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Review

A Review of Global $PM_{2.5}$ Exposure Research Trends from 1992 to 2022

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Abstract: Exposure to air pollutants of fine particulate matter ($PM_{2.5}$) is a major threat to human health. Research on $PM_{2.5}$ exposure has been on the rise in recent years, but there has been a lack of systematic literature analysis in this field. To address this research gap, we conducted a bibliometric analysis of the existing publications on $PM_{2.5}$ exposure over the past three decades and analyzed the current state and historical trends of research using the open-access tool, KNIME. Our results show that the number of publications on $PM_{2.5}$ exposure has been increasing at an accelerating rate over the last 30 years. The authors of the publications are primarily from developed nations, such as countries in North America, Europe, East Asia, and Oceania. Published research is mainly from the fields of Environmental Sciences and Ecology, Environmental Sciences, and Public, Environmental and Occupational Health. The main research hotspots are exposure, air pollution, and $PM_{2.5}$. Research is trending toward the intersection and integration of multiple subjects. Our results highlight the rapid growth of $PM_{2.5}$-related research and provide insights into the structure, impact, and trends of this interdisciplinary field.

Keywords: $PM_{2.5}$; exposure; bibliometric analysis; Web of Science; KNIME

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1. Introduction

Urbanization is the predominant trend of population aggregation and development globally over the past decades [1,2]. The rapid advancement of urbanization and industrialization has led to issues of uncoordinated development and high-intensity operations, resulting in global energy and resource crises, as well as severe air pollution and the continuous degradation of the ecological environment [3,4]. Air pollution, which is a prevalent companion in the process of urbanization, is considered a new form of disastrous weather and has garnered significant attention among scholars [5,6]. The growing issue of air pollution in urban areas has placed significant stress on the urban environment and human health, and this problem is becoming increasingly severe considering the conflicting demands for the high-quality and sustainable development of cities and towns [7–9].

According to the established convention, fine particulate matter ($PM_{2.5}$) is characterized as particulate matter that possesses an aerodynamic equivalent diameter of 2.5 microns or less [10]. $PM_{2.5}$ has become a prevalent pollutant in urban areas and is a significant contributor to air pollution [11,12]. $PM_{2.5}$ particles are characterized by their small diameter, light weight, high reactivity, and ability to remain suspended and drift in the atmosphere for extended periods [13,14]. The suspended particles can decrease atmospheric visibility, resulting in haze conditions, and have an impact on the radiation balance and the Earth's biological cycle [15,16]. Additionally, $PM_{2.5}$ particles have the ability to easily combine with toxic substances and can serve as carriers for virus transmission [17,18]. $PM_{2.5}$ exposure refers to the contact between the human body surface and air pollutants such as $PM_{2.5}$ [19]. Extensive research has demonstrated that exposure to $PM_{2.5}$ air pollution can have a severe impact on human respiratory and cardiovascular systems, resulting in elevated incidence rates and an increased risk of mortality related to pulmonary and cardiovascular diseases [20–22]. As a result, $PM_{2.5}$ exposure has become a topic of widespread concern among scholars globally and has led to a significant accumulation of scientific research findings [23,24].

Bibliometrics is an informative analysis framework to identify the key authors, institutions, countries, and journals within a particular research area [25]. It is used to gain insights into the research trends, patterns, and dynamics within a field. Additionally, by looking at the frequently cited articles in a particular field, a bibliometric examination of existing research can offer a neutral assessment of seminal works and peer acknowledgment of research work [26]. In the current study, Konstanz Information Miner (KNIME) and Python were used to visualize the descriptive statistical analysis. KNIME is an open-source platform for data integration, processing, analysis, and exploration that offers both ease of use and a wide range of capabilities [27,28]. It is designed to be user-friendly and provides a comprehensive set of features for data manipulation and analysis. KNIME also supports R, Python, and other multi-language extensions for program integration and encompasses a variety of data processing tasks. In this study, we utilized Python to retrieve data from the Web of Science server, which allows flexible data processing. Subsequently, KNIME was employed for pre-processing, data counting, and data visualization. In addition to the specific visualizations for the research questions of this paper, the workflow created in KNIME can be used for the reproducible cross-domain analysis of data in other fields of research.

Research on $PM_{2.5}$ exposure has been gaining increased attention in recent years, driven by the ambitious vision of the United Nations Sustainable Development Goals, such as good health and well-being and sustainable cities and communities [29]. To provide a crucial indirect insight into the current state of the field and future research trends, we conducted a bibliometric analysis of publications on $PM_{2.5}$ exposure over the past three decades. Utilizing a bibliometric analysis workflow, we investigated the following scientific questions:

(1) What are the spatio-temporal characteristics of the scientific literature on $PM_{2.5}$ exposure?
(2) Which are the hotspots of research areas for studying $PM_{2.5}$ at different stages?
(3) What are the key questions addressed and potential research trends in the field?

2. Materials and Methods

2.1. Literature Search Strategy

Web of Science (WOS) is one of the most authoritative bibliographic databases in the world and a widely accepted and used bibliometric database [30]. In this study, we selected WOS Core Collection (WOSCC) as our database to provide the literature search results. The search formula used for our research topic was: TS = (pm2.5 or pm 2.5 or pm(2.5)) AND exposure. We accessed these data through the WOS API, and as of 1 December 2022, a total of 16,913 documents were retrieved. All the records were processed in JSON file format for subsequent data cleaning and processing with "full record and cited references". After obtaining all the records, we excluded the parts where access was not available and the publication language was not English, and finally obtained 16,471 records of published articles.

