Archives of Environmental Protection
Vol. 50 no. 1 pp. 56–71

PL ISSN 2083-4772
DOI:10.24425/aep.2024.149432

Bibliometric and visual analysis of heavy metal health risk assessment: development, hotspots and trends

Yingsen Zhang, Xinwei Lu*, Sijia Deng, Tong Zhu, Bo Yu

School of Geography and Tourism, Shaanxi Normal University, China

* Corresponding author's e-mail: luxinwei@snnu.edu.cn

Keywords: Bibliometrics; CiteSpace; Heavy metal; Health risk assessment; Research trends.

Abstract: Due to the widespread presence and harmfulness of heavy metals in the environment, scholars around the world have evaluated the exposure characteristics and health risks of heavy metals. To understand the status, hotspots, and development treads of heavy metal health risk assessment research, we used bibliometric analysis tools to conduct scientometric analysis of the literature related to the health risk assessment of heavy metals in the Web of Science database from 2000 to 2022. The analysis results indicate that research related to heavy metal health risk assessment is rapidly developing in both developed and developing countries. China's significant international influence in this field is worth noting, as there are many publications and highly cited documents related to China. France and other developed countries also play an important role in this field due to their high centrality and strong bursts. The results of co-citation cluster analysis and keyword co-occurrence analysis indicate that in the past two decades, the primary research domains and hotspots of heavy metal health risk assessment have been the study of heavy metals in soil, dust, drinking water, vegetables, fish, and sediment. There is a specific focus on bioaccumulation, bioavailability, source apportionment, and spatial distribution of heavy metals. The main types of heavy metals studied are lead, cadmium, mercury, and zinc. The results of the bursts keywords analysis suggest that future research trends may focus more on the health risks of heavy metals in different functional areas of cities.

Introduction

In the process of socio-economic development and urbanization, many pollutants enter the surface environment with human activities, leading to a decrease in environmental quality and damage to ecosystems (Fan et al. 2022). Different types of harmful substances, such as heavy metals, are released into the environment through a series of pathways, including vehicle emissions, industrial discharges, agricultural production processes, etc. (Ali et al. 2019). Heavy metals refer to metals and metalloids with specific gravity exceeding 5g/cm^3, including Cr, Hg, Cd, Pb, Zn, Co, Cu, Mn, and As (Chen et al. 1999). Heavy metals have characteristics such as non-biodegradability, easy accumulation, and persistence, posing a significant threat to the environment (Gong et al. 2018; Rai et al. 2019). Besides, considering the cytotoxicity and potentially carcinogenic effects of heavy metals, excessive intake in the human body may have adverse effects on health (Trujillo-González et al. 2016, Alam et al. 2021, Luo et al. 2022). For instance, long-term inhalation of Cd can result in kidney damage, while Pb is associated with reproductive toxicity, embryotoxicity, and teratogenicity (Fei et al. 2023). Long term exposure to Cr can lead to respiratory and intestinal diseases, as well as carcinogenicity (Ivaneev et al. 2023). Heavy metal poisoning incidents have been widely reported in various countries around the world. For examples, a cadmium-induced renal tubular osteomalacia called itai-itai disease was found in the Cd-polluted Jinzu River basin in Toyama, Japan (Aoshima 2012); serious arsenic poisoning has occurred in Bangladesh, India, and many other places (Smith et al. 2000; Saha 2003); and children in developing countries such as Pakistan and China still face the risk of lead poisoning (Khan et al. 2010, Ji et al. 2011). Hence, studying heavy metal pollution is of vital significance for ensuring environmental quality and human health and safety.

As people pay more and more attention to health, the health risks of heavy metals have become a hot topic of global concern. In recent decades, scholars have conducted extensive research on heavy metal pollution (Antoniadis et al. 2017, Men et al. 2018, Grochowska et al. 2021, Eslami et al. 2022), studying the sources, concentrations, and health risk assessment of heavy metals in different media such as soil, dust, water, and food (Lu et al. 2014, Fathabad et al. 2018, Huang et al. 2018, De Rosa et al. 2022). In order to gain a better understanding of the current status of global research on heavy metal health risk assessment, a comprehensive review is warranted. In addition, it is important for researchers to learn about the research hotspots, explicate research frontiers, and delineate future research trends.

Due to many research literature on heavy metal health risk assessment, traditional literature review methods are difficult to provide a comprehensive summary of research in this field. Although there are some relevant review articles, they are usually limited to a single medium such as soil or road dust (Yang et al. 2018, Shahab et al. 2023). Bibliometrics offers a quantitative analysis of published literature in a specific disciplinary field. It is a useful tool for analyzing research structures, distributions, trends, and scientific collaboration patterns. Furthermore, it can achieve high-level analysis of many literature (Ellegaard and Wallin 2015). However, up to now, there have been few bibliometric studies on heavy metal health risk assessment. Existing bibliometric research also tends to focus on a single geographic region or research perspective (Guo et al. 2014, Chen et al. 2021, Kumari and Bhattacharya 2023). Therefore, we conducted a comprehensive visual scientometric analysis using CiteSpace on research published over the past 22 years. The aims of this study are to: (1) summarize the overall trend of heavy metal health risk assessment literature from 2000 to 2022; (2) analyze the publication contributions and collaborations among authors, institutions, and countries; and (3) identify the current research hotspots and future directions of worldwide research on heavy metal health risk assessment.

