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Analysis of Status Quo of Research on Heavy Metals in Rivers and Lakes Based on Bibliometrics

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Abstract: Heavy metal pollution in rivers and lakes arising due to rapid economic development has been extensively studied by various countries due to its direct impact on ecological health and human well-being. However, there is a lack of comprehensive and systematic reviews addressing the current research status of this subject. In this study, we conducted a visual metrological analysis of the literature from 2001 to 2021 using the Web of Science (WoS) and China National Knowledge Infrastructure (CNKI) citation databases. The results show that studies conducted in other countries initially outnumbered those in China; after 2010, China emerged as the foremost contributor. Furthermore, both the WoS and CNKI databases indicate active engagement of Chinese researchers through a significant proportion of published papers on metal research, with prominent contributions coming from institutions such as the Chinese Academy of Sciences (CAS) and University CAS. Nevertheless, Chinese research institutions still have relatively low total paper citation numbers and have yet to establish themselves as key players in international scientific research efforts. Additionally, core authors from different countries share substantial similarities in their research directions and focuses. Consistent research hotspots regarding heavy metals in rivers and lakes were identified across both databases, including heavy metal pollution, adsorption, human activities, water quality, and sediment.

Keywords: heavy metal; rivers and lakes; bibliometrics; Web of Science (WoS); China National Knowledge Infrastructure (CNKI)

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1. Introduction

The rapid advancement of global industrialization has led to an increasing focus on heavy metals, which are persistent, highly toxic, and bioaccumulative environmental pollutants that pose significant risks to human health [1]. Among various environmental systems, heavy metal pollution in the water ecosystem, especially in rivers and lakes, exerts a direct impact on ecological health and human well-being, thus necessitating significant attention. Rivers and lakes are the main ecological elements of the water ecosystem. Rivers, as intricate, dynamic, open systems characterized by non-equilibrium and nonlinear behavior, play a crucial role in water circulation and pollutant migration; lakes serve as the key node of the watershed water ecosystem and hydrological cycle, and are also the primary reservoirs for pollutant accumulation [2]. Thus, rivers and lakes are important for the transportation and accumulation of pollutants including heavy metals. During the hydrological cycle, pollutants can migrate and transform between different carriers, such as rivers and lakes, significantly affecting the health and integrity of the ecosystem [3]. Therefore, research on heavy metals in rivers and lakes has become the focus of ecological environment protection.

The first study on heavy metals in rivers and lakes, initiated in 1972, investigated the levels of dissolved cadmium (Cd), zinc (Zn), copper (Cu), and other metals in the water of the Tasmania River in northern Australia [4]. China is a vast country with diverse landforms and a complex climate, resulting in the development of water systems characterized by abundant water, diverse species, and rich resources. However, the pollution of water resources by heavy metals has become increasingly severe in recent decades due to the rapid development of industries, agriculture, and tourism [5]. The earliest study on heavy metal pollution in the water of China dates back to 1979, when a study reported the concentrations of dissolved Cd, lead (Pb), Zn, and Cu in Xiangjiang River [6]. Subsequently, during the 1980s and 1990s, a limited number of studies investigating heavy metal pollution in waters of the Pearl River, Yangtze River, and Yellow River gradually appeared [7,8]. After the onset of the 21st century, an increasing number of studies have been conducted on heavy metals in Chinese waters, with a notable shift in focus from large rivers and lakes to small and medium-sized ones [9]. This reflects the common concern regarding heavy metal contamination in China.

In recent years, research in this field has increasingly established connections with a variety of keywords, including enrichment factor, human activities, antibiotic resistance, adsorption behavior, sequential extraction, and water quality. Researchers have employed a range of methodologies, such as statistical analysis, simulation models, experimental methodologies, and big data technology, to investigate these subjects. For instance, researchers have employed statistical analysis and modeling techniques to assess the degree of metal enrichment and identify potential metal sources in rivers and lakes [10,11]. These studies usually reveal a strong correlation between heavy metal enrichment and human activities [12]. Moreover, researchers have studied the contribution of various production activities (including industrial processes, mining, agriculture, and urbanization) to heavy metal pollution in rivers and lakes [13–15]. Their findings indicated that the wastewater and emissions resulting from these activities contain high levels of heavy metals and can contaminate nearby waters through direct discharge or atmospheric deposition. Regarding the association between heavy metals and antibiotic resistance, several studies have demonstrated a positive correlation between heavy metal pollution and increased antibiotic resistance in bacterial populations [16,17]; however, further research is warranted to comprehensively elucidate the underlying mechanisms [18,19]. In contrast, the adsorption of heavy metals onto different substrates has been extensively analyzed. Previous studies have revealed that composite materials exhibit an enhanced ability in heavy metal adsorption compared to individual substrates, which can be attributed to their characteristics, such as an increased surface area, modified surface chemistry, and functional groups facilitating metal binding [20–22]. Similarly, the chemical speciation of heavy metals has also been widely analyzed through sequential extraction techniques to assess the potential mobility of heavy metals in aquatic systems. Some studies have shown that manganese (Mn), cobalt (Co), and Cd have strong exchangeability in sediment, suggesting their greater potential for release into the water and consequent elevated risks to aquatic organisms [23–25]. Therefore, the levels of heavy metals in waters are also crucial indicators for water quality evaluation, and various concentration thresholds for heavy metals have been established in water quality standards, such as the Guidelines for Drinking-Water Quality by the World Health Organization (WHO) and the Environmental Quality Standards for Surface Water by the State Environmental Protection Administration of China.

In general, numerous countries have conducted extensive research on heavy metals in rivers and lakes. To comprehensively and systematically review the progress made in the above research direction and obtain reliable results that can provide important theoretical foundations for informed decision making and pollution risk control of heavy metals in aquatic systems, bibliometrics is acknowledged as a valuable methodology. Bibliometrics is a research methodology that employs quantitative analysis and statistical techniques to depict the research trends across various research fields [26], enabling objective, quantitative, and visually enhanced analysis of scientific and technical papers. This facilitates

the identification of influential studies, reputable sources, and key contributors, thereby providing valuable guidance for researchers in their subsequent studies and collaborations. This methodology has been employed to evaluate the scientific outputs and research patterns of authors, journals, countries, and institutions as well as to identify and quantify international collaborations [27]. In recent years, bibliometric-based data-driven analysis has been carried out for various aspects related to aquatic ecosystems, such as lake eutrophication [28], river habitat quality assessment [29], global lake wetland [30], sediment [31], and heavy metal pollution in rivers and lakes [32,33].