2.2. Bibliometric Analysis

A classic bibliometric analysis process consists of five steps: study design, data collection, data pre-processing, analysis, visualization, and the interpretation of results [31]. The complete analysis workflow is shown in Figure 1 below. For the study design step, we selected $PM_{2.5}$ exposure as our research keyword for literature searching, and then we defined three scientific questions. The WOSCC, which includes the SCI expanded database and the SSCI, was chosen as the database. Second, during the data collection phase, we ended up with 16,471 papers. These publication data include attributes such as the year of publication, the authors' countries/territories, affiliation, abstract, keywords, WOS automatically generated keywords, journal source, research area, co-cited literature, etc. Next, we categorized the literature with the help of KNIME and Python, and open-source extensions. In the fourth stage, we used the KNIME platform's bar charts, network analysis, and bubble charts to create a statistical visualization of the various attributes.

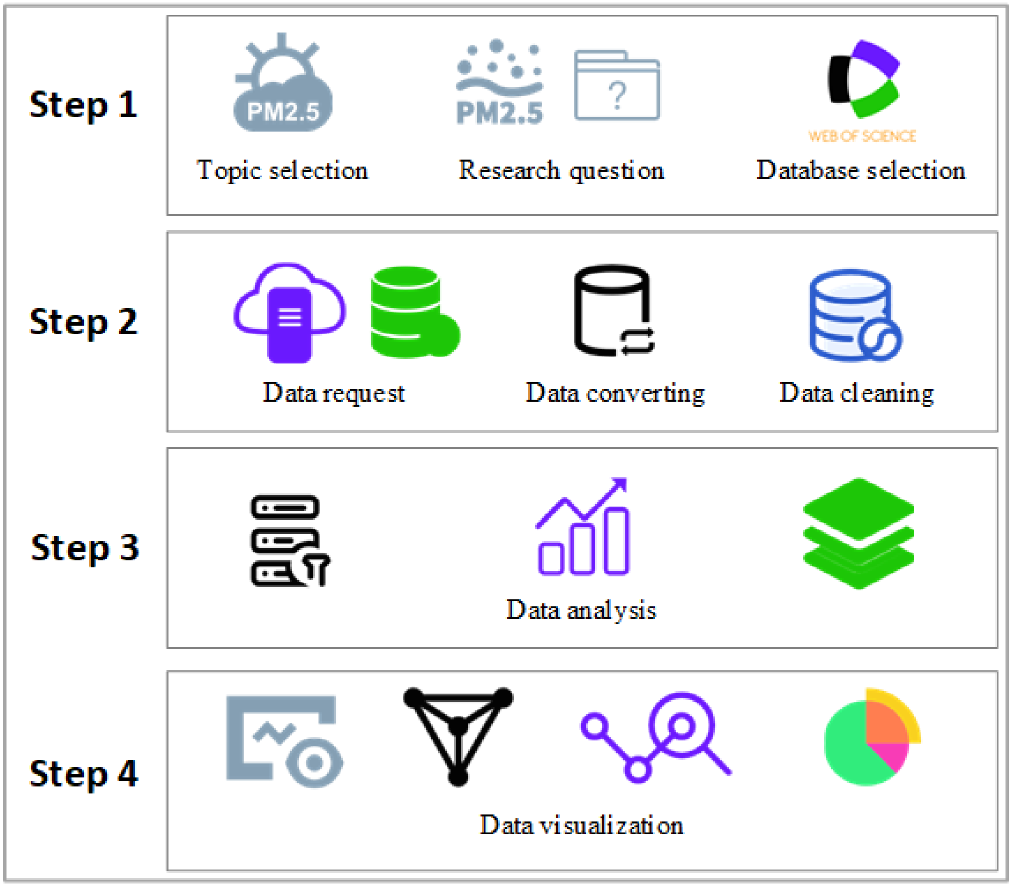

Figure 1. Flowchart of the bibliometric analysis methodology.

3. Results

3.1. Descriptive Bibliometric Analysis of Publications

The published literature relating to $PM_{2.5}$ exposure from 1992 to 2022 showed a continuously growing trend (Figure 2). The publication of Walkinshaw's seminal article, "Indoor Air'90: the 5th in a Series of International Conferences on the Indoor Environment" in 1992, marked the beginning of scholarly attention towards the issue of $PM_{2.5}$ exposure [32]. As research in this area has grown in quantity, the number of published articles on the topic has risen, with a marked increase in the last 30 years; specifically, the number of articles surpassed 100 in 2004, 1000 in 2017, and reached a record high of 2537 in 2022.

To provide quantitative insights into the temporal trends of $PM_{2.5}$-related research across different disciplines, we classified the 16,471 published articles into four groups: Science Citation Index (SCI) [33], SSCI (Social Science Citation Index) [34], SCI&SSCI, and Others. The category "Others" refer to the literature published as a conference paper, a book chapter, or in a journal that is not included in the SCI or SSCI databases. Overall, the number of publications in all four categories has been increasing over the past three decades, with the largest number of publications (13,649) in SCI journals, followed by a total of 1732 papers published in SCI and SSCI journals, 1235 papers published in SSCI, and 1073 papers in the "Others" category. To better analyze the temporal trends in the publications on $PM_{2.5}$ exposure, we divided the study period (1992–2022) into three stages. The first stage, which spans from 1992 to 2002, marks the initial phase of $PM_{2.5}$ exposure research, during which 248 articles were published. During this phase, with rapid industrialization at the global scale, people began to realize the association between air quality and certain diseases [35,36]. Research on $PM_{2.5}$ was explored as an emerging area of research at this stage. Between 2003 and 2012, which marks the second stage, there is a significant increase in the number of published articles, with a total of 2128 articles. This surge in publications can be attributed to globalization [37,38] and the consequent dramatic urbanization experienced by many emerging economies, which led to the emergence of a high prevalence of respiratory diseases [39,40]. Take China as an example, there has been a significant increase in cases of atherosclerosis, congenital malformations, and childhood respiratory diseases during this period [41,42]. This trend has garnered global attention, leading to the formulation of Sustainable Development Goals (SDGs) with a specific target (11.6.2) for controlling $PM_{2.5}$, which were first proposed by governments worldwide during the Rio+20 UN Conference in June 2012 [43,44]. In response, countries began to enact a series of policies to promote greener, more sustainable development after 2012 [45,46]. This worldwide mobilization has further fueled academic interest in air pollutants such as $PM_{2.5}$. As a result, from 2013 to 2022, there was an exponential growth in scientific research related to $PM_{2.5}$ exposure, with a total of 14,055 research articles published on this subject.

