graph. If the color of the line corresponds to the brown color on the left side of the color bar, it means that the authors collaborated a long time ago, and if the color of the line corresponds to the green color on the right side, it means that the authors collaborated recently.



Figure 3. Chinese literature author cooperative network.

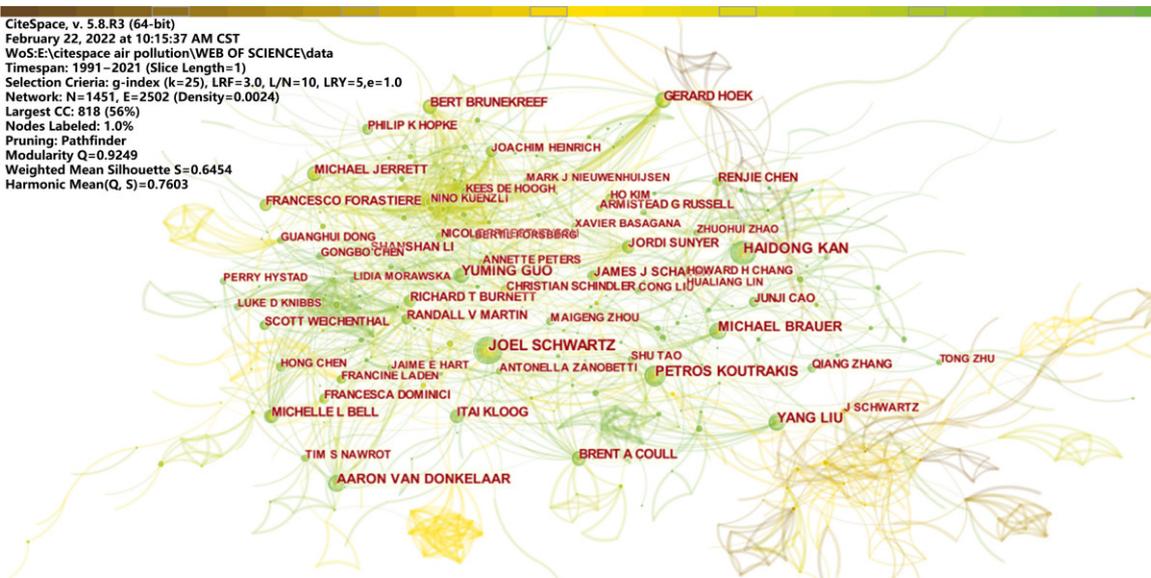


Figure 4. English literature author cooperative network.

The author network mapping shows some of the major authors generated based on the Chinese literature, where the number of nodes is 805, the number of connections is 1366, and the density is 0.0042. This small density value indicates that the network of the whole mapping is more fragmented. As can be seen from Figure 3, the scholars with a larger number of nodes are Haidong Kan, Dongqun Xu, Bingheng Chen, Xiaochuan Pan, Xinbiao Guo, Tiantian Li, Renjie Chen, Shuzhu Wu and Xin Zhang, and larger nodes indicate more publications. In addition, the mapping shows several author sub-networks, implying that scholars communicate and cooperate with each other, and the sub-collaboration networks centered on teachers such as Xiaochuan Pan, Dongqun Xu, and Yinlong Jin are more obvious. The color of the connecting line corresponds to the color bar at the top of the

figure. If the color of the connecting line corresponds to the brown color on the left side of the color bar, it means that the authors collaborated many years ago, and the green color on the right side means that the authors collaborated in recent years. It can be seen that the color of the collaboration network line of Xiaochuan Pan and Dongqun Xu is yellow and green, which indicates that the teachers have maintained their research in this field and contacted and cooperated with many other scholars for a long time, while several teachers, such as Haidong Kan, Bingheng Chen and Renjie Chen, who have also published more articles, have formed a mutual collaboration network, but have less communication with other scholars in comparison. The color of Shuzhu Wu’s collaborative network line shows that the time of publication and collaboration has been very early.

The number of nodes in the network map of English literature authors is 1451, the number of connections is 2502, and the density is 0.0024. This small density value indicates that the network of the whole mapping is more fragmented. As can be seen from Figure 4, the scholars with larger nodes are Joel Schwartz, Haidong Kan, Yuming Guo, Yang Liu, Petros Koutrakis, Aaron van Donkelaar and Michael Brauer. From the point of view of node color, these scholars have been researching for a long time and continue to plow deeply in this field. It is worth mentioning that Prof. Haidong Kan’s English posting volume is very high, but his cooperation network is not large compared with other scholars with a large amount of writing, combined with the previous Chinese literature analysis. Prof. Haidong Kan is a world leader in the number of Chinese and English publications in this field. In addition, the cooperation networks are mostly green and yellow, indicating that with the development of time, scholars pay more and more attention to mutual communication and cooperation; the cooperation has increased in recent years; and that there are many cooperative papers among various scholars.

### 3.3. Analysis of Research Institutions

The research institutions that published Chinese research in this field of the relationship between air pollution and health are shown in Figure 5. Three institutions—Peking University, CDC, and Fudan University—lead other institutions in China in terms of the number of Chinese publications, with Peking University having the highest number of publications, and all of the above institutions have more than 60 publications. Figure 6 shows the number of publications in English by research institution, where the top five institutions in terms of the number of publications are the University of California System, Harvard University, Chinese Academy of Sciences, Harvard T H Chan School of Public Health, and Peking University. As we can see, Peking University is still on the list, with a large number of publications in both English and Chinese, and has accomplished much in this field.