Considering the importance of research on heavy metal levels in aquatic ecosystems, coupled with the current lack of comprehensive analysis on its changing trends, we conducted a bibliometric analysis on relevant research concerning heavy metals in rivers and lakes. Our study primarily visualized the overall advances in this field in various countries, major research institutions and scholars, popular journals, research institutions, and highly cited papers. The results exhibit scientific productivity, influence, and developmental potential in this field, and clarify the main research directions based on relevant technical development trends, aiming to update researchers on the current situation, introduce cutting-edge dynamics, and establish future steps.

2. Data Sources and Research Methods

2.1. Data Sources

Science Citation Index-Expanded (SCI-E, part of the WoS Core Collection) and China National Knowledge Infrastructure (CNKI) were applied in this study to guarantee the accuracy and trustworthiness of the data. The WoS database contains a large number of citations and covers a comprehensive range of articles, and it is internationally recognized as a major search tool for scientific statistics and assessments [34]. Meanwhile, CNKI is the most influential academic journal database in China. Previous bibliometrics studies have demonstrated the robustness of analysis results by employing WoS and CNKI as the principal research databases [35–37]. To consider the quality of the literature comprehensively, data from 2001 onwards were collected for analysis in this paper.

In this study, an advanced search function was employed in the WoS database to conduct a precise search of English-language literature from 1 January 2001 to 31 December 2021. Similarly, we performed a precise search in the CNKI database for Chinese-language literature related to the topics of interest. All the collected literature was screened article-by-article to identify and remove any duplicates or irrelevant publications. The search formula and results are shown in Table 1, and the search was conducted on 10 August 2022. A set of valid studies were obtained after the screening process. To further enhance the analysis, several visual and analytical tools, such as Bibexce1 V16.2 [38], Pajek V3.11 [39], VOSviewer V1.6.14 [40], and CiteSpace V5.6.R5 [41], were utilized. Furthermore, visual analysis software and Origin drawing software were applied to visualize and assess the number of publications, authors, countries, institutions, and highly cited papers in their fields. This multidimensional analysis provided insights into the developments and research trends related to heavy metals in lakes and rivers.

Table 1. Search formula and database search results.

Database	Search Type	Number of Active Papers
SCI-E Database From 1900 to present	Theme = lake, heavy metal [1] OR Theme = river, heavy metal [1] And Publication date = from 1 January 2001 to 31 December 2021	16,701
CNKI	Fuzzy article abstract = river, heavy metal OR Fuzzy article abstract = lake, heavy metal Date = from 1 January 2001 to 31 December 2021	3608

[1] Fuzzy article abstract refers to fuzzy matching including keywords, authors, institutions, fundings, classification numbers, literature sources, or DOI containing search terms.

2.2. Methodology and the Main Procedure

The bibliometric analysis involves a systematic approach to assessing the influence of research on heavy metals in rivers and lakes. This process encompasses several key steps, including literature collection, data extraction, citation analysis, author analysis, visualization, and interpretation.

Firstly, a comprehensive collection of pertinent scientific publications was conducted using reputable databases such as WoS and CNKI. The data from the selected publications were carefully extracted, encompassing article titles, authors, affiliations, journals, publication years, abstracts, and keywords.

Secondly, citation analysis was performed to assess the influence and recognition of the selected publications, providing valuable insights into the research's impact within the scientific community.

Thirdly, author-level metrics, such as the h-index, were employed to evaluate the individual influence and productivity of authors, offering a robust assessment of their scholarly impact.

Furthermore, network analysis and visualization techniques, such as co-authorship networks or keyword co-occurrence networks, were employed to identify collaborative patterns and emerging research topics. These visual representations enable researchers to identify clusters of related studies and potential research gaps.

Lastly, the findings of the bibliometric analysis were interpreted and discussed in light of the existing literature. The implications of the analysis, including the identification of influential studies, key contributors, research trends, and research gaps, were thoroughly examined and emphasized.

By adhering to this rigorous and systematic methodology, bibliometric analysis provides a nuanced understanding of the influence of research on heavy metal pollution in lakes and rivers. It assists in identifying key contributors, delineating research trends, and pinpointing areas that require further exploration and investigation.

Table 1 exhibits the search formula and the database search results for studies on heavy metals in rivers and lakes conducted during 2001–2021. The selected papers served as a foundation for subsequent visual and quantitate analyses.

3. Results and Discussion

3.1. Analysis of the Results Based on the WoS Database

Based on the selected papers from the WoS database, the number of published articles, countries, authors, research direction, institutions, keywords, and highly cited papers were analyzed using quantitative statistics in conjunction with Bibexce1, Pajek, VOSviewer, and CiteSpace.

3.1.1. Number of the Published Articles

A total of 16,701 papers were examined, of which 16,188 (96.93%) were research papers, 570 (3.41%) were conference papers, 438 (2.62%) were reviews, and 187 (1.12%) were other types of papers. English was the predominant language of these papers (16,477), while other languages included Spanish (66), Portuguese (49), Chinese (43), Polish (32), and Japanese (14).

The number of publications on heavy metals in rivers and lakes from 2001 to 2021 is shown in Figure 1. It can be seen that the number of publications on heavy metals in rivers and lakes has increased rapidly since 2001. For example, the number of publications in 2021 was 7 times larger than in 2001, with an average annual growth rate of 19.38%, which indicates a consistent and steady upward trend in research output. The results highlight the increasing attention and interest of researchers in this field. Notably, this annual growth rate also exhibits a strong positive correlation with the increasing degree of pollution of lake sediments from 2001 to 2021, aligning with the economic and social development of China over the past 20 years [42]. In terms of the number of the published articles, the top three countries included China, the USA, and India. The number of documents published

by the USA and India has risen steadily since 2001. In comparison to these two countries, during 2001–2010, China exhibited a relatively smaller volume of publications. However, its growth in the past decade was the fastest among all the countries considered, surpassing that of both the USA and Germany and exhibiting an average annual publication volume 4.6 times greater than that of these two countries. This is closely related to the recent development of the Chinese economy and the pervasive presence of heavy metal pollution in many surface and drinking water sources. The water environment has gained increasing significance in the eyes of the government, leading to increased investment in research and control efforts targeting heavy metal pollution in rivers and lakes.