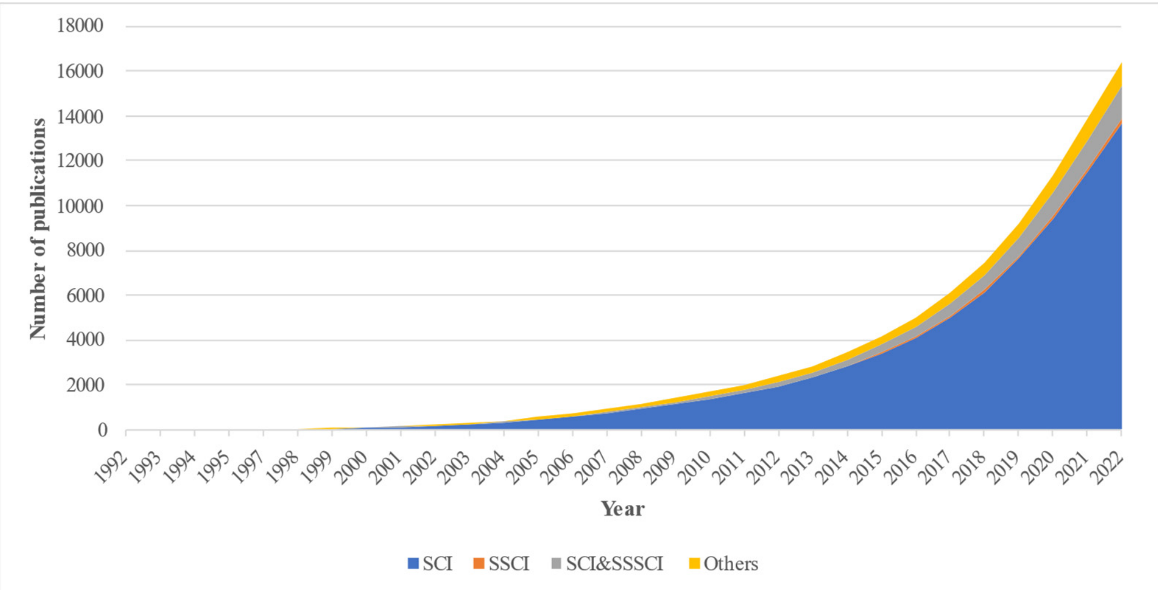

Figure 2. Number of published articlesfrom 1992 to 2022.

3.2. Contribution of Countries/Territories and Institutions

We used two different publication metrics to measure the contribution to $PM_{2.5}$ research from each country: the total number of publications from the country and the average number of publications by each author in the country. The spatial distribution map (Figure 3a) shows that the authors of the articles on $PM_{2.5}$ exposure published from 1992 to 2022 are from a wide range of countries/territories. Countries and territories in North America, Europe, East Asia, and Oceania have actively participated in scientific research on $PM_{2.5}$ exposure at both the total outputs and the average output per author. The USA and China contributed the most, and the number of published articles accounts for 22.04% and 19.59% of the total publications, respectively. This may be due to the fact that these countries are developed or rapidly developing nations with strong economies, leading to an increased sense of responsibility and heightened awareness among citizens regarding the issue of $PM_{2.5}$, resulting in higher research output in these regions.