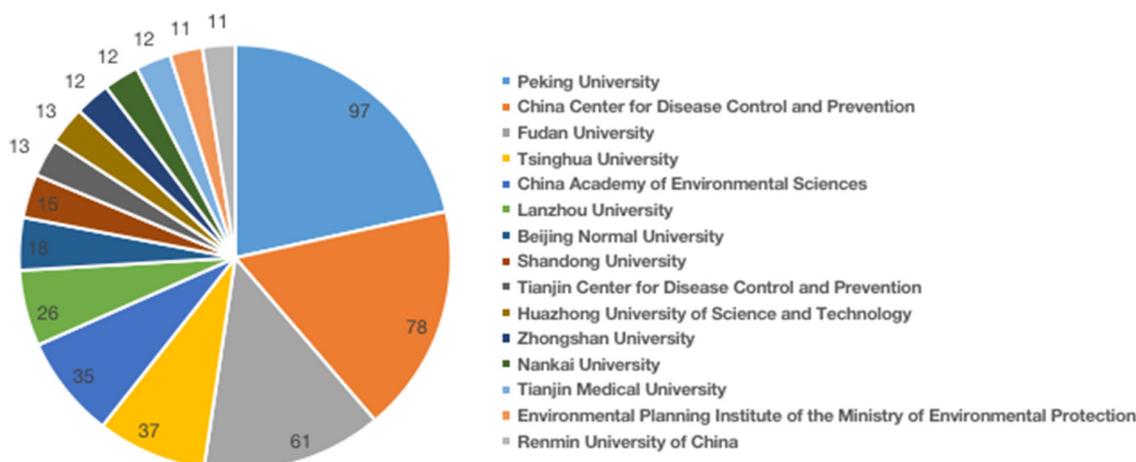


Figure 5. Chinese publication institutions of air pollution and health research.

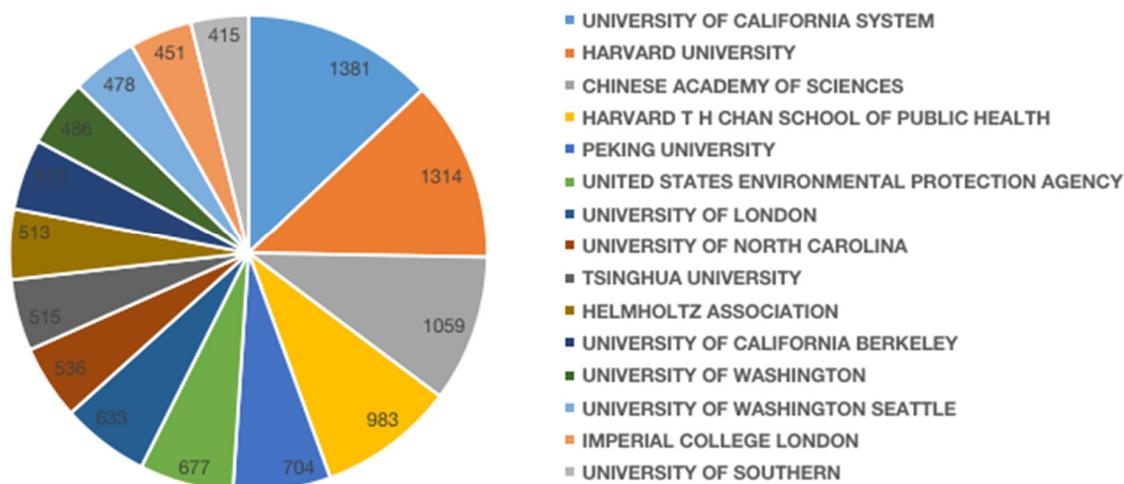


Figure 6. English publication institutions of air pollution and health research.

### 3.4. Country Analysis

According to the map of national co-occurrence knowledge drawn by the Web of Science database (Figure 7), the USA ranked first in node size and number of connections, indicating that the United States not only published the most papers in this field but also had the most extensive foreign exchanges and cooperation. The United States, China, the United Kingdom, Canada, Italy, Germany, India, and Spain are the countries with the highest number of publications, indicating that these countries have strong scientific research capacity in the field of the relationship between air pollution and health. On the one hand, it can be seen from the analysis results of the above research institutions that many universities in these countries have strong scientific research and academic strength. On the other hand, most of these countries are mature industrialized developed countries, which have accumulated rich experience in the impact of air pollution on health. It can also be seen that the study of the impact of air pollution on health has become a hot issue worldwide.