Data and methods

Data source

We used the Web of Science Core Collection (WoSCC) of Clarivate Analytics, established by Thomson Reuters, as the data source (www.webofscience.com). The WoSCC database is widely regarded as a prestigious and highly utilized academic research database (Cai et al. 2021). It contains more than 9,000 world-authoritative, high-impact journals and over 12,000 academic conferences spanning, covering nearly 250 disciplines (Merigó and Yang 2017, Shen et al. 2022).

We conducted a comprehensive search on the WoSCC for research published between January 2000 and December 2022. In order to obtain an objective and comprehensive record of the research literature, we selected all synonyms as much as possible during the search process. Thus, the search criterion was based on the TS (Topic Search) formula: ((("health risk assessment") OR ("health risk appraisal") OR ("health risk evaluation") OR ("health risk estimation")) AND (("heavy metal*") OR ("metal*") OR ("potentially toxic metal*") OR ("potentially toxic element*") OR ("toxic metal*") OR ("toxic element*") OR ("trace metal*") OR ("trace element*") OR ("harmful metal*") OR ("harmful element*"))). Related variants of words were captured with the wildcard '*', such as 'heavy metal*' representing 'heavy metal', 'heavy metals', 'heavy metal (loid)' and 'heavy metal (loid)s'. We restricted our search to English literature, filtering out conference abstracts, book chapters, repetitive content, and revisions to get the most representative research. A total of 4556 publications were retrieved, of which 3672 were the final research samples obtained after manual screening to exclude irrelevant literature. The information about the title, year of publication, author, keywords, abstract, and reference records of the publications was saved in plain text format for analysis purposes.

Methods

CiteSpace is a powerful and internationally renowned information visualization software developed in Java, specifically designed for constructing visual maps of scientific knowledge systems based on literature citation data and author relationship networks (Chen et al. 2012, Han et al. 2021). It can conduct a systematic review of knowledge domains through an intensive analysis process, emphasizing the identification of key elements in the evolution of a domain or field. CiteSpace helps users better understand academic collaborations, prominent issues, and research trends in specific fields by processing and analyzing publication data (Chen 2006). The numerous advantages of CiteSpace make it a common choice for bibliometric research in different fields such as bioscience (Cai et al. 2021), medicine (Chen et al. 2012), as well as information science (Cui et al. 2018). The input parameters employed in our analysis are as follows: time slices from 2000 to 2022, with each time slice covering one year; term source selection includes title, abstract, author, keywords, and keywords plus; the node types for analysis are selected in order of author, institution, country, keywords, cited author, cited journal, and references; the pruning selected pathfinder, pruning sliced networks and pruning the merged network; since the *g*-index captures both the quality and quantity of researchers' academic output, as well as highlight highly-cited papers, we utilized it as our selection criterion and set the value of *k* to 10 for clear visualization of the network (Egghe 2006, Dhital et al. 2022).

CiteSpace generates two important quantitative metrics for its networks: 'betweenness centrality' and 'burst' (Chen et al. 2012). The degree to which a node lies on the shortest path between others measures betweenness centrality (BC). Therefore, nodes exhibiting high BC represent critical turning points for information in control networks, whereas literature with high BC tends to serve as a critical link between two different domains (Freeman 1977). The formula for BC is as follows (Chen 2005):

$$BC_i = \sum_{s \neq i \neq t} \frac{n_{st}^i}{g_{st}} \qquad (1)$$

In this equation, BC_i denotes the betweenness centrality value of node *i*; g_{st} represents the amounts of shortest routes from node *s* to node *t*; and represents the amounts of shortest routes among the g_{st} routes from node *s* to node *t* that passing through node *i*. In terms of information transmission, the weight of a node increases with its BC value (Xiao et al. 2017).

CiteSpace applies the Kleinberg algorithm to detect bursts of highly cited publications or terms that peak within a particular time frame (Kleinberg 2003). In CiteSpace, clusters with many burst nodes suggest a more dynamic research field with more emerging trends (Chen et al. 2012). In this article, we used CiteSpace 6.2.R2, a widely recognized analysis software, to visualize the research literature on heavy metal health risk assessment and used Origin 2018 software to analyze publication trends.