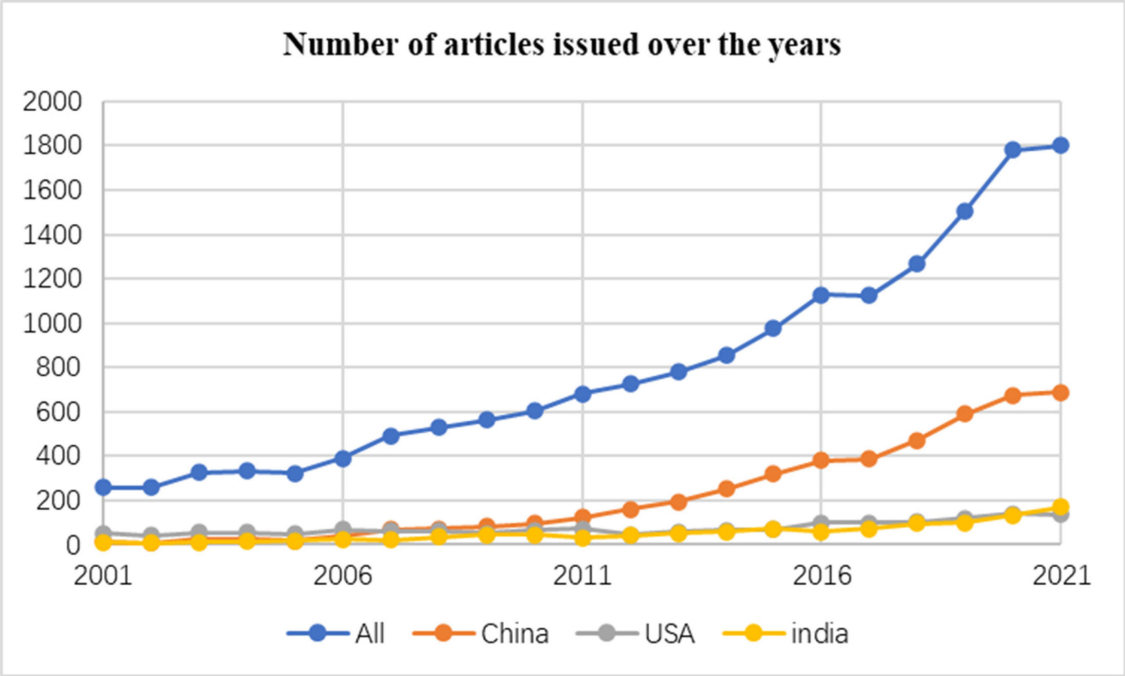


Figure 1. Publications on heavy metals in rivers and lakes from 2001 to 2021.

3.1.2. Country Analysis

VOSviewer [43] can be used to establish and visually analyze the cooperative relationships among different countries or regions in a certain research field [44]. The circles in various colors and sizes represent different countries or regions, with the size of each circle reflecting the number of publications from that specific country or region. Connecting lines indicate cooperative relationships between these countries or regions, and shorter lines denote closer collaborations [45,46]. A total of 24 countries have collectively published at least 300 (inclusive) papers on heavy metals in rivers and lakes. The international collaborative network (i.e., co-authors) involved in this research was analyzed using VOSviewer, with the results presented in Figure 2. The countries within the network have published at least 10 articles in this research field. When considering only the most prominent sub-networks, it becomes evident that the five clusters in the cooperative network, led by China, the USA, India, the UK, and Australia, exhibit strong interconnections and foster a robust cooperative relationship. The yellow-green clusters, which represent collaboration between Japan and other countries, exhibit relatively low levels of cooperation intensity. Consistent with findings in other scientific research fields, collaborative efforts tend to be concentrated among geographically proximate countries and are centered around the most productive country in terms of paper outputs [47].

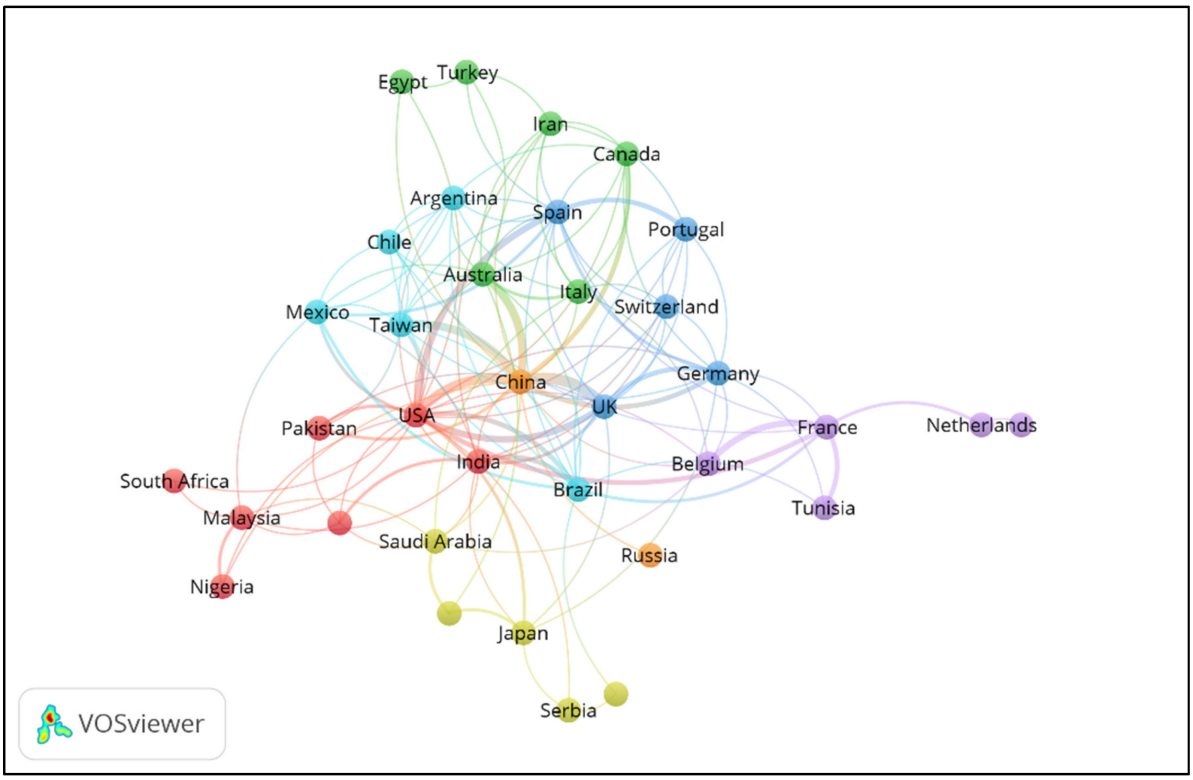


Figure 2. Research cooperation network between countries in the research on heavy metals in rivers and lakes.