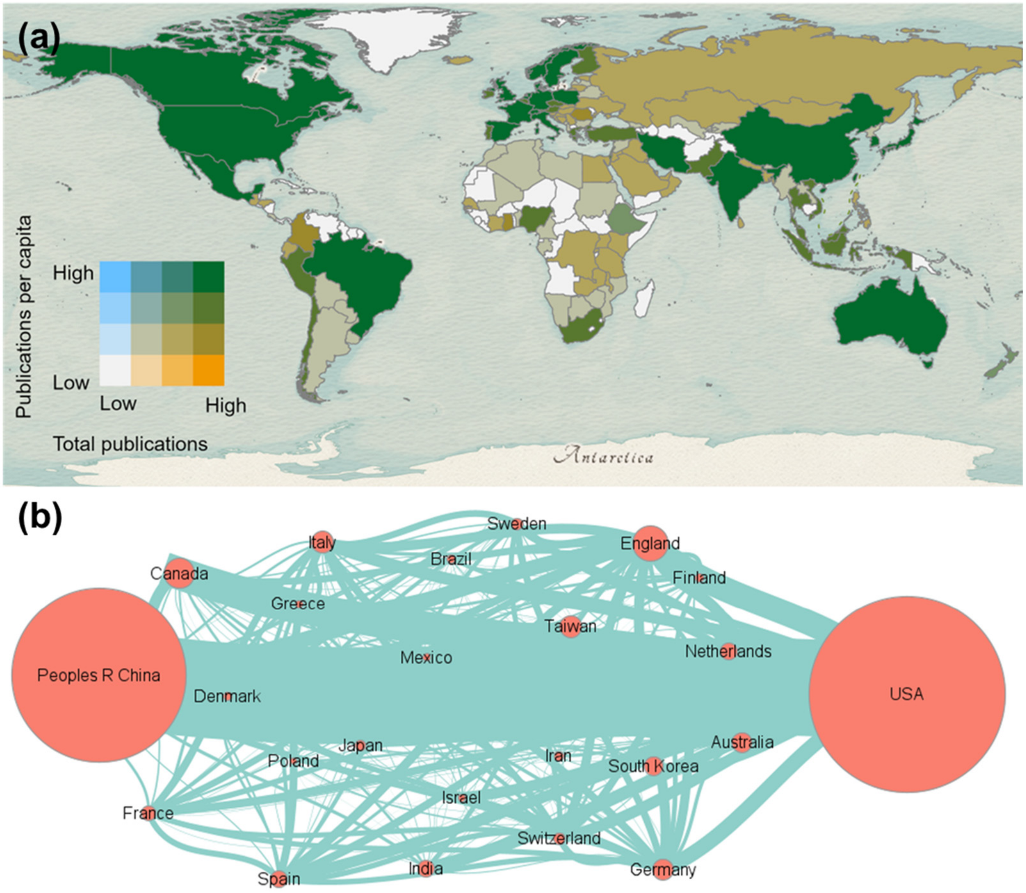

Figure 3. Contribution of countries/territories from 1992 to 2022. (**a**) Geographical distribution of total and per capita publications between countries/territories map; (**b**) global academic cooperation network map.

The network map of countries/territories engaged in $PM_{2.5}$ exposure research from 1992 to 2022 (Figure 3b) reveals a high level of cooperation among countries and territories in the field of $PM_{2.5}$ exposure research. This is particularly evident among countries with large volumes of publications, such as the USA, China, the UK, and Canada. This trend is closely related to the ranking of research and development expenditures among sovereign states. The aforementioned four countries are among the top 15 in the world in terms of research spending [47].

Building on the analysis of the contributions of countries and institutions, we further identified the top 10 institutions in terms of the number of published papers on $PM_{2.5}$ exposure (as shown in Figure 4). The results indicate a wide participation of universities and research institutions worldwide in the study of $PM_{2.5}$ exposure. Among them, Peking University, Harvard University, and the Chinese Academy of Sciences stand out as key institutions in this field, with a total of 406, 389, and 349 publications, respectively.

3.3. Contribution of Authors and Most Influential Publications

In this section, we calculated the top 10 authors in terms of the number of publications on $PM_{2.5}$ exposure to reflect their contributions to the field (as shown in Figure 5). The results indicate that each of these authors has engaged in at least 131 publications and made significant contributions to the scientific research on $PM_{2.5}$ exposure. Most of these authors are affiliated with universities or research institutions in the USA, China, the Netherlands, and Australia. Among them, Schwartz from Harvard School of Public Health stands out as the most active scholar in this field, having published about 224 articles, primarily focusing on air pollution and public health research.

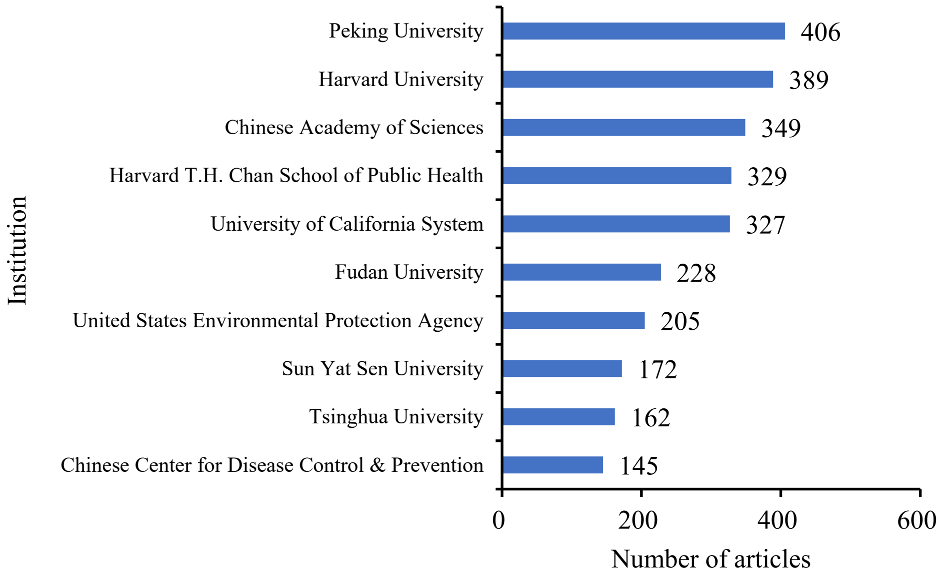

Figure 4. Contribution of institutions from 1992 to 2022.