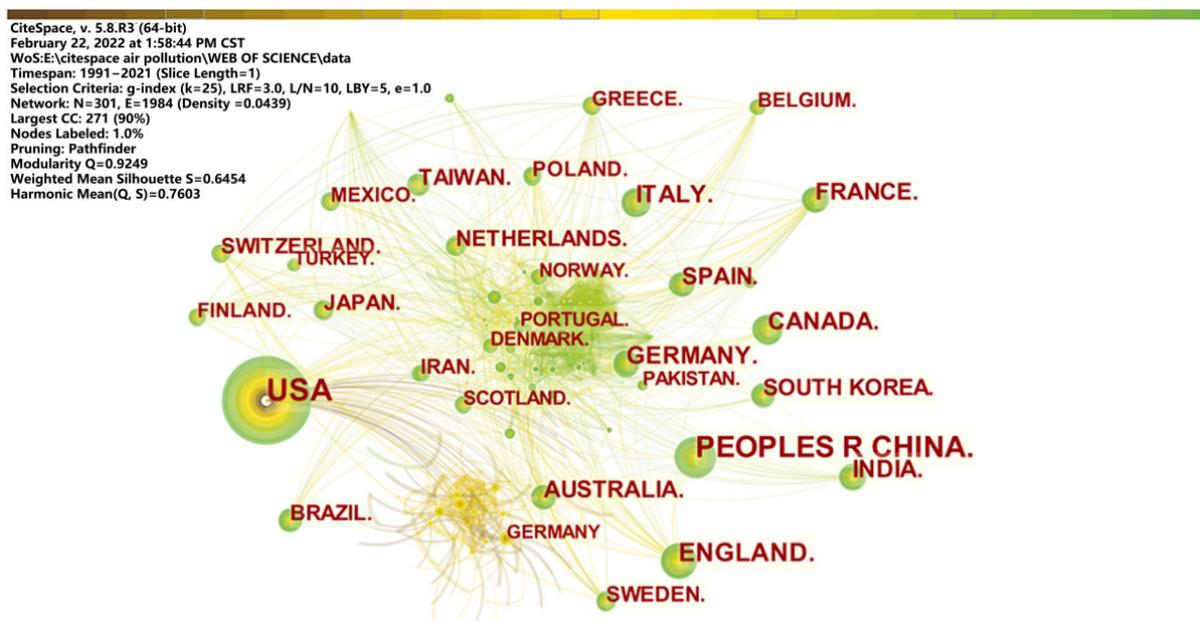


Figure 7. Co-occurrence knowledge mapping of the issuing countries.



**Table 1.** Highly cited Chinese literature.

Subject	Literature	Main Content	Cited Frequency
Health effects, health economic losses	[10]	Exposure response relationships for health effects of particulate matter	275
	[11]	PM <sub>10</sub> and economic losses to health	306
	[12]	PM <sub>2.5</sub> and premature death, respiratory disease	402
	[13]	PM <sub>10</sub> , PM <sub>2.5</sub> and daily mortality	243
	[14]	A comprehensive review of the health effects of haze	338
	[15]	A review of the health effects of TSP, PM <sub>10</sub> , and PM <sub>2.5</sub>	200
	[16]	Haze pollution causes, solutions	243
Economic losses from environmental pollution	[17]	Estimation of economic losses from environmental pollution	230
	[18]	Estimation of economic losses from environmental pollution	207
Climate change	[19]	Air pollution and climate change	196

**Table 2.** Main research hot topics in this field in English literature.

Number	Keyword	Frequency	Year	Centrality
1	Air Pollution	92,062	1991	0.3
2	Health	4072	1991	0.07
3	Exposure	3505	1991	0.11
4	Particulate Matter	3350	1994	0.15
5	Mortality	2580	1991	0.05
6	Pollution	2252	1991	0.07
7	Association	1803	1992	0.13
8	Impact	1533	2006	0
9	PM <sub>2.5</sub>	1392	2007	0.03
10	Particle	1348	1994	0.04
11	Risk	1319	2001	0
12	Emission	1301	1992	0.15
13	Disease	1011	1991	0.08
14	Children	829	1991	0.21
15	Quality	825	2009	0
16	Particulate Air Pollution	823	1994	0.04
17	Air Quality	770	2016	0

**Table 3.** Highly cited English literature.

Literature	Published Journals and Years	Main Content	Cited Frequency
[20]	LANCET 2017	Global burden of disease due to ambient air pollution	2432
[21]	LANCET 2012	Global burden of disease	6961
[22]	LANCET 2015	Global burden of disease	1690
[23]	LANCET 2018	Global burden of disease	1666
[24]	LANCET 2020	Global burden of disease	1414
[25]	NATURE 2015	Outdoor Air Pollution and Premature Mortality	2564
[26]	NATURE 2014	Secondary Aerosol and Particulate Pollution	2581

CiteSpace software provides two metrics, Modularity Q (Q value) and Mean Silhouette (S value), as a basis for judging the effectiveness of mapping based on network structure and the clarity of clustering. In general, the Q value is generally in the interval [0,1), the structure of the delineated associations is significant for Q value > 0.3, the clustering is reasonable for S value > 0.5, and the clustering is efficient and convincing for S value > 0.7.

#### 4.1.1. Research Hot Topics in Chinese Literature

##### Analysis of Chinese Literature Keyword

The clustering view of Chinese literature keywords is shown in Figure 8. The parameters in the upper left corner show that the Modularity Q value is 0.6846 and the Mean Silhouette value is 0.8782, indicating that both parameter values are within the ideal range, indicating that the mapping effect is good and the clustering effect is significant. The keyword co-occurrence network in the figure is clustered into many irregular regions, where each region has its own clustering label; the smaller the clustering number, the more keywords contained in the clusters. Figure 8 shows part of the clustering labels.

As shown in Figure 8, in addition to the subject terms of air pollution and health studied in this paper, the hot topics of the Chinese literature related to the study of the relationship between the two are mainly respiratory system, health risks and benefits, particulate matter, health effects and effects, air quality, human health, children's health, spatial layout, hypertension, diffusion simulation, and lung cancer incidence. These high-frequency and high-centrality keywords represent, to some extent, the hot issues of research concerns on the relationship between air pollution and health in the Chinese literature during 1991–2021. Based on these words, the hot topics are summarized as follows. First, the types of air pollutants with health effects; second, the health effects of air pollution, which are found by the clustering results that the health effects of air pollution are mainly focused on making the public suffer from respiratory and cardiovascular diseases; third, the study groups are more all-age samples, as many articles focus on their effects on children's health; fourth, what the spatial layout of air pollution is and the simulation of pollutant dispersion; and fifth, the causal effects of air pollution on health, and the assessment of health risks and benefits.

##### Analysis of Chinese Highly Cited Literature

The Chinese highly cited literature covers three main topics: first, the health effects of air pollution, including health risks and health economic losses; second, the economic losses due to environmental pollution; and third, the synergistic management of air pollution and meteorological changes.

Kan et al. (2002) [10] established an exposure–response relationship for particulate matter–health effects in China based on Chinese air pollution and health data, establishing the relative risk of occurrence of adverse health effects in the population for each unit increase in atmospheric particulate matter concentration at each health effect endpoint from morbidity to mortality. This literature has been cited many times and has been used by many scholars to evaluate the health risks of atmospheric particulate matter pollution and the health economic losses in China.