3.1.3. Author Analysis

According to the statistical results, the research group in the field of heavy metal pollution in rivers and lakes comprised approximately 1001 authors from diverse countries. Among them, 30 authors contributed more than 30 articles, 87 authors published over 20 articles, and 346 authors published over 10 articles. Among the top 10 first authors in this field (Table 2), Zhang, Y.Y., from China, published a total of 111 articles and ranked first in terms of the number of publications. VOSviewer was used to analyze the collaborative network mapping of authors in the field of heavy metal pollution in rivers and lakes, and the results are shown in Figure 3. The authors included in the network were from the top ten author groups in this field in terms of number of publications, and the authors who did not have any associations with other authors in the network were not included. The collaborative network reveals the distinct clusters of authors. Among them, Zhang, Y.Y., Admiraal, W., Boughriet, A., and Grande, J.A., emerged as the principal researchers within this network, and other researchers were found to be associated with one of these principal researchers. Notably, it was observed that authors sharing the same name cannot be distinguished from each other, and when an author changes their name due to marital reasons, the different names used by the same author cannot be consolidated. To address this issue in academic publishing, the implementation of a mandatory unique numerical identification number (e.g., ORCID) for researchers upon their first publication is recommended [48,49].

As shown in Table 2 and Figure 3, the cooperative relationship among countries in research on heavy metals in lakes and rivers is limited. The cooperation groups were usually from the same institution in the same country, thereby fostering increased research cooperation opportunities among diverse countries and institutions in order to internationalize the field and generate novel perspectives and directions.

Table 2. Top 10 first authors in the research on heavy metals in rivers and lakes from 2001 to 2021.

Order	First Author	Country	Affiliated Institution	Number of Articles/Papers
1	Zhang, Y.Y.	China	Institute of Geographic Sciences and Natural Resource Research, CAS	111
2	Wang, J.	China	South China Agricultural University	108
3	Ouddane, B.	France	Lille University	100
4	Billon, G.	France	Lille University	89
5	De La Torre, M.L.	Spain	Universidad de Huelva	76
6	Zhang, H.	China	Xi'an University of Architecture and Technology	75
7	Grande, J.A.	Spain	Universidad de Huelva	67
8	Liu, Y.	China	Henan Normal University	63
9	Recourt, P.	France	Lille University	20
10	Boughriet, A.	France	Lille University	20

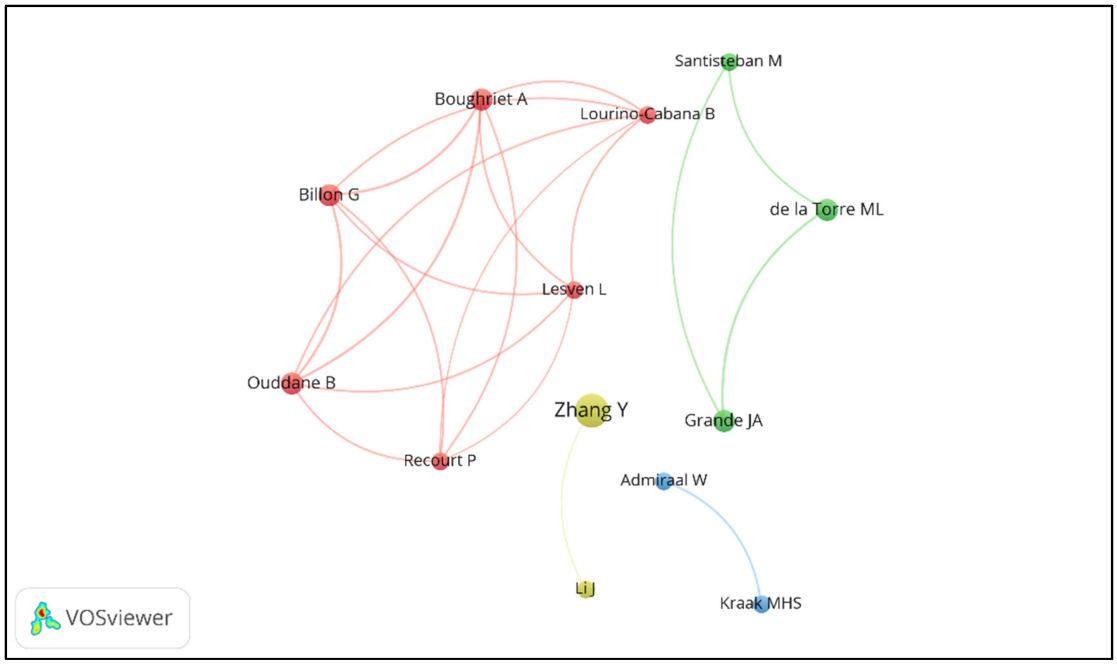
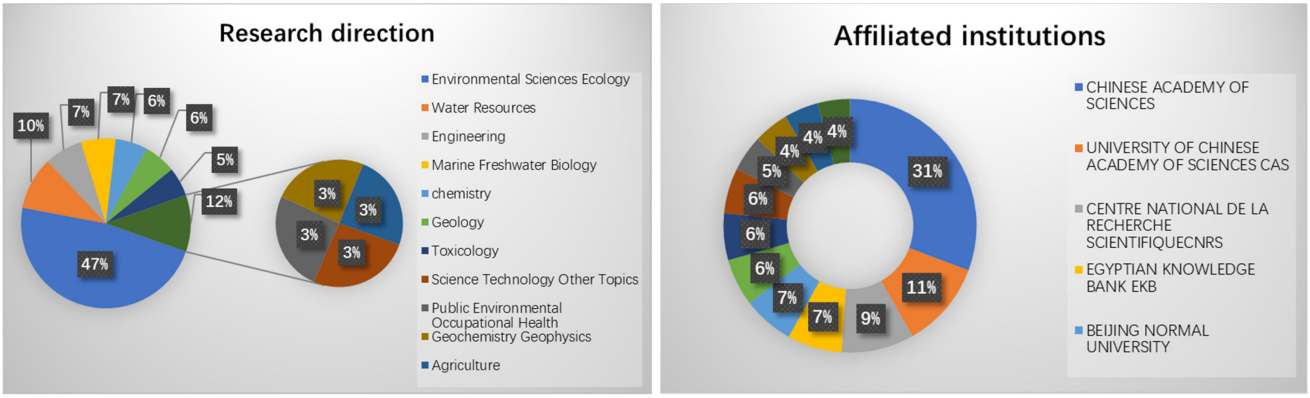


Figure 3. Inter-author collaboration network in the research on heavy metals in rivers and lakes.

3.1.4. Research Direction and Affiliated Institutions

Statistical analysis of the research direction of the topic under study and the institutions can clarify the key institutions and research hotspots in the field, aiding researchers in selecting pivotal journals and pertinent contents for literature reviews and research result publications [50,51]. The main international research directions for heavy metals in rivers and lakes are shown in Figure 4a. The main research directions can be observed to be primarily focused on "Environmental Science Ecology" (10,908 articles, accounting for 47%), followed by "Water Resources" (2304 articles, accounting for 10%), "Engineering" (1657 articles, accounting for 7%), "Marine" (1519 articles, accounting for 7%), "Chemistry" (1412 articles, accounting for 6%), "Geology" (1391 articles, accounting for 6%), and "Toxicology" (1266 articles, accounting for 5%). Additionally, "Science Technology Other Topics", "Public Environmental Occupational Health", "Geochemistry Geophysics", and "Agriculture" accounted for about 3% of the total number of articles, corresponding to 649, 625, 603, and 601 publications, respectively.