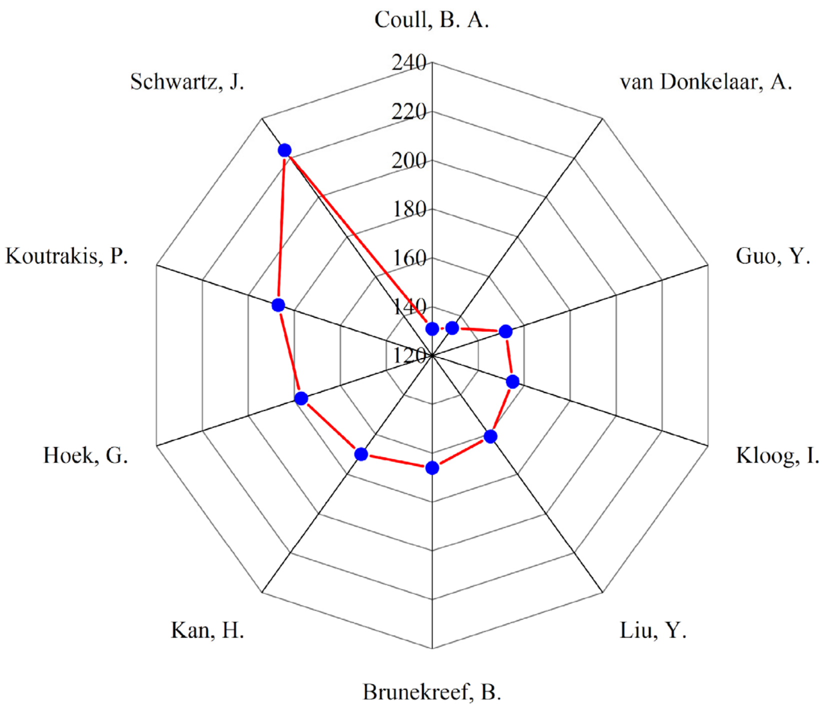

Figure 5. Contribution of authors from 1992 to 2022.

By conducting a bibliometric analysis, we identified the top 10 most highly cited articles on $PM_{2.5}$ exposure in the past 30 years (as shown in Table 1). These publications were mainly published between 2000 and 2019 in journals such as *Circulation*, *the Lancet*, *Environmental Pollution*, *Jama*, *the Proceedings of the National Academy of Sciences*, *Environment International*, *Environmental Health*, and *Environmental Health Perspectives*, and have been cited between 1011 and 4205 times. The articles mainly focus on subjects such as General and Internal Medicine, Environmental Sciences and Ecology, Science and Technology—Other Topics, Public Environmental and Occupational Health, Toxicology, and Cardiovascular System and Cardiology, among others.

Among them, the article titled "Particle material air pollution and cardiovascular disease an update to the scientific statement from the American Heart Association" published by Brook and other scholars in the *Journal of Circulation* has been cited the most, up to 4205 times [48]. This article provided a comprehensive analysis of the relationship between $PM_{2.5}$ exposure and cardiovascular disease and pointed out that $PM_{2.5}$ exposure is a modifiable factor contributing to cardiovascular morbidity and mortality. Exposure to $PM_{2.5}$ over a few hours to weeks can trigger cardiovascular disease-related mortality. Meanwhile, long-term exposure to $PM_{2.5}$ significantly increases the risk of cardiovascular death. It is consistent with the conclusion in early research by Peters that the increase in particulate air pollution will aggravate the triggering of myocardial infarction [49].

In addition, Kampa, Hoek, Kim, and other scholars carried out a review to discuss the impact of $PM_{2.5}$ exposure on human health in the field of Environmental Sciences and Ecology [50–52]. Laden et al. analyzed the relationship between fine particulate matter from different sources and mortality [53]. In addition, Cohen et al. discussed the spatial and temporal trends in mortality and disease caused by ambient air pollution, indicating that reducing $PM_{2.5}$ exposure is an important way to alleviate the global disease burden [54].

Moreover, many scholars have introduced quantitative assessment methods into the study of $PM_{2.5}$ exposure. For example, Burnett et al. constructed an integrated risk function to estimate the global disease burden caused by $PM_{2.5}$ exposure [55]. Dominici et al. evaluated the risk of cardiovascular and respiratory hospital admissions caused by short-term exposure to $PM_{2.5}$ in the USA [56]. Zhang et al. used an integrated evaluation approach to estimate the drivers of the improved $PM_{2.5}$ air quality in China from 2013 to 2017 in the field of Science and Technology—Other Topics [57]. In conclusion, this literature analyzed $PM_{2.5}$ exposure from different perspectives, providing important references for research in related fields.

Table 1. Most influential publications from 1992 to 2022.

Author	Year	Research Direction	Total Citations	Reference
Brook, R. D.	2010	General and Internal Medicine	4205	[48]
Cohen, A. J.	2017	General and Internal Medicine	2897	[54]
Kampa, M.	2008	Environmental Sciences and Ecology	2391	[50]
Dominici, F.	2006	General and Internal Medicine	1814	[56]
Zhang, Q.	2019	Science and Technology—Other Topics	1630	[57]
Kim, K. H.	2015	Environmental Sciences and Ecology	1464	[52]
Hoek, G.	2013	Environmental Sciences and Ecology; Public Environmental and Occupational Health	1165	[51]
Burnett, R. T.	2014	Environmental Sciences and Ecology; Public Environmental and Occupational Health; Toxicology	1114	[55]
Peters, A.	2001	Cardiovascular System and Cardiology	1079	[49]
Laden, F.	2000	Environmental Sciences and Ecology; Public Environmental and Occupational Health; Toxicology	1011	[53]

3.4. Analysis of Historical and Current Research Fields

The subjects engaged in $PM_{2.5}$ exposure research in the past 30 years (Figure 6a) show that the research on $PM_{2.5}$ exposure spans multiple subjects and is a research hotspot with interdisciplinary properties. As shown in Figure 6b, the top 10 research fields of published literature are Construction and Building Technology, Engineering, Engineering, Environmental, Environmental Sciences, Environmental Sciences and Ecology, Meteorology and Atmospheric Sciences, Public, Environmental and Occupational Health, Respiratory System, Science and Technology—Other Topics, and Toxicology.