Results and discussion

Publication trend analysis

As shown in Fig. 1, since the beginning of the 21st century, there has been a growing amount of academic literature on

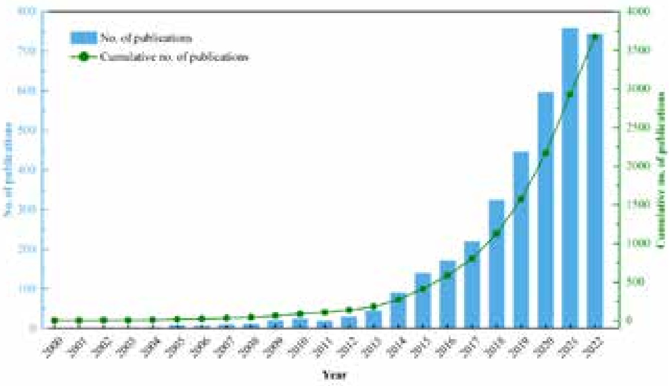

Figure 1. Number of papers on health risk assessment of heavy metals from 2000 to 2022.

health risk assessment of heavy metals. Although the number of publications published before 2011 grew slowly, totaling less than 100, the number of studies rapidly increased between 2011 and 2022 and peaked in 2021. In the past decade, an average of 298 publications have been published annually, and 573 papers were published in the past five years. From Fig. 1, it can be concluded that the number of publications related to heavy metal health risk assessment has significantly increased since 2014. A few key articles were published in this year, such as a review of heavy metal contamination and health risk assessment of soils in mining areas in China by Li et al. (2014) and an article on heavy metal risk assessment of contaminated vegetables for human health in Pakistan by Mahmood and Malik (2014). Together with other articles, they have stimulated the development of research in this field.

Overall, the field of health risk assessment for heavy metals has grown rapidly worldwide in the last two decades, and the reasons for this may be multifaceted. This is not only due to the increasing public attention to environmental pollution and health issues, but also because with the continuous progress of science and technology, research methods and techniques are constantly improving. The emergence of new research methods and technologies, such as inductively coupled plasma-mass spectrometry (ICP-MS), enables researchers to further investigate the health risks of heavy metals (Ferreira-Baptista and De Miguel 2005, Komárek et al. 2008). What is more, over the past 22 years, policies such as the European Union's Restriction of Hazardous Substances Directive and the U.S. Toxic Substances Control Act have provided more support and attention for related research (European Parliament and Council of the European Union 2003, USEPA 2008).

Co-authorship analysis

Co-authorship analysis demonstrates communication between academics within a research subject (Li et al. 2022). CiteSpace can provide collaborative analysis on authors, institutions, and countries. We imported the information from 3672 retrieved papers into CiteSpace for analysis and obtained co-occurrence network graphs and related information for authors, institutions, and countries, respectively. We have conducted a detailed analysis of them, as described below.

Analysis of author groups

The visualization of author co-occurrence analysis helps to identify the main authors and their collaboration degree in the research field (Qin et al. 2022). The co-occurrence network of authors and the top ten authors with the highest amounts of publications and the strongest bursts are shown in Table 1 and Fig. 2. Fakhri, Yadolah has the highest number of publications (31), followed by Khaneghah, Amin Mousavi (24), Li, Fei (19), and Khan, Sardar (15). Fakhri, Yadolah and Khaneghah, Amin Mousavi are members of the same research group from Iran, which is dedicated to health risk assessment of metal contaminants in foodstuff (Fakhri et al. 2022), while Li, Fei belongs to another research group from China, which focuses on human health risk assessment of metal contaminants in environmental matrices, including soil, dust, and ground water (Li et al. 2020). Our scientometric analysis confirms that Fakhri, Yadolah and Li, Fei are the primary authors in the field of heavy metal health risk assessment, demonstrating considerable activity and prominence They lead the field with the highest number of published articles and exhibit the strongest burst among the top ten authors. Notably, both have formed distinct a research group dedicated to heavy metal health risk assessment. In a recent review study published by the Fakhri, Yadolah's team, the concentrations of Cd, Hg, Pb, Ni, and As in canned tuna from around the world were investigated, and the potential health risks associated with the consumption of these products by adults and children were estimated. The results indicate that the non-carcinogenic risk to children from heavy metals in canned tuna in many countries exceeded the thresholds (Mahmudiono et al. 2023). Li, Fei 's research group recently conducted a bibliometric analysis of Cd, Cr, Hg, Pb, As, Cu, Zn, and Ni pollution in the water environment of the Yangtze River. The results indicate that heavy metal pollution in sediments is severe, and the pollution in the water of the Yangtze is mainly related to the development and smelting of mineral resources (Yan et al. 2021).

As displayed in Fig. 2, each node represents an author, and the links between nodes represent collaborative relationships between authors. The dark purple color in the nodes and links indicates the earlier year, while yellow represents the most recent year. It can be observed that several research teams have formed strong internal communication among researchers. However, there is little collaboration between different research teams, indicating a need for strengthening inter-team

Table 1. Top 10 authors with the most published articles and the strongest bursts.