(**a**) (**b**)

Figure 4. Distribution of (**a**) research directions and (**b**) affiliated institutions of international journals focused on heavy metals in rivers and lakes.

It can be seen from Figure 4b that the Chinese Academy of Sciences (CAS), University of CAS, Centre national de la recherche scientifique (CNRS), Egyptian Knowledge Bank (EKB), and Beijing Normal University collectively contributed approximately 65% of the total number of the published articles. The primary contributor was CAS, accounting for 31% of the total number.

3.1.5. Keyword Time Cluster Analysis

Keywords serve as summaries of the main contents of studies and are often used to analyze emerging trends in a research field [52]. In this study, CiteSpace [53] was used to perform co-occurrence and temporal cluster analysis of keywords.

Cluster analysis is an approach that utilizes cluster statistics to group related keywords into distinct classes [54]. The analysis was conducted through visual mapping of co-cited timelines to provide guidance for subsequent research endeavors. To gain a clearer understanding of the keywords, keyword time clusters from 2016 to 2021 were analyzed, and the literature was imported into CiteSpace V. A total of 24 clusters, consisting of 897 nodes and 1282 connected lines, were obtained for the co-citation network map (Figure 5). The mapped network exhibited a well-defined cluster structure (modular Q-function of 0.4873), with distinct thematic clusters identified (a mean of 0.5089). The nodes identified as "fish", "enrichment factor", "human activities", "antibiotic resistance", "adsorption", "sequential extraction", "water quality", and "pm2.5" were the most frequently utilized keywords during this period, and all the nodes appeared in 2016. The number of new research directions for these frequently utilized keywords witnessed an increased from 2016 to 2021.

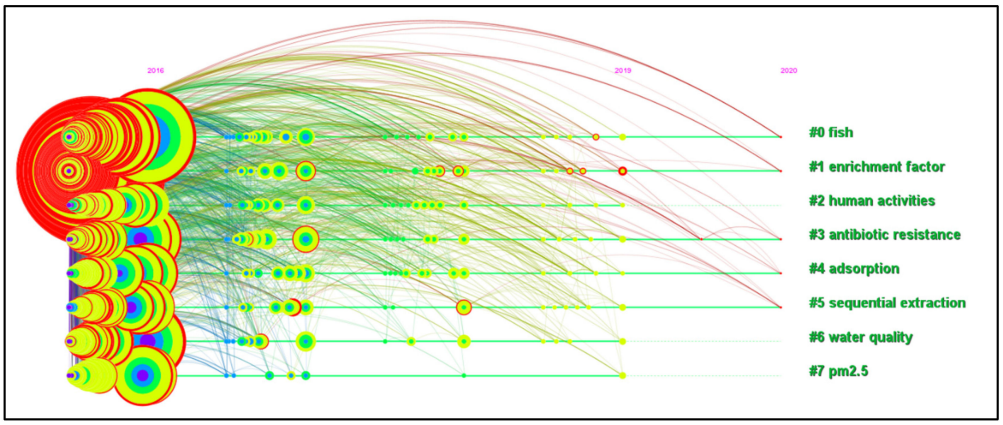


Figure 5. Cluster analysis of keywords in research on heavy metals in rivers and lakes from 2016 to 2021.

3.1.6. Analysis of Highly Cited Papers

The highly cited papers reflect the hotspots and developmental trends of the field. There were five articles on heavy metals in rivers and lakes garnering over 400 (inclusive) citations from 2001 to 2021, as shown in Table 3. The most frequently cited study was a 2019 research paper authored by Ali et al. [55] from the University of Malakand, USA, in Chemistry. The paper has received extensive academic attention, with 728 citations and 114 references, providing detailed insights into the environmental association of highly hazardous heavy metals (including chromium (Cr), nickel (Ni), Cu, Zn, Cd, Pb, mercury (Hg), and arsenic (As)). Nutrient transfer of the above elements in aquatic and terrestrial food chains/food chain webs is of great importance for wildlife and human health 10. Therefore, it is crucial to assess and monitor the concentrations of potentially toxic heavy metals in various environmental media as well as organisms. Similarly, Ma et al. [21], Zhang et al. [32], and Ali et al. [55] analyzed the distribution characteristics and biogeochemical cycling of heavy metals such as Zn and Cu. The existing studies on the environmental chemistry and ecotoxicology of hazardous heavy metals and metal compounds have demonstrated the necessity of implementing measures to mitigate the impacts of these elements on human health and the environment. The second study measured the levels of six heavy metals (Cr, Ni, Cu, As, Cd, and Pb) in the surface water and sediment of urban rivers in Bangladesh [56]. The findings showed a declining trend in heavy metal concentrations; however, they still exceeded the permissible limits for water safety. The third article is a review that assesses the extent of metal pollution in the coastal areas of China by examining the recorded metal concentrations in sediments and marine organisms over the past decade [57]. This review reveals a strong correlation between metal pollution in the coastal environment and the rapid economic growth over the past decade, which supports the close relationship, as reported by Zhang et al. [42], between lake sediment pollution and economic growth. Elevated metal concentrations were detected in the sediments collected along the Chinese coast. Specifically, remarkably high levels of metals were observed in the sediments, water, and organisms collected from heavily industrialized regions. The metal levels observed in marine bivalves also serve as indicators of elevated metal pollution. It was concluded that the increased prevalence of heavy metal contamination in China's coastal environment amplifies the potential risk of human exposure to metals through seafood consumption, thereby emphasizing the urgent need for stricter regulation on metal release into the environment. The fourth article aims to emphasize artificial wetland purification as a long-standing green technology for treat wastewater, providing sustainable solutions for the performance and application of this method through a review on recent advancements in the sustainable design and operation of artificial wetland purification systems [58]. Additionally, it explores future research directions aimed at improving the stability and sustainability of chemical pesticide removal. The last article investigates the increasing concentrations of heavy metals, including Cd, Cr, Cu, Ni, Pb, and Zn, in surface sediments of the northwest coast of Bohai Bay [59]. It showed that the accumulation of heavy metals in the sediments of Bohai Bay is significantly affected by anthropogenic factors; however, the accumulation levels remain relatively low compared to some other substantial anthropogenic input regions. The results, in conjunction with other related studies [12–15], further substantiate the influence of human activities on heavy metal pollution in water systems. Additionally, the toxicity probability of surface sediments in the northwest of Bohai Bay was determined to be 21% using the mean effect range–median quotient.