Chen et al. (2010) [11] roughly estimated the related health economic losses based on the annual average PM<sub>10</sub> concentration and health data in China in 2006, and the article found that the health losses caused by PM<sub>10</sub> pollution were mainly premature death, respiratory diseases, and cardiovascular diseases, and based on the outpatient and hospitalization costs incurred in dealing with these health problems, the health economic losses were calculated to be CNY 341.403 billion. Among them, the loss caused by premature death accounts for the largest percentage. High PM<sub>2.5</sub> exposure resulted in a significant increase in acute population health risk in Beijing during the study period, with a significant increase in sudden deaths, hospitalizations for respiratory diseases, hospitalizations for cardiovascular diseases, pediatric outpatient visits, and internal medicine outpatient visits. The article measured the economic loss of health of the population based on the population risk evaluation [12]. Based on the data from Shanghai, the same conclusion was obtained that PM<sub>10</sub> and PM<sub>2.5</sub> pollution significantly cause health risks and have potential health hazards for the acute population [13]. Bai (2004), Wang (2005), and Wang (2014) [14–16], on the other hand, conducted a review of the literature on the health effects of haze and particulate matter.

In the discussion of economic losses of environmental pollution, the losses involved mainly include economic losses caused by air pollution, water pollution, solid waste, and other pollution, among which economic losses caused by air pollution are further divided into economic losses of human health, industrial production, household cleaning and corrosion of construction materials, so economic losses of health caused by air pollution are only a part of the environmental pollution losses [17,18].

Another highly cited paper on climate change and air pollution points out that global climate change is mainly caused by increasing greenhouse gas emissions, while air pollution is mainly caused by aerosol particles, and the causes of both are largely common, mainly caused by emissions from fossil fuel combustion. Since the two problems (air pollution and climate change), not only coexist but also have the same causes to a large extent, it is necessary to formulate a synergistic or coupled management strategy to address both problems from the same source [19].

#### 4.1.2. Research Hot Topics in English Literature

##### Analysis of English Literature Keyword

Figure 9 shows the results of co-occurrence keyword analysis in the English literature. In this figure, each node represents a keyword, the size of the node indicates the frequency of the keyword, and the connection between the nodes is the co-occurrence relationship between the keywords. Table 2 shows the keyword centrality, which indicates the amount of information flow between keywords and the degree of control over the literature network. The larger the centrality, the more important the node is in the network. The larger the circle of nodes, the greater the centrality of the keyword, and the more it can represent the research hot topic in the research field.

In Figure 9 and Table 2, excluding the article's subject word "air pollution" and "health", the key words that appear more frequently in the field of air pollution-health relationship research are mainly "exposure", "association", "mortality", "particulate matter", "particulate air pollution", "pollutant", "disease", "emission", "children", "asthma", "PM<sub>2.5</sub>", "risk". From Table 2, the keywords with high centrality are mainly "air pollution", "children", "particulate matter", "emission", "association", "exposure". These high-frequency and high-centered keywords represent, to some extent, the hot issues in the field of air pollution and health that generally concerned the international academic community during 1991–2021. Based on these words, this paper classifies the hot topics into four categories: types of air pollutants that have health effects, ways of air pollutants affecting health, health consequences caused by air pollution, and groups affected by air pollution.

Combining the relevant literature and the analysis of the above results, firstly, from some high-frequency keywords—"particulate matter", "particulate air pollution", "pollutant", and "PM<sub>2.5</sub>"—we can see that the field focuses on the exploration of the types of air pollutants that affect health, and particulate matter is the main source of pollution affecting health. The WHO reported that atmospheric particulate matter can have harmful effects on public health in both developed and developing countries [27]. Second, keywords such as "exposure" and "emission" reflect the pathways through which air pollutants affect health. Much of the research studies the dispersion and emission of pollutants. The typical sources of air pollution such as outdoor motor vehicle emissions, coal combustion emissions and heavy industrial pollutant emissions, and indoor emissions of pollutant gases caused by smoking, cooking, and formaldehyde emissions from interior decoration, all lead to higher levels of human exposure to pollutants. One of the research components of the health effects of air pollution is to determine the exposure–response relationship of pollutants, where either short-term or long-term exposure to pollutants can have adverse health effects on humans [28], which also involves the third research hot topic attributed above—the health consequences caused by air pollution. Third, the adverse health effects of air pollution are mainly reflected in the positive correlation between the concentration levels of air pollutants and the incidence of respiratory diseases as well as other diseases and

human mortality. Fourth, atmospheric pollution can cause damage to the health of people at different ages, and the academic community has focused more on choosing children as a group as a research sample [29,30].

#### Analysis of English Highly Cited Literature

Exposure to ambient air pollution increases morbidity and mortality and is one of the major contributors to the global burden of disease [20], so it is necessary to cite articles that study the topic of disease burden when conducting research on the relationship between air pollution and health. Most of the highly cited research in the English-language literature focuses on studies of the global burden of disease, where the contribution of different risk factors to the burden of disease often changes significantly and where the health effects of the burden of disease are both general and more geographically specific, so that new studies are regularly updated with improved methods, new combinations of risks and risk effects, and new data on the association between risk exposure levels and risk outcomes assessments to report on the details and underlying causes of population health, thereby helping policymakers identify successes in disease control that can be emulated and opportunities for improvement [21–24].

As research progresses, we gain an increasingly detailed understanding of trends in exposure and each risk, and also gain insight into the magnitude of health losses attributable to the risk and how changes in exposure have contributed to health trends.