Authors	Publications	Authors	Bursts
Fakhri,Yadolah	31	Domingo, Jose L	5.49
Khaneghah, Amin Mousavi	24	Li, Fei	5.12
Li, Fei	19	Nadal, Marti	4.94
Khan, Sardar	15	Liu, Guijian	4.72
Ahmad, Kafeel	15	Nazmara, Shahrokh	4.51
Domingo, Jose L	14	Moore, Farid	4.11
Shariatifar, Nabi	13	Praveena, Sarva Mangala	4.06
Islam, Md Saiful	12	Fakhri, Yadolah	3.79
Liu, Guijian	12	Iqbal, Javed	3.76
Moore, Farid	11	Keshavarzi, Behnam	3.73

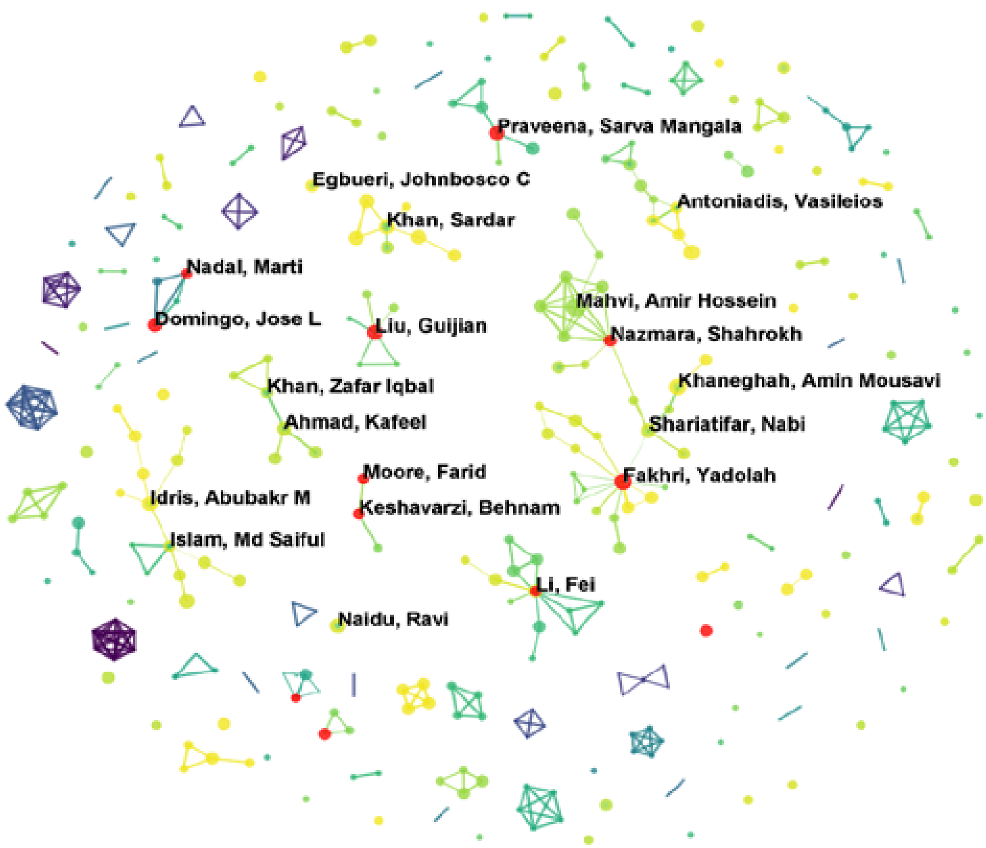

Figure 2. Co-occurrence network of authors (Each node represents an author's number of publications, and larger nodes indicate a larger publication output; The range of colors used in the nodes and links represents the year of publication, with dark purple indicating earlier and yellow representing the most recent publication; Red circles are used to represent bursts in the publication output; Links with high density indicate strong collaborations, while sparse links indicate weaker collaborations).