We conducted an analysis of the evolution of key research fields in $PM_{2.5}$ exposure over the past 30 years, which indicates the following trends: during the initial stage (1992–2002), published research on $PM_{2.5}$ exposure is primarily from fields such as Environmental Sciences, Environmental Sciences and Ecology, and Meteorology and Atmospheric Sciences. However, scholars paid increasing attention to the subject of Public, Environmental and Occupational Health, with the largest amount of literature being published in this field.

During the second stage (2003–2012), Public, Environmental, and Occupational Health remained a key area of focus, with a total of 1562 published works. Additionally, a significant number of studies on $PM_{2.5}$ exposure were also conducted in fields such as Environmental Sciences and Ecology, Environmental Sciences, and Toxicology, resulting in the publication of thousands of articles. Finally, during the third stage (2013–2022), research in all subjects experienced explosive growth, with the number of published articles in Environmental Sciences and Ecology, Environmental Sciences, and Public, Environmental and Occupational Health reaching 9047, 8912, and 7006, respectively, which are now considered key current research fields in the field of $PM_{2.5}$ exposure.

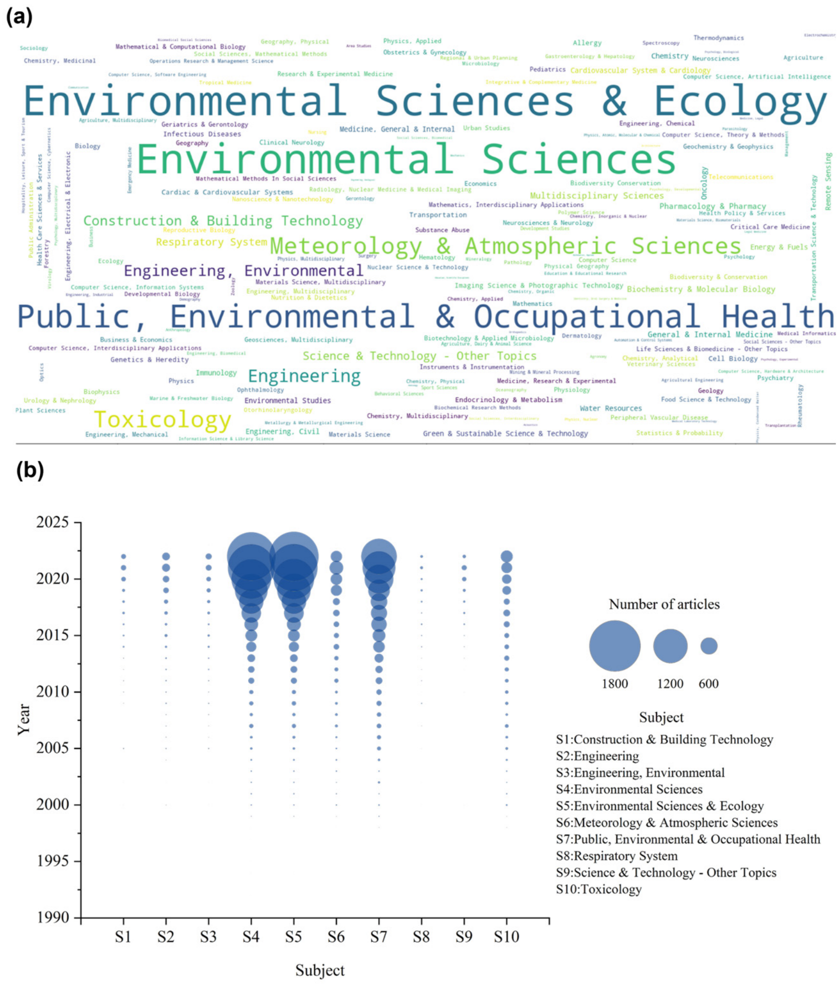

Figure 6. Research fields of publications from 1992 to 2022. (**a**) Subject map, (**b**) bubble chart.

3.5. Analysis of Historical and Current Research Hotspots

To more clearly identify the research hotspots of $PM_{2.5}$ exposure, we analyzed the top 10 keywords in terms of the number of published articles from 1992 to 2022, using both the keywords selected by the authors and those identified by WOS in the relevant literature.

The two statistical results (Figure 7) show that the air pollution, $PM_{2.5}$, particulate matter, and mortality are key research hotspots, with a high frequency of published literature. Specifically, according to the author-selected keywords, air pollution, $PM_{2.5}$, and particulate matter are the top research hotspots, with 3688, 3143, and 2637 publications, respectively. However, it should be noted that these keywords are subjective and may not provide a comprehensive view of the literature. In contrast, the automatic keyword recognition method through WOS provides a more objective analysis. The results of WOS identification show that exposure, air pollution, and $PM_{2.5}$ are relatively important research hotspots and the numbers of published articles containing those words are 4677, 4064, and

3595, respectively. In addition, compared with the keywords identified based on authors, the WOS method highlights the "Exposure" and "Long-Term Exposure" issues in $PM_{2.5}$ related research. The number of relevant articles is up to 6224, which is a potential research hotspot in the world.