3.2. Analysis of the Results Based on CNKI Database

Based on the selected papers from the CNKI database, the numbers of published articles, authors, keywords, and institutions were analyzed using quantitative statistics in conjunction with VOSviewer and CiteSpace.

Table 3. Studies on heavy metals in rivers and lakes with more than 400 citations from 1985 to 2019.

SN	Title	Year	Total Citations	References/Papers
1	Environmental chemistry and ecotoxicology of hazardous heavy metals: Environmental persistence, toxicity and bioaccumulation [55]	2019	728	114
2	Heavy metal pollution in surface water and sediment: A preliminary assessment of an urban river in a developing country [56]	2015	720	71
3	Trace metal contamination in estuarine and coastal environments in China [57]	2012	555	139
4	A review on the sustainability of constructed wetlands for wastewater treatment: Design and operation [58]	2015	531	70
5	Heavy metal pollution status in surface sediments of the coastal Bohai Bay [59]	2012	445	41

3.2.1. Number of the Published Articles

A total of 3608 publications were examined, comprising 1598 (44.3%) academic journal articles, 1583 (43.87%) dissertations, and 148 (4.1%) other types of articles. Notably, the majority of studies on heavy metals in rivers and lakes were found in academic journals and dissertations, with both categories contributing equally, which indicates that research carried out for master's and doctoral dissertations constitutes an significant portion of the literature. The annual publication volume is shown in Figure 6. The development of research on heavy metals in rivers and lakes can be classified into three distinct stages. The first stage, spanning from 2001 to 2005, can be characterized as the development phase. During this period, the number of published articles experienced a gradual increase, reaching a total of 210 publications. These articles accounted for 5.82% of the total published articles. The period from 2006 to 2012 marked a prosperous stage characterized by significant growth. The year 2012, in particular, witnessed a noticeable surge, with a growth rate of about 1.36 times (234 articles) compared to 2011 (172 articles). And the cumulative number of published articles during this period amounted to 1043, contributing 28.90% of the total published articles. On average, an impressive 145.94 articles were published annually during this prosperous era. Subsequently, from 2012 to 2021, the annual number of published articles exhibited relative stability without significant fluctuations. This period comprised the largest portion of total published articles, with a cumulative count of 2346 publications, accounting for 65.02% of the overall body of literature. Such findings suggest a sustainable and stable research output in this field. Furthermore, the average annual number of published articles stood at 260, indicating a growing presence of research paper and researchers in recent years.

3.2.2. Author Analysis

The results of the collaborative network analysis of authors using CiteSpace are shown in Figure 7a. It is evident that the author network exhibits clustering behavior for individuals with five or more publications. Notably, due to the distinct research directions regarding heavy metals in rivers and heavy metals in lakes, the author cooperation clusters appear less prominent in the author network map. For further analysis, we visualized and analyzed the top ten authors and their affiliated institutions based on publication count. It can be seen from Figure 7 that the core authors included Shan, B.Q. (Research Center for Eco-Environmental Sciences, CAS); Xu, Y.N. (China Geological Survey); Zhang, J.H. (China Geological Survey); Fu, S.M. (Guangzhou University); Zhou, Y.Z. (Sun Yat-sen University); Liu, E.F. (Shandong Normal University); Liu, C.Q. (Tianjin University); Shen, J. (Nanjing University); Zhang, H. (CAS); and Zhao, S.N. (Inner Mongolia Agricultural University). Among them, the following were observed to be grouped closely within the same clusters, indicating strong relationships, cooperation, and leadership dynamics: Fu, S.M.; Zhou, Y.Z.; Shan, B.Q.; Zhang, H.; Xu, Y.N.; and Zhang, J.H.