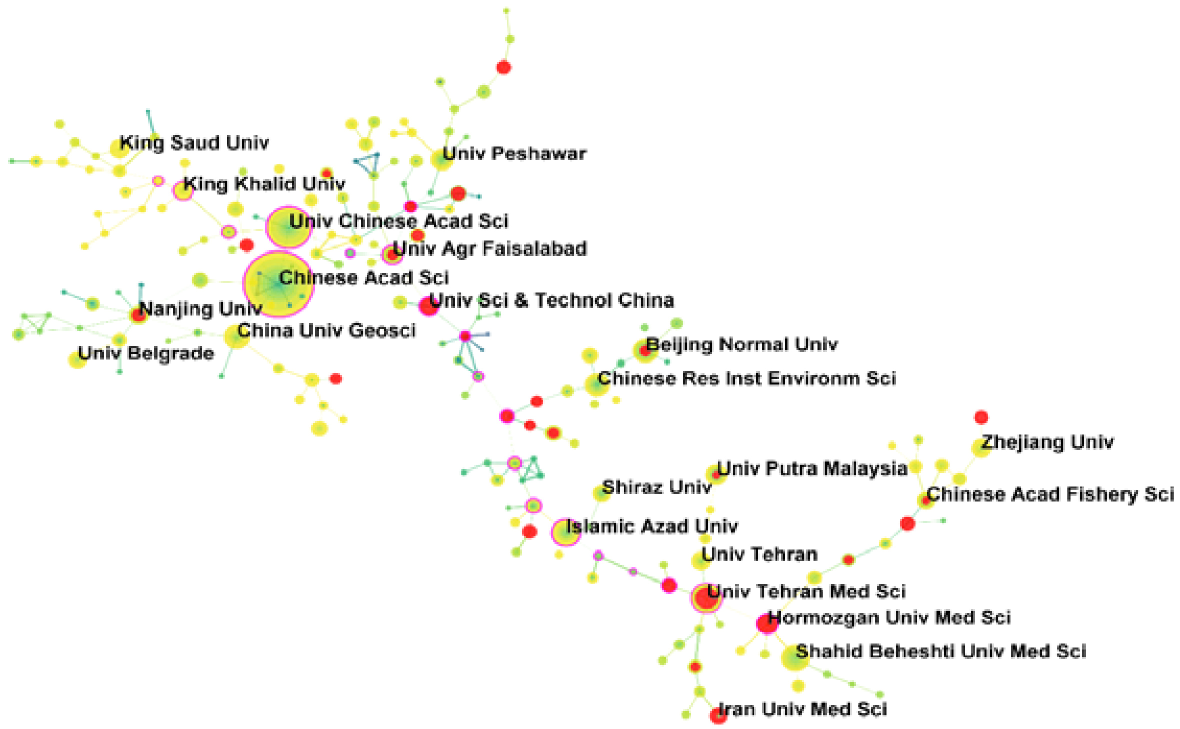

Figure 3. Co-occurrence network of institutions (Larger nodes indicate larger publication size; The outermost purple ring in the graph denotes the level of centrality (>0.1); The range of color in the links denotes publication year; The dark purple color signifies early publication, while the yellow color symbolizes the latest publications, and the dense link in the network represents strong collaboration; Red circles represent frequency bursts).

relationships. Furthermore, this network reveals that smaller research groups were formed among early researchers, while larger research groups, in terms of both size and scope, have emerged among newer researchers.

Analysis of institutions

Collaborative networks can shed light on the academic influence of countries and institutions (Wang et al. 2021). Fig. 3 shows the collaborative institutional network comprising 330 nodes and 294 links. The larger nodes represent institutions with higher publication volumes, while the dense links represent strong inter-institutional collaboration. Nodes with a centrality greater than 0.1 are considered key points (Dhital et al. 2022), denoted by the outermost purple ring. Red represents nodes with high burst strength.

Table 2 illustrates the top ten institutions with the largest amounts of publications, centrality, and bursts. The top three institutions with the largest number of publications on the health risk assessment associated with heavy metals are the Chinese Academy of Sciences, China (305), the University of Chinese Academy of Sciences, China (127), and the Tehran University of Medical Sciences, Iran (61). The University of Chinese Academy of Sciences, which has a high centrality and large number of publications, recently published a paper on the spatial distribution, ecological risk, and sources of heavy metals in soils of southeast China (Wu et al. 2021). The Tehran University of Medical Sciences is the institution with the strongest burst and large number of publications, and it has recently published a review on the toxicological effects of Cr (VI) and Cr (III), as well as their toxicity and carcinogenic mechanisms (Hossini et al. 2022).

Among the top ten institutions with the highest number of published articles, five are from China, three are from Iran, one is from Malaysia, and one is from Pakistan. The top ten institutions with the highest centrality are mainly from developing countries, with six coming from China, two from Pakistan, and one each from Iran and Greece. The top ten institutions with the strongest burst are also primarily from developing countries, including China, Pakistan, and Iran. These results indicate that scholars from developing countries in Asia attach greater importance to research on heavy metal health risk assessment. In addition, the network map shows that close communication and cooperation between institutions have developed globally.

Analysis of countries

The collaborating countries co-occurrence network and the top ten countries with the largest amounts of publications, centrality, and bursts are presented in Fig. 4 and Table 3, respectively. China has the highest publication count (1433), followed by Iran (333), India (279), Pakistan (217), and the USA (210). These countries have made significant contributions to the

Table 2. Top 10 institutions with the highest number of publications, centrality and bursts.

Institutions	Publications	Institutions	Centrality	Institutions	Burst strength
Chinese Acad Sci	305	Univ Agr Faisalabad	0.37	Univ Tehran Med Sci	10.56
Univ Chinese Acad Sci	127	Minist Environm Protect	0.32	Quaid I Azam Univ	9.01
Univ Tehran Med Sci	61	City Univ Hong Kong	0.32	Minist Agr	6.9
Beijing Normal Univ	54	Univ Sci & Technol China	0.31	Univ Rovira & Virgili	6.13
Shahid Beheshti Univ Med Sci	52	Jinan Univ	0.3	Zhongnan Univ Econ & Law	5.75
Chinese Res Inst Environm Sci	50	Univ Chinese Acad Sci	0.28	Univ Putra Malaysia	5.55
Islamic Azad Univ	49	Peking Univ	0.27	Univ Sci & Technol China	5.1
China Univ Geosci	45	Govt Coll Univ	0.25	Univ Nigeria	4.99
Univ Peshawar	37	Aristotle Univ Thessaloniki	0.24	Hunan Univ	4.95
Univ Putra Malaysia	34	Islamic Azad Univ	0.23	ComsatsUniv Islamabad	4.61

Table 3. Top 10 countries with the highest number of publications, centrality and bursts.