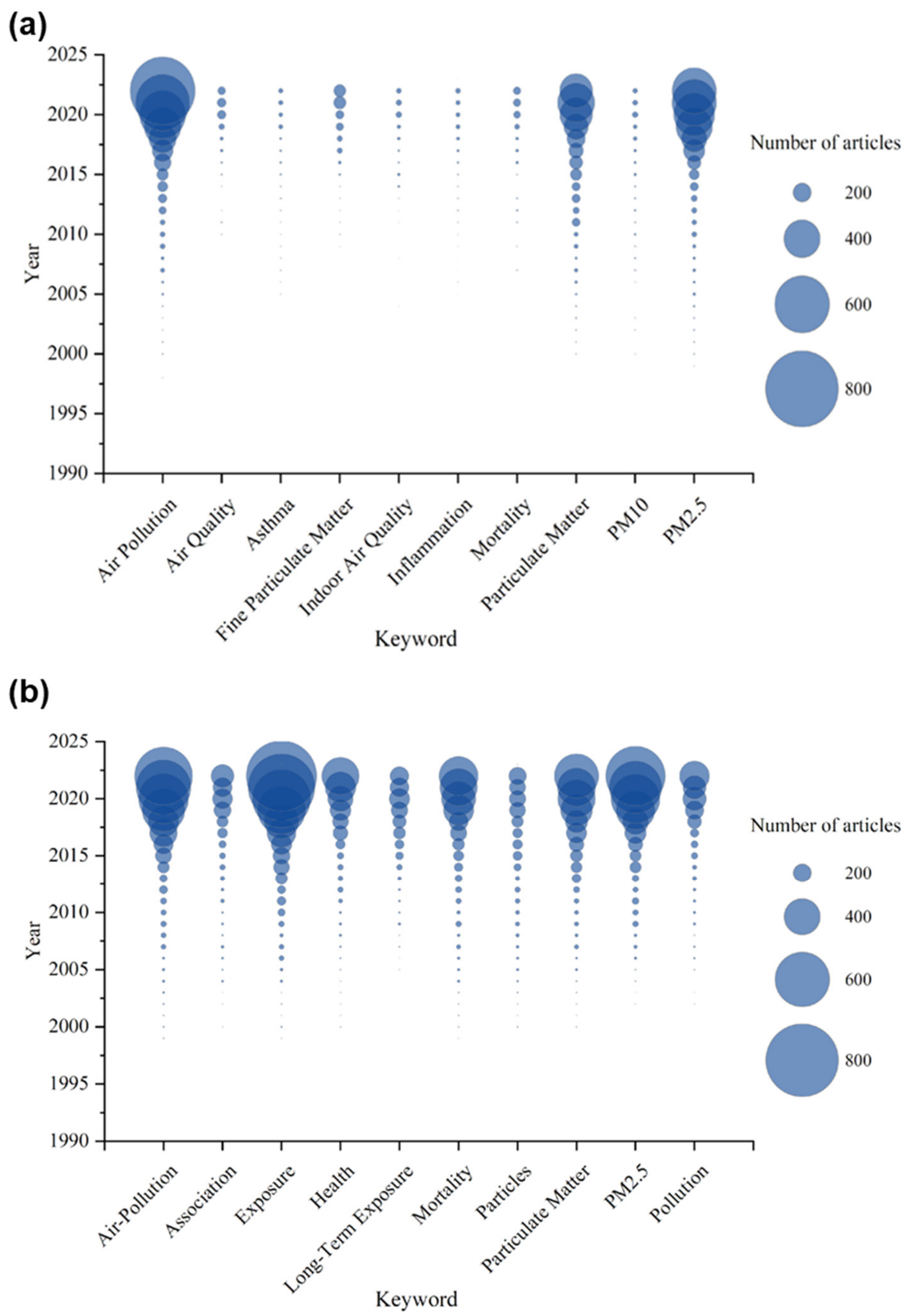

Figure 7. Research hotspots of publications from 1992 to 2022. (**a**) Keywords based on authors, (**b**) keywords based on WOS.

Then, we analyzed the changes in the research hotspots of $PM_{2.5}$ exposure in the past 30 years and the results are shown in Figure 7b. The keywords that scholars pay more attention to are exposure, air pollution, $PM_{2.5}$, particulate matter, mortality, health, pollution, particles, association, and long-term exposure, and the number of published articles is more than 1000. During the first stage (1992–2002), exposure to $PM_{2.5}$ air pollution seriously affected the life and health of residents and aggravated the occurrence of respiratory diseases. Therefore, the keywords that scholars pay more attention to are air pollution, exposure, mortality, and particles, etc. at this stage, and the total number of published articles is 278. During the second stage (2003–2012), the research related to $PM_{2.5}$ exposure grew rapidly. Exposure, air pollution, mortality, and $PM_{2.5}$ are the research hotspots, and the numbers of published articles are 557, 511, 425, and 400, respectively. During the third stage (2013–2022), pollution, air pollution, and health are the research background, and the number of articles reached 5037. $PM_{2.5}$, particulate matter, and particles are the research objects, and the number of articles reached 7153. Exposure and long-term exposure emphasized the state of research, and the number of articles reached 5478. Moreover, air pollution can cause mortality. The association of mortality with $PM_{2.5}$ exposure is also a research hotspot.

4. Discussion and Conclusions

Long-term exposure to $PM_{2.5}$ and other particles poses a significant threat to the health and well-being of residents and hinders the sustainable development of cities [58,59]. We aimed to summarize the past research progress related to $PM_{2.5}$ exposure and provide an automated, reusable, and extensible framework for a bibliometric analysis of the literature. This research took "$PM_{2.5}$ exposure" as the research theme, used KNIME software 4.7 to conduct a bibliometric analysis on the published literature obtained from WOS, and focused on three scientific issues to guide the future research direction, and promote high-quality development on $PM_{2.5}$ exposure research.