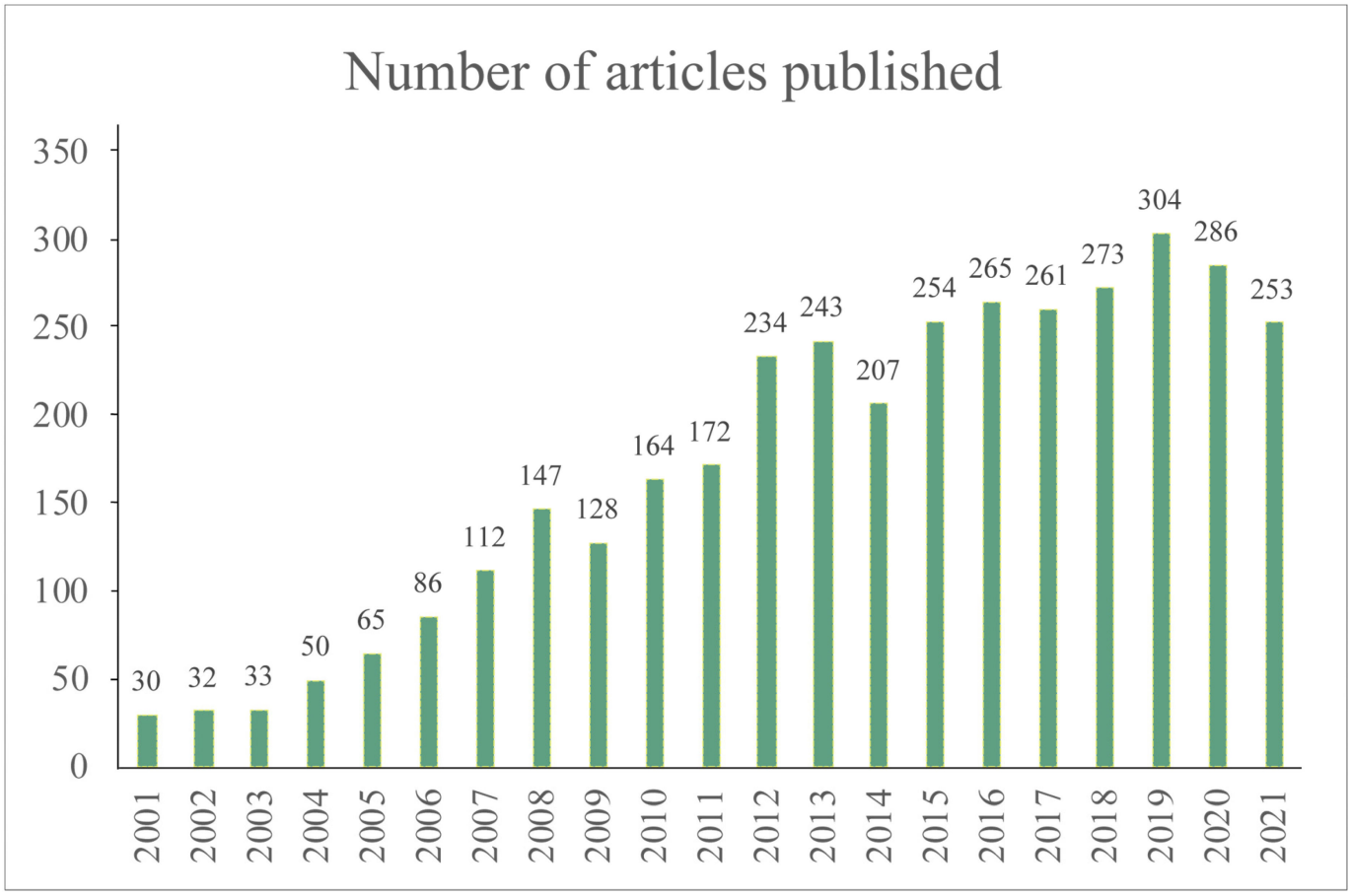
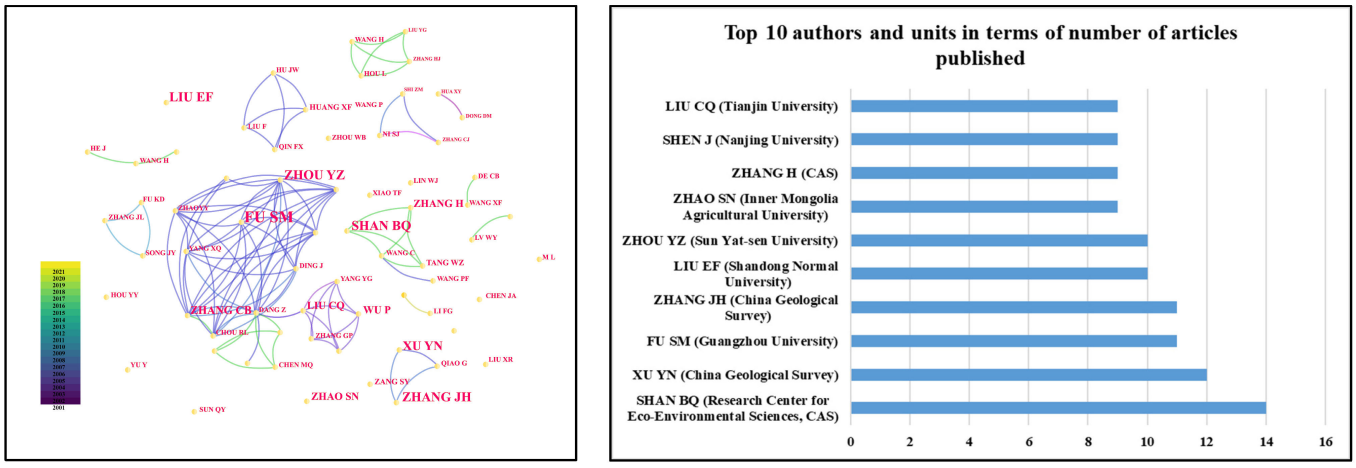


Figure 6. Number of articles published in CNKI on heavy metals in rivers and lakes from 2001 to 2021.



(**a**) (**b**)

Figure 7. (**a**) Collaborative network of authors in the research field of heavy metals in rivers and lakes in CNKI; (**b**) top ten authors and units in CNKI in the research field of heavy metals in rivers and lakes.

3.2.3. Keyword Analysis

The temporal cluster mapping of keywords in the research on heavy metals in rivers and lakes from 2001 to 2021 is presented in Figure 8. The cluster themes are well defined, with a mean value of 0.5077 and a modularity Q-function of 0.3829. A total of 12 clusters consisting of 785 nodes and 2413 interconnected lines were obtained [42]. The keywords related to research on heavy metals in rivers and lakes display a clear temporal clustering pattern, indicating a regular pattern in their occurrence. Notably, several high-frequency cluster keywords included heavy metals, sediment, soil, risk assessment, bottom sediment, pollution assessment, lake sediment, aquatic plants, pollution, adsorption, ecological risk, human activities, and sewage irrigation, which largely coincide with research on water eutrophication [60]. The results show that there are different research directions in the field of heavy metal pollution in rivers and lakes, focusing on sediment, risk assessment, aquatic plants, human activities, etc. This reflects that heavy metal contamination primarily originates from natural sources and human activities, leading to their accumulation in sediments, which may subsequently impact aquatic plants.

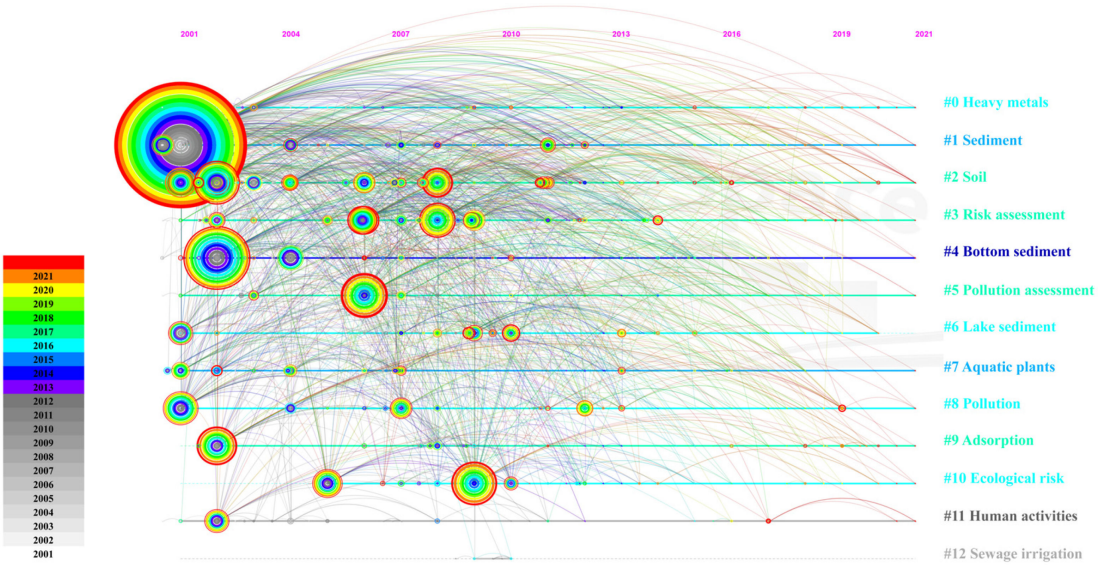


Figure 8. Temporal cluster mapping of keywords in CNKI for papers on heavy metals in rivers and lakes from 2001 to 2021.