In terms of research on air pollution as one of the risk factors in the global burden of disease, one study quantified the global burden of disease due to air pollution based on the global range of pollution exposure and estimated the relative risk of death from cardiovascular and respiratory diseases using a combined exposure–response function for each cause of death, which found that air pollution contributed significantly to the global burden of disease in 2015, with PM<sub>2.5</sub> as the fifth-ranked risk factor for mortality, and exposure resulting in 4.2 million deaths and 103.1 million disability-adjusted life years (DALYs) in 2015, accounting for 7.6% of total global deaths and 4.2% of global DALYs, while reducing exposure has the potential to provide significant health benefits [20]. Lelieveld J et al. (2015) [25] studied the global contribution of outdoor air pollution sources to premature mortality, and the article used a global atmospheric chemistry model to study the association between premature mortality and seven air pollution emission source categories, calculating that outdoor air pollution, mainly PM<sub>2.5</sub>, contributes to 3.3 million premature deaths per year worldwide. In addition, one of the highly cited articles is a study on air pollution in China, which found that secondary aerosols contribute significantly to particulate pollution in Chinese haze weather, and that severe haze pollution events are largely secondary aerosol driven, with contributions of 30–77% and 44–71% to PM<sub>2.5</sub> and organic aerosols, respectively. Therefore, reducing emissions of secondary aerosol precursors from fossil fuel combustion and biomass burning, in addition to mitigating primary particulate emissions, may be important for controlling PM<sub>2.5</sub> levels and reducing the environmental, economic, and health impacts of particulate pollution in China [26].

#### 4.2. Research Frontier and Trend Analysis

Research frontiers are theoretical trends and new topics that are emerging in a given time period. CiteSpace software uses a burst detection algorithm to extract burst keywords from articles in order to detect sudden growth in research interest in a subject area and to identify and track the research frontiers and trends in the subject area. The burst keywords strength can reflect the influential research topics over a period of time. In Figures 10 and 11, the red line segment indicates the time period of the keyword burst, which is a visual representation of the begin and end years. In this paper, the analysis of research frontiers is based on the analysis of burst keywords, and, combined with the analysis of the literature where the burst words are located, we make a comprehensive judgment, generalization, and discussion.

### Top 16 Keywords with the Strongest Citation Bursts

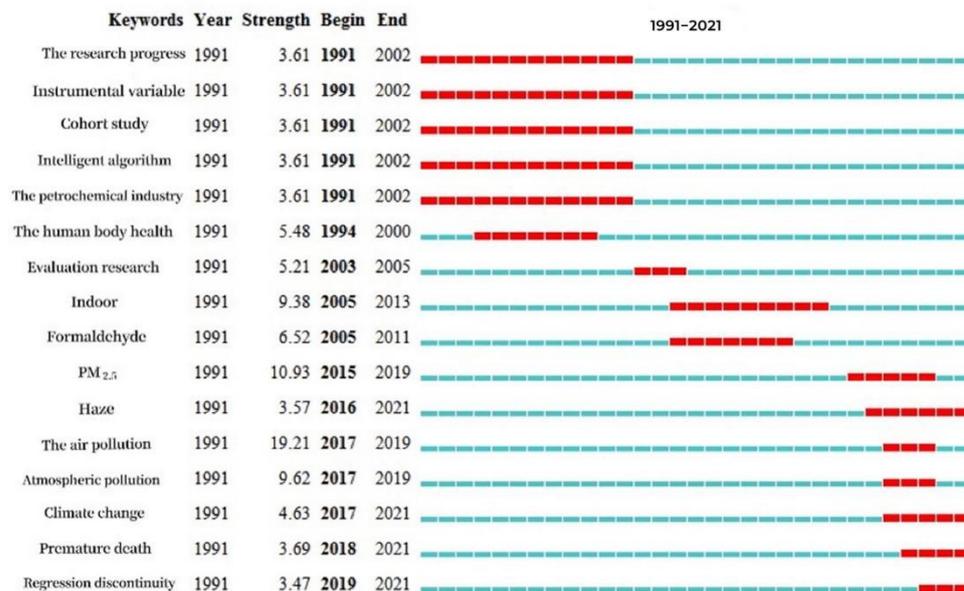


Figure 10. Chinese literature keyword bursts.

### Top 25 Keywords with the Strongest Citation Bursts

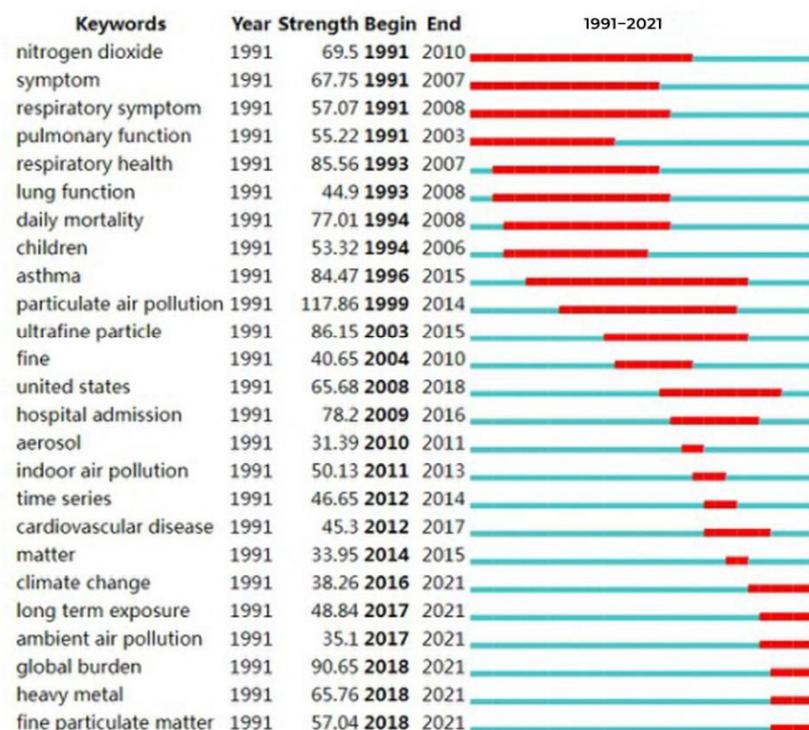


Figure 11. English literature keyword bursts.