Countries	Publications	Countries	Centrality	Countries	Burst strength
China	1433	France	1.15	France	8.19
Iran	333	Italy	0.59	Canada	6.66
India	297	Canada	0.56	Malaysia	6.49
Pakistan	217	USA	0.51	USA	5.96
USA	210	Australia	0.43	UK	4.69
Nigeria	179	Sweden	0.38	Portugal	3.93
Turkey	143	Switzerland	0.38	South Korea	2.95
UK	119	Malaysia	0.35	Switzerland	2.94
Saudi Arabia	119	South Korea	0.31	Pakistan	2.53
Australia	113	Slovenia	0.26	Finland	2.4

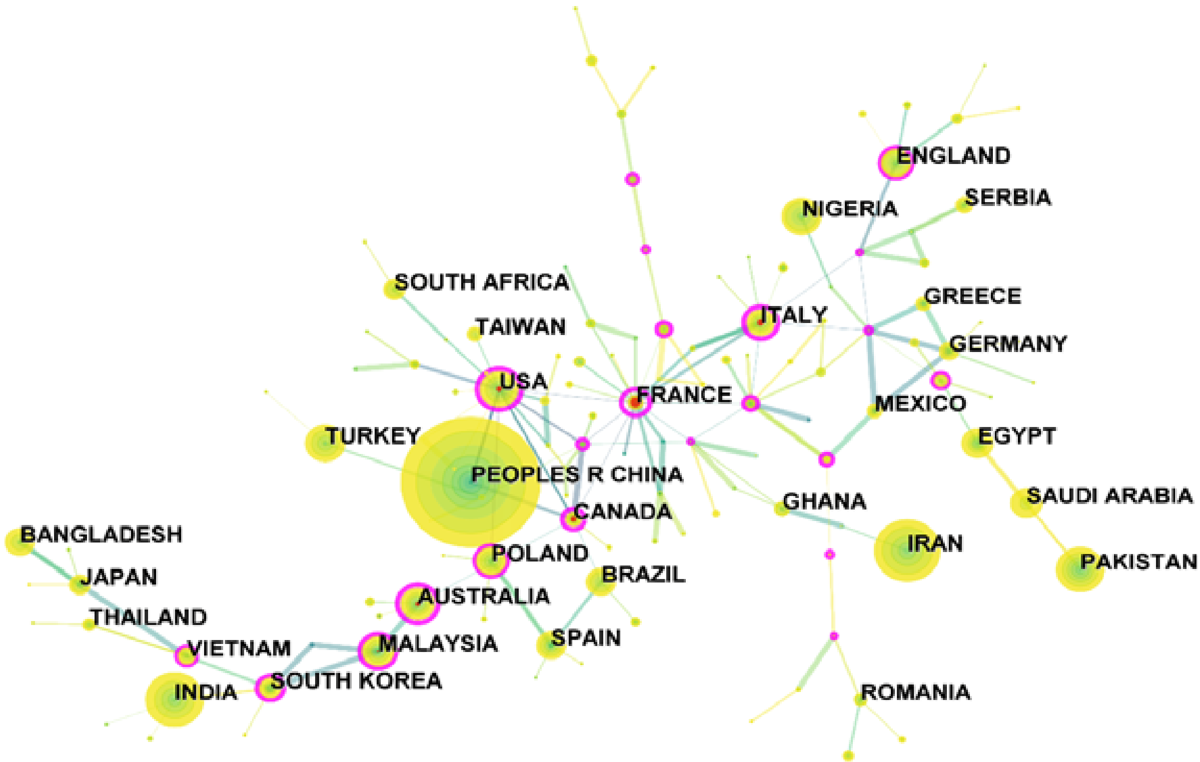

Figure 4. Co-occurrence network of collaborating countries (Larger nodes indicate larger publication size; The outermost purple ring in the graph denotes the level of centrality (>0.1), and a red circle represents frequency bursts; The range of color in the links denotes publication year; The dark purple color signifies early publication, while the yellow color symbolizes the latest publications, and the dense link in the network represents strong collaboration).

study of heavy metal health risk assessment. Moreover, there has been a substantial increase in publications from developing countries, consistent with the co-authorship analysis of authors and institutions. This trend is likely because although heavy metal emissions in developed countries began to decline at the end of the 20th century (Järup 2003), some developing countries still face serious heavy metal contamination issues (Yang et al. 2018). Peng et al. studied heavy metal contamination of industrial legacy soil in China in 2022 and conducted a health risk assessment on it. The results showed that heavy metal pollution in industrial legacy soil in China was severe, with the main pollutants being Pb, Cd, Zn, Ni and As; children faced more serious non-carcinogenic and carcinogenic risks than adults (Peng et al. 2022). A study on the health risk assessment of heavy metals in coal and chromite dust in Pakistan found that heavy metals in the dust were moderately contaminated, while heavy metals in chromite posed a significant health risk to workers (Sultana et al. 2023).