First of all, this paper analyzed the spatio–temporal characteristics of scientific literature on $PM_{2.5}$ exposure. In previous studies, scholars such as Li, Lin, and Yang et al. mostly conducted literature reviews on $PM_{2.5}$, but a systematic bibliometric analysis of the literature on the more targeted concept of "$PM_{2.5}$ exposure" is still lacking [15,60,61]. The research results show that the article on $PM_{2.5}$ exposure was first published in 1992, and in the following 30 years, the number of articles continued to grow, including a total of 16,431 published articles. Lots of countries and territories in North America, Europe, East Asia, and Oceania have actively participated in scientific research on $PM_{2.5}$ exposure. Peking University, Harvard University, and the Chinese Academy of Sciences are three key institutions with the largest number of published articles. Furthermore, cooperation between countries and institutions in $PM_{2.5}$ exposure research became increasingly frequent between 1992 and 2022. In addition, Schwartz is the most active scholar and Brook writes the most influential article in the field of General and Internal Medicine.

Secondly, we analyzed the dynamics of hotspot research fields related to $PM_{2.5}$ exposure by dividing them into three different research stages for comparison. In the first stage (1992–2002), the research on $PM_{2.5}$ exposure was in the initial stage, and only 248 articles were published. Public, Environmental and Occupational Health is the most important subject and the hot keywords are air pollution, exposure, mortality, etc. In the second stage (2003–2012), the research on $PM_{2.5}$ exposure developed rapidly, with 2128 published articles. At this stage, Public, Environmental and Occupational Health is still the most important subject, with 1562 articles. At the same time, Environmental Sciences and Ecology, Environmental Sciences, and Toxicology have also received a lot of attention. Exposure, air pollution, mortality, and $PM_{2.5}$ are the research hotspots, and the number of published articles exceeds 400. In the third stage (2013–2022), the research on $PM_{2.5}$ exposure ushered in explosive growth, with 14,055 published articles. At this stage, scholars pay more attention to $PM_{2.5}$ exposure from the perspective of the ecological environment. The most popular keywords are exposure, air pollution, and $PM_{2.5}$. At the same time, the largest number of articles was issued in the fields of Environmental Sciences and Ecology, and Environmental Sciences, with 9047 and 8912 articles, respectively.

Thirdly, we analyzed the past and potential research trends on $PM_{2.5}$ exposure. Through the quantitative analysis of the published literature in the past 30 years, it is found that exposure, air pollution, and $PM_{2.5}$ are the research hotspots, and the research on $PM_{2.5}$ exposure has the characteristics of multi-disciplinary participation. Environmental Sciences and Ecology and Public, Environmental and Occupational Health are all key subjects to carry out $PM_{2.5}$ exposure research. With the continuous development of society and the economy, the research on $PM_{2.5}$ exposure is gradually transitioning from public health to protecting the ecological environment. Therefore, the intersection and integration of multiple subjects may become the trend of research in the future. In addition, Liu, Shen, Dong, and other scholars have shown how to reasonably evaluate the temporal and spatial distribution pattern of $PM_{2.5}$ and quantitatively analyze the $PM_{2.5}$ exposure and the health risks are a key problem to be solved [44,62,63]. Meanwhile, Miranda, Santana, and other scholars pointed out that predicting air pollution levels such as $PM_{2.5}$ in different cities under different environmental conditions through modeling and data simulation can be an important research direction for future research [64,65].

As in other bibliometric reviews, although our study can provide insights into the research history of $PM_{2.5}$, hotspots in this research field, and identified influential papers, it has some limitations that can be addressed by future research. For example, our study did not analyze the evolution and trends in the data sources, study areas (countries/territories, urban/suburban), and the pollution sources that contribute to the $PM_{2.5}$ exposure. This is because such analysis requires coding of the methodology of every article on the research topic manually and is challenging when the publication number is huge. In our case, we have identified more than 16,000 articles that meet our search criteria. It is challenging to code every article to gain insights into the trends of the methodology. $PM_{2.5}$ is an interdisciplinary research topic that includes a diverse discipline such as environmental science [66], medicine [67], urban science [68], ecology [69], atmospheric science [70], public health [71], and toxicology [72], which use various data and methods for answering a diverse set of questions. Future research may narrow down the scope of the literature, and then provide a detailed compendium of the methods, study area, the data, and the main conclusions obtained for each article [73–75]. Such analyses can also help identify specific research gaps or future research directions.

Despite the limitations, our study provides insights into the structure, impact, and trends of $PM_{2.5}$-related research over the last 30 years. Furthermore, the reusable workflow developed based on KNIME can provide a low-code, user-friendly approach for researchers who want to understand other research fields systematically. Our study highlights that $PM_{2.5}$-related research is a rapidly growing interdisciplinary field. New techniques and methods have emerged in recent years to advance this field. For instance, previous studies found that $PM_{2.5}$ exposure and health risk assessments mostly used census-based population data [76,77]; they claimed that such research ignores the spatial distribution heterogeneity and mobility of the population, and the static assessment method gives rise to the geographic context of uncertainty problem (UGCoP) [78]. With the rise of the Internet of Things, Location Based Services (LBSs) have been considered an optional data source to integrate with $PM_{2.5}$ data to analyze the dynamic migration of the population and air pollutants, and effectively improve the assessment accuracy of the $PM_{2.5}$ exposure risk [79–82]. Therefore, the study of $PM_{2.5}$ exposure based on LBS dynamic population distribution can become an important direction in the future.

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