#### 4.2.1. Research Trends in Chinese Literature

The burst keywords map of Chinese literature related to this paper is shown in Figure 10, and a total of 16 burst keywords were obtained. For example, it can be seen that the burst keywords during 1991–2002 are “research progress”, “instrumental variables”, “definite group research”, “intelligent algorithm”, “petrochemical industry”. Most of the keywords with large burst strength are atmospheric pollutants. It is worth noting that phrases such as “climate change”, “premature death”, and “regression discontinuity” have

burst in recent years and continue to be used today, so they can be regarded as the main research trends in this field in China at present. The Chinese research frontier can be broadly summarized into three stages of evolution: early research frontier, middle research frontier, and latest research frontier.

The early research frontier (1991–2005) reflected the research themes of “instrumental variables”, “definite group research”, “intelligent algorithms”, “petrochemical industry”, “human health” and “evaluation research”, which were mostly focused on the selection of research methods at this time, while it can be seen that most of the air pollutant emissions from crude heavy industries during this period came, and the petrochemical industry was a key concern at that time. For example, PAHs released from petrochemical areas are carcinogenic to humans, and Xia (2014) [31] explored the health risks caused by PAHs through the respiratory route and studied their effects on residents’ exposure.

The research themes in the mid-term research frontier (2005–2013) mainly focused on indoor pollution and human health hazards, with the burst keywords “indoor” and “formaldehyde”. At that time, due to the lack of supervision, inadequate laws and regulations, and low quality of products, the industry failed to develop with high quality in parallel with economic development, resulting in serious threats to human health caused by indoor air pollution, which became a research hot topic in the field, and poor-quality interior decoration led to formaldehyde pollution, which in turn affected the health of the public’s eyes and respiratory system [32].

The latest research frontiers (2013–2021) are “PM<sub>2.5</sub>”, “haze”, “air pollution”, “climate change”, “premature death” and “regression discontinuity”, which can be summarized into three aspects. Firstly, air pollution was focused on the public view in that period, and the research of major pollutants mostly focused on haze, PM<sub>2.5</sub> and other particulate matter, which is due to the fact that, at that stage, haze events were frequent in China, and PM<sub>2.5</sub> pollution was its root cause, and such air pollution was prone to causing human respiratory, cardiovascular, neurological and other diseases, and even lead to cancer [33]. The serious health consequences have caused great concern in society.

Secondly, premature human deaths caused by air pollution are also another key direction of academic concern. Air pollutant emissions lead to premature human deaths, which in turn cause health economic losses. At this stage, the country has implemented several environmental policies to control air pollution to avoid premature death of the population and save health economic losses, thereby increasing health benefits. Therefore, many scholars in this field also evaluate the causal effects of environmental policies on air quality and health [34,35].

Thirdly, studies have found that the causes of climate change are largely the same as those caused by air pollution; climate change is due to the increase in greenhouse gas concentrations, which are mostly caused by the combustion emissions of fossil fuels. This is consistent with the causes of air pollution, so the actions and strategies taken in the two works on air pollution control and greenhouse gas emission control are also consistent [19]. In addition, some studies have estimated the effects of air pollution by exploring climate change, such as wind and thermal inversion as IV [8,36], and wind can disperse pollutants and have a spillover effect on health. Thermal inversion occurs when warm air settles on the cold air and, in turn, atmospheric pollution becomes trapped and cannot be dispersed, greatly increasing air pollution concentrations.

Fourthly, Figure 10 shows that compared with the research methods in the early research frontier period, the research methods of the latest studies mostly use causal inference methods, such as regression discontinuity. Thistlethwaite first proposed regression discontinuity in 1960, which is a quasi-natural experiment, and Angrist used the method to study the effect of class size on achievement [37]. In recent years, the method has become one of the most widely used methods in causal inference and policy evaluation mostly applied in the fields of education economics, labor economics, environmental health economics and regional economics. The use of regression discontinuity for research on the effect of

atmospheric pollution on health mostly focused on mental health, population well-being, population migration, and health insurance needs [38–41].

#### 4.2.2. Research Trends in English Literature

The keyword burst graph of the English literature shows 25 burst keywords (Figure 11). Unlike the visualization results of burst keywords in the Chinese literature, the overall results of the English literature do not seem to present obvious phase characteristics, so this section will analyze the contents of the figure from a broader perspective and summarize the characteristics of research frontiers in the English literature. From different evaluation indicators, first, the keywords with high burst strength are “particulate air pollution”, “global burden”, “respiratory health”, “asthma”, “hospital admission”, “daily mortality”, “nitrogen dioxide”, “symptom”, “heavy metal”, and “united states”. This represents that these words are influential research topics during their burst cycle. Second, many of the hot words have a longer burst time, and the keywords with a longer burst cycle include: “respiratory symptom”, “symptom”, “lung function”, “daily mortality”, “children”, “ultrafine particle”, “pulmonary function”, “united states”, “nitrogen dioxide”, and “asthma”. Third, keywords with burst end dates between 2010 and 2021 represent the more frontier research themes of recent years, mainly including: “nitrogen dioxide”, “asthma”, “particulate air pollution”, “ultrafine particle”, “fine”, “united states”, “hospital admission”, “aerosol”, “indoor air pollution”, “time series”, “cardiovascular disease”, “matter”, “climate change”, “long term exposure”, “ambient air pollution”, “global burden”, “heavy metal”, and “fine particulate matter”. Fourth, the keywords that have suddenly broken out in recent years and have been hot until now represent the latest frontier research themes in the field, which mainly include “climate change”, “long term exposure”, “ambient air pollution”, “global burden”, “heavy metal”, and “fine particulate matter”. According to the above analysis, this paper will discuss the key research frontiers and the development stages of research frontiers combined with relevant literature based on two perspectives: the strength of keyword burst and the evolution of burst keywords over time.