The rapid industrial development of developing countries in the past few decades has resulted in serious environmental pollution and raised public awareness of environmental protection and public health. In contrast, developed countries have relatively low research output on this issue, which may be due to the transfer of advanced technologies and production to other countries, thereby reducing domestic pollution (López et al. 2018).

Among the 22 countries with centrality exceeding 0.1, France has the highest centrality value (1.15), signifying that France plays a crucial role in the network (Dhital et al. 2022). Following France closely are Italy (0.59), Canada (0.56), the USA (0.51) and Australia (0.43), with most of the countries with high centrality values being developed countries. Developed countries play a significant role in this field. Recently, scholars from Italy studied cadmium exposure in the diet of people in northern Italy, evaluated the relationship between four different dietary patterns and cadmium exposure, and found that people who adhered to the healthy dietary patterns tested had higher cadmium intake (Urbano et al. 2023). The United States has a higher number of publications, centrality values, and burst strength, indicating its important position in this field. Masri et al. (2021) investigated soil heavy metal contamination in Santa Ana, California, and the research findings provide a scientific basis for community-oriented policy formulation. In addition, it can be easily observed from the network map that countries around the world have formed close collaborative relationships.

Co-citation analysis

Co-citation means that two (or more) objects are cited together by one or more later sources (Börner et al. 2003). This creates a relationship called co-citation between the two objects. This technique is used to identify the core literature structure of specific research areas (Small 1973). Based on the information of 3672 documents retrieved from the WoSCC database, we conducted the analysis of co-cited authors, journals and references using CiteSpace.

Analysis of co-cited authors

If an author is highly cited, it indicates that the author has a significant influence in the research field (Yang and Meng

Table 4. Top 10 co-cited authors in terms of frequency.

Authors	Frequency	Centrality	Burst
USEPA	2425	0.88	34.07
WHO	1078	0.22	10.63
Zheng, N.	432	0.00	38.90
Håkanson, L.	431	0.12	0.05
Khan, S.	349	0.38	12.53
Müller, G.	330	0.01	0.05
Li, Z.Y.	328	0.01	0.05
Ferreira-Baptista, L.	301	0.07	17.71
Hu, X.	288	0.08	6.25
Chen, H.Y.	283	0.34	0.05

2019, Geng et al. 2022). Table 4 displays the top ten co-cited authors on the basis of citation frequency. The most frequently co-cited author is USEPA (the United States Environmental Protection Agency), with 2425 citations. The second and third most frequently co-cited authors are WHO (World Health Organization) with 1078 citations and Zheng, N. from the Chinese Academy of Sciences, China, with 432 citations, respectively. According to Table 4, we can conclude that the top ten most frequently co-cited authors include not only environmental and health-related agencies that issue regulations and establish standard methods (USEPA 1989, WHO 2011), but also authors with significant influence in fields related to heavy metal health risk assessment (Håkanson 1980, Zheng et al. 2010).

Analysis of co-cited journals

Journal co-citation analysis is a valuable method of bibliometric research in a quantitative way that helps to identify the primary journals in which articles related to a particular field are published and identify the associations between journals (Zhang et al. 2021). Table 5 illustrates the top ten co-cited journals ranked by frequency of citations. Science of the Total Environment holds the largest amounts of citations (3162) for publications related to heavy metal health risk assessment, followed by Chemosphere (2621) and Environmental Pollution (2513). Science of the Total Environment is a widely recognized interdisciplinary scientific journal with an impact factor (IF) of 9.8 in 2022, publishing original and influential research related to the global environment. Associated co-cited journals with Science of the Total Environment include Human and Ecological Risk Assessment, Scientific Reports, Environmental Science and Pollution Research, and Journal of Hazardous Materials. Chemosphere is an international journal that publishes research papers and reviews on chemicals in the environment, with an IF of 8.8 in 2022. The closely related co-cited journal to Chemosphere is Environmental Pollution. Environmental Pollution publishes review articles and academic papers on environmental pollution and its impact on human health and ecosystems, with an IF of 8.9 in 2022. The closely related co-cited journals include Journal of Hazardous Materials, Human and Ecological Risk Assessment, and Environmental Science and Technology. Among the top ten journals, Science of the Total Environment, Chemosphere, Environmental Pollution, Journal of Hazardous Materials, and Environmental Science and Technology are journals with high frequency, centrality,

Table 5. Top 10 co-cited journals in terms of frequency.

Journals	Frequency	Centrality	Burst	IF
Science of the Total Environment	3162	0.27	25.51	9.8
Chemosphere	2621	0.31	6.83	8.8
Environmental Pollution	2513	0.39	23.02	8.9
Environmental Monitoring and Assessment	2194	0.14	0.05	3.0
Ecotoxicology and Environmental Safety	2192	0.01	0.05	6.8
Environmental Science and Pollution Research	2172	0.02	0.05	5.8
Journal of Hazardous Materials	1933	0.25	11.34	13.6
Environment International	1817	0.07	21.34	11.8
Environmental Geochemistry and Health	1574	0.34	4.09	4.2
Environmental Science and Technology	1414	0.24	39.03	11.4

bursts, and impact factor. This indicates that these journals are well-respected in the research area of heavy metal health risk assessment and have significant impact in this field.