3.2.4. Literature Sources and Major Institutions

By statistically analyzing the distribution of paper sources and major institutions in the research on heavy metals in rivers and lakes, the core journals and research contents in this field can be useful for literature reviews and publishing research findings. The distribution of paper sources and major institutions in the research of heavy metals in rivers and lakes is depicted in Figure 9. The primary journals included Environmental Science, Environmental Science & Technology, Ecology and Environment, Agricultural and Environmental Science, and Environmental Science Research, among which Environmental Science had the highest percentage of publications, accounting for 15.77% of the total number. Furthermore, the papers from East China Normal University, China University of Geosciences (Beijing), Nanjing University, and Hunan University were mostly master's dissertations, indicating that research groups affiliated with these four universities have conducted more in-depth studies in the field. Among them, East China Normal University had the highest percentage of papers, accounting for 9.68% of the total number.

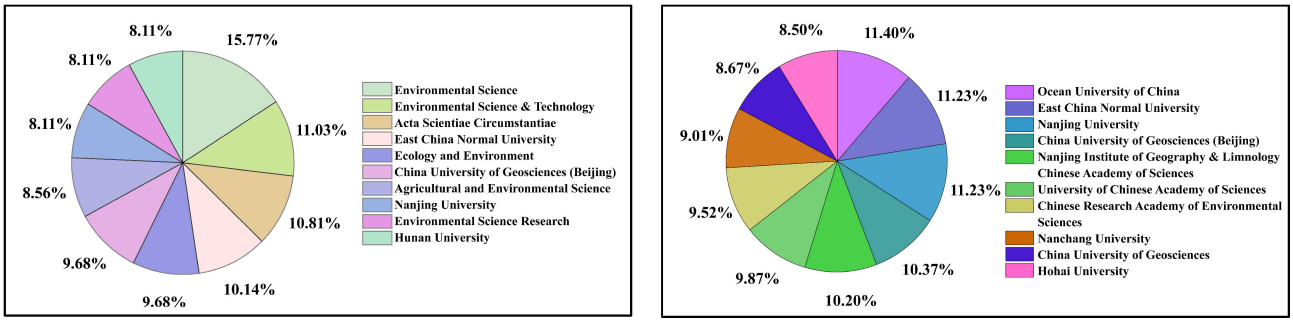


Figure 9. (**a**) Literature sources and (**b**) major institutions in the research on heavy metals in rivers and lakes in CNKI.

3.3. Comparison of WoS and CNKI Database Analysis Results

From 2001 to 2021, research on heavy metals in rivers and lakes witnessed a rapid increase in the number of articles published in both the WoS and CNKI databases. China, the USA, and India emerged as the top three countries in terms of the number of the published articles and the influence of their papers. The developmental stage lasted from 2001 to 2005, with a gradual increase in the number of articles published during this period. The prosperous stage spanned from 2006 to 2012, characterized by a significant growth in publications, particularly evident from 2011 to 2012, with an average annual number of publications of 145.94. The stable stage, from 2012 to 2021, demonstrated little fluctuation in the yearly publication count, indicating an overall stable tendency.

In terms of author collaboration network analysis, the core authors identified in the CNKI database included Shan, B.Q. (Research Center for Eco-Environmental Sciences, CAS); Xu, Y.N. (China Geological Survey); Zhang, J.H. (China Geological Survey); Fu, S.M. (Guangzhou University); Zhou, Y.Z. (Sun Yat-sen University); Liu, E.F. (Shandong Normal University); Liu, C.Q. (Tianjin University); Shen, J (Nanjing University); Zhang, H. (Research Center for Eco-Environmental Sciences, CAS); and Zhao, S.N. (Inner Mongolia Agricultural University). The top two core authors of the WoS database are from China, namely Zhang, Y.Y. (Institute of Geographic Sciences and Natural Resource Research, CAS) and Wang, J. (South China Agricultural University). Overall, the core authors of papers in both databases focused on the same issues related to heavy metals in rivers and lakes, such as the spatial and temporal distribution of heavy metals in sediments, as well as pollution prevention and control.

In terms of keywords, commonly used keywords in both databases included heavy metal pollution, adsorption, influence of human activities, water quality, sediment, etc. In addition, the WoS database papers focused on enrichment factors, antibiotic resistance, sequential extraction, etc., while the CNKI database papers emphasized risk assessment, aquatic plants, sewage irrigation, etc., indicating that China has followed global trends in the research of heavy metals in rivers and lakes in the past twenty years, integrating national sediment pollution issues and treatment requirements to reflect new research topics and hotspots. As reported in [61], the international cooperation rate of China is growing rapidly, which reflects the important position of China in international cooperative relations. Western research teams are generally influential in international cooperation; accordingly, Chinese research teams need to improve their academic influence.

Based on the comprehensive analysis of the impact factors and highly cited papers in the journals associated with research on heavy metals in rivers and lakes in the two databases, it is evident that China has produced the greatest number of studies worldwide, reflecting its substantial contribution to this field. However, its level of international cooperation is not quite high enough.

4. Conclusions

In this study, we conducted a quantitative and visual analysis of the literature on heavy metals in rivers and lakes from 2001 to 2021 using the WoS and CNKI citation databases. Summarily, our findings reveal a significant increase in publication number related to this research topic across various countries, underscoring its growing importance in the field.

During the initial stage, research output from countries other than China surpassed Chinese research in terms of quantity. However, after 2010, China emerged as a leading contributor in this field. The research directions and focuses of core authors in different countries are generally consistent, and most articles published in the WoS and CNKI databases are authored by Chinese researchers, highlighting their prominent position. Additionally, the research hotspots regarding heavy metals in rivers and lakes across different countries were similar during 2001–2021. These hotspots mainly encompassed heavy metal pollution, adsorption, human activities, water quality, and sediments. And the research directions align well with those pursued by the top-ranked authors.

Overall, China has distinct advantages in the theoretical and technical aspects of heavy metal research on rivers and lakes due to its extensive sediment pollution issues and treatment requirements. However, there is a lack of transnational technical exchange and cooperation. Therefore, it is essential to enhance communication among scholars working in the same research domain across different countries.

However, the inherent limitations of bibliometrics methodology should also be considered. For instance, bibliometric analysis primarily focuses on research articles published in academic journals, and other scholarly contributions, such as books, conference papers, and non-traditional publications, are often excluded from the bibliometric results. Additionally, the accumulation of bibliometric data is a time-consuming process, potentially leading to delays in identifying and evaluating the contributions of the research. Consequently, it is suggested that the academic databases be expanded and quantitative bibliometrics be integrated with qualitative literature reviews in the future, aiming to pro-mote a comprehensive understanding of the trends in specific research fields.

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