#### Key Research Frontiers in English Literature

If the keywords have a high burst strength and a long burst period, they can represent the core research hot topics of the field in a certain period of time, and the keywords that meet this characteristic include “asthma”, “daily mortality”, “symptom” and “united states”. Among them, the impact cycle of “asthma” is from 1996 to 2015, the impact cycle of “daily mortality” is from 1994 to 2008. The impact cycle of “asthma” is from 1991 to 2007, and the impact cycle of “united states” is from 2008 to 2018. The keywords “asthma”, “daily mortality” and “symptom” represent the health consequences caused by air pollution, and air pollutants can cause health damage to the human respiratory system, triggering respiratory diseases and presenting symptoms of asthma, cough, bronchitis, and even leading to an increase in mortality among the population. It is worth noting that air pollution in the United States has been a key concern for a long time, since the United States is a highly developed industrial country that has experienced severe pollution during its rapid industrial development. Based on this background, the U.S. decided to establish the Clean Air Act, which not only helped the U.S. to improve air quality effectively, but also thus became a model for many countries in the world to learn from in the construction of the Clean Air Act. Many scholars have studied the health hazards of environmental pollution and evaluated the effects of environmental policies based on the U.S. sample.

#### Research Development Stage in English Literature

From an overall perspective, the research frontiers embodied by the burst keywords can be mainly categorized into three major categories, namely, types of air pollutants and pollution modes, health effects of air pollution, and synergistic management of air pollution. With the passage of time, there are stage characteristics for each topic category, as shown in Table 4.

**Table 4.** Evolution of research frontiers in English literature.

Topic	Stage	Burst Keyword	Begin-End	Burst Period	Strength	
Air pollution	Early stage	Nitrogen dioxide	1991–2010	20	69.5	
		Particulate air pollution	1999–2014	16	117.86	
		Ultrafine particle	2003–2015	13	86.15	
		Fine	2004–2010	7	40.65	
	Mid-term stage	Indoor air pollution	2011–2013	3	50.13	
		Matter	2014–2015	2	33.95	
	Latest stage	Long term exposure	2017–2021	5	48.84	
		Heavy metal	2018–2021	4	65.76	
		Fine particulate matter	2018–2021	4	57.04	
	Health effect	Early stage	Symptom	1997–2007	11	67.75
Respiratory symptom			1991–2008	8	57.07	
Pulmonary function			1991–2003	3	55.22	
Respiratory health			1993–2007	5	85.56	
Lung function			1993–2008	6	44.9	
Daily mortality			1994–2008	5	77.01	
Asthma			1996–2015	20	84.47	
Mid-term stage		Hospital admission	2009–2016	8	78.2	
		Cardiovascular disease	2012–2017	6	45.3	
Latest stage		Global burden	2018–2021	4	90.65	
Collaborative Governance			Aerosol	2010–2011	2	31.39
			Climate change	2016–2021	6	38.26

(1) Types of atmospheric pollutants and pollution modes. Scholars have mostly researched atmospheric pollutants such as NO<sub>2</sub>, atmospheric particulate matter, and heavy metal pollution, and the research hot topics about the types of atmospheric pollutants have gradually evolved and refined. First, the early air pollutants that have been paid attention to include nitrogen dioxide, particulate air pollution, ultrafine particles, and fine particles, and these air pollutants have been paid attention to for a long time. Second, after 2010, indoor air pollution and matter began to be widely studied, but the impact cycle of these two key words is only two years. Third, the latest research frontiers of atmospheric pollutants are long-term exposure, heavy metal, and fine particulate matter. In recent years, haze pollution has received great attention, and fine particulate matter (PM<sub>2.5</sub>) is the primary pollutant causing haze pollution, which has the characteristics of fine particles and large specific surface area, and it easily adsorbs more pollutants, especially for heavy metals with strong adsorption, resulting in secondary aerosol, which makes the heavy metal pollutants in fine particulate matter enter the human body through the respiratory exposure pathway and then cause health hazards [42,43]. Due to the more serious health hazards caused by heavy metal and fine particulate matter, they have gradually become a research hot topic in recent years. Of course, long-term exposure is a way for air pollution to affect health, and compared to short-term pollution exposure, long-term pollution exposure will be considered to cause greater damage to human health [44,45], and therefore is also the focus of regulation.

(2) The impact of atmospheric pollution on human health is mainly reflected in causing respiratory disease, cardiovascular disease, and death, so health indicators are mostly used for respiratory disease, cardiovascular disease, and hospitalization rate and daily mortality rate, and the health hazards caused by atmospheric pollution have created a serious global disease burden. In addition, Figure 11 shows that the burst interval of “children” is 1994–2006, and the early studies mostly focus on the effects of air pollution on children’s health, while the later samples are no longer limited to children.

Table 4 shows that, first, in the 1991–2008 period, scholars mostly explored the health consequences of mortality and respiratory disease; second, in the 2009–2017 period, hospital

admission and cardiovascular disease began to be used as indicators of human health; third, in the 2018–2021 period, the burst keyword is global burden.