Analysis of co-cited references

Co-citation analysis is the foundation of many scientific mapping techniques, creating a network of co-cited references to understand the knowledge structure (Small 1973). Table 6 displays the top ten frequently co-cited references, while Table 7 shows the top ten co-cited references by centrality. The most frequently cited article is written by Li et al. (2014), published in Science of the Total Environment in 2014. This paper also holds the highest centrality in the co-cited literatures. This article analyzed the data of heavy metal contaminated soil in mines in China from 2005 to 2012. Then, the author assessed the level of soil pollution and quantified the related risks to human health. To date, this article has been cited 308 times.

The analysis of highly cited literature with both high frequency and centrality reveals the significant contributions of Chinese scholars in this research area. In addition, more than half of the top ten high-frequency and high-centricity cited literature, respectively, examined the health risk assessment of heavy metals in soil, showing a hot research situation.

Clustering analysis

Co-citation analysis assists researchers identify pivotal articles that affect the development of the discipline, while cluster analysis helps identify primary research domains (Dhital et al. 2022). In CiteSpace, cluster names are determined by nomenclature terms extracted from the citing literature, which reflects the research frontiers of the cluster (Chen et al. 2010).

Cluster analysis of co-cited references

Based on the co-citation network analysis of the above references, we utilize keywords as the basis for clustering with

Table 6. Top 10 references with strong frequency in the co-citation network of references.

Frequency	Centrality	Burst	References	Title of publication	Cluster
308	0.19	0.05	(Li et al. 2014)	A review of soil heavy metal pollution from mines in China: Pollution and health risk assessment	#5
183	0.07	0.05	(Chen et al. 2015)	Contamination features and health risk of soil heavy metals in China	#5
144	0.08	4.00	(Liu et al. 2013)	Human health risk assessment of heavy metals in soil-vegetable system: A multi-medium analysis	#5
137	0.07	0.05	(Wei et al. 2015)	Pollution characteristics and health risk assessment of heavy metals in street dusts from different functional areas in Beijing, China	#1
130	0.09	4.63	(Xiao et al. 2015)	Assessment of heavy metal pollution and human health risk in urban soils of steel industrial city (Anshan), Liaoning, Northeast China	#5
119	0.03	0.05	(Jiang et al. 2017)	Source apportionment and health risk assessment of heavy metals in soil for a township in Jiangsu Province, China	#0
106	0.13	0.05	(Cao et al. 2014)	Health risks from the exposure of children to As, Se, Pb and other heavy metals near the largest coking plant in China	#5
104	0.02	46.66	(Zheng et al. 2010)	Health risk assessment of heavy metal exposure to street dust in the zinc smelting district, Northeast of China	#4
97	0.05	0.05	(Men et al. 2018)	Pollution characteristics, risk assessment, and source apportionment of heavy metals in road dust in Beijing, China	#1
97	0.02	19.91	(Hu et al. 2012)	Bioaccessibility and health risk of arsenic and heavy metals (Cd, Co, Cr, Cu, Ni, Pb, Zn and Mn) in TSP and PM2.5 in Nanjing, China	#1

the LLR (log-likelihood ratio) algorithm. The co-cited reference network during 2000-2022 generated clusters with a modularity score of 0.7473 and a mean weighted silhouette score of 0.8758, as shown in Fig. 5. A high modularity score (Q>0.3) indicates clear specialties in this research area, while a high silhouette score (S>0.7) suggests strong homogeneity within the clusters (Chen et al. 2010). The top eight largest clusters are as follows.

Cluster #0, which is the largest cluster labeled as 'soil heavy metals', has a silhouette score of 0.821 and comprises 58 articles primarily published around 2018. Jiang et al. (2017) has the highest cited frequency of references in this cluster. This study investigated the level of trace metal contamination in soil in an unconventional rural industrial town situated in southern Jiangsu Province, China. The authors used a PMF model and geostatistical analysis to identify the common heavy metal sources, quantify their impact, and evaluate their potential health risks. The articles within this cluster involve developing countries such as Iran, India, and China, mainly

Table 7. Top 10 references with strong centrality in the co-citation network of references.

Centrality	Frequency	Burst	References	Title of publication	Cluster
0.19	308	0.05	(Li et al. 2014)	A review of soil heavy metal pollution from mines in China: Pollution and health risk assessment	#5
0.13	106	0.05	(Cao et al. 2014)	Health risks from the exposure of children to As, Se, Pb and other heavy metals near the largest coking plant in China	#5
0.13	32	19.69	(De Miguel et al. 2007)	Risk-based evaluation of the exposure of children to trace elements in playgrounds in Madrid