Numerous epidemiological studies have shown that air pollutants can produce long-term [46,47] or short-term [48,49] health damage to the human respiratory system, triggering respiratory diseases and presenting symptoms of asthma, cough, and bronchitis; moreover, exposure to air pollution is significantly associated with increased mortality in the population, and the effects on mortality from cardiovascular and respiratory diseases are even more significant [50–52]. In addition, as mentioned in the previous analysis of research hot topics, the health loss caused by air pollution contributes significantly to the global burden of disease.

(3) Synergistic governance. As with the Chinese literature, the English literature also focuses on the relationship between air pollution and climate change, and aerosols are one of the topics of interest in this field since atmospheric aerosols are the main cause of air pollution, greenhouse gas emissions cause climate change, and the formation of aerosols is consistent with the increase in greenhouse gas emissions (both caused by fossil fuel combustion emissions). Therefore, atmospheric pollution and climate change need to be managed synergistically.

In addition, scholars usually use changes in meteorological conditions to address the endogeneity of air quality, such as wind and thermal inversion [8,36]. Wind can disperse pollutants and thus may produce spillover effects of air pollution, and the increase in pollution levels can have significant negative health effects downwind in the short term; thermal inversion occurs when warm air settles over cold air, and when it occurs, atmospheric pollutants are trapped and cannot be dispersed, thus greatly increasing ground-level air pollution concentrations. Therefore, thermal inversion is another commonly used air pollution research instrumental variable for air pollution studies.

## 5. Conclusions

In this paper, we use Chinese core journals in the CNKI and Web of Science core collection as data sources and use the CiteSpace software to visualize and analyze the basic situation, research hot topics, and research frontiers of the relationship between air pollution and health, and objectively explain the basic development trend of research results in this field in recent years, and we believe that the research results will become richer and more in-depth in the future.

- (1) Through the overall study of the health effects of air pollution, it is found that: firstly, the number of relevant Chinese and English studies has gradually increased with time, indicating that this field has attracted widespread attention from the academic community. Secondly, through the analysis of the author co-occurrence knowledge map, it can be seen that Prof. Haidong Kan is highly accomplished in this field, and the number of articles published in both Chinese and English is far ahead. In addition, several sub-collaborative networks of authors have been formed throughout the network map, and English-language publishers have increasingly focused on collaborative exchanges in recent years. Thirdly, the research institution with the highest number of Chinese publications is Peking University, which has published more articles in both English and Chinese in this field, and the institution with the highest number of English publications is University of California System. In addition, the United States not only has the largest number of articles but is also the country with the most extensive foreign exchange and cooperation.
- (2) Keyword co-occurrence analysis, clustering analysis, and analysis of highly cited literature were used to explore the research hot topics in this field. First, the results of keyword co-occurrence and clustering show that the research hot topics in the Chinese and English literature are generally similar. They mainly focus on four aspects: the types of air pollutants that affect health, the pathways through which air pollutants affect health, the health and economic consequences caused by air pollution, and the groups affected by air pollution. Second, the analysis of the highly cited literature

showed that scientists often explored the themes of quantifying the global burden of disease due to air pollution, health risks and health economic losses from air pollution, and synergistic management of air pollution and climate changes.

- (3) The frontiers and trends of the Chinese and English literature are summarized through the analysis of burst keywords. The Chinese literature has obvious stage research characteristics, and this paper divides its evolution process into three stages: the early research frontier (1991–2005) stage has more burst keywords focusing on the choice of research methods, and other burst keywords show that the industries causing air pollution are also mainly focused on the petrochemical industry. The medium-term research frontier (2005–2013) focuses on the impact of indoor pollution on human health. The research themes of the latest research frontier (2013–2021) are mainly focused on air pollution caused by haze, the relationship between climate change and air pollution, and premature death caused by air pollution. The research frontiers in the English literature can be summarized into three main categories: types of atmospheric pollutants and pollution patterns, health economic effects of atmospheric pollution, and synergistic governance of atmospheric pollution and climate change. Here, each category has a significant stage evolution.

## 6. Discussion

This article provides a broad overview of existing research results studying the relationship between air pollution and health, which provide strong evidence that air pollution around the world has significant health effects, deepen our understanding of environmental issues, and serve as a cautionary tale for newly industrializing countries in the prevention of air pollution. Some of the findings have already begun to have policy implications, and we anticipate that research in this area is likely to make an increasing contribution to environmental policymaking in the relevant countries covered in the article.

Combining the above analysis in this paper and the related literature, we believe that several possible important directions for future research on the relationship between air pollution and health are still worth further deepening and expanding. First, studying the health consequences of sustained pollution exposure is one of the most important research topics for the future. How to collect credible evidence of the long-term effects of air pollution, how to break through the difficulty of identifying exogenous changes in long-term pollution exposure, and breakthroughs in research methods may have to be continued in depth in future studies.

Second, the negative impacts of air pollution are not only an issue in terms of direct physical health damage, but air pollution affects long-term human capital acquisition, human cognition, and productivity by affecting physical health in turn. Given this, the economic loss of health based on direct health consequence measures is greatly underestimated, and therefore the negative health impacts of air pollution should be further explored fully in future studies.

Third, through this paper, we can clearly find that  $PM_{2.5}$ ,  $PM_{10}$ , and  $NO_2$  air pollutants still seriously affect public health, and we have to continue to make efforts for air pollution control. For example, we can continue to research the sources and control of air pollutants, air pollution policy formulation and policy evaluation, and air pollution synergistic governance. Among them, the synergistic management of air pollution and climate change is one of the latest research frontiers in this field. The common emission sources imply that there are many links between air pollution and climate change, and the implementation of climate policies can also reduce air pollution and thus benefit health, so the question concerning whether there is an optimal combination of air pollution and climate change policies is also worth further exploration by scientists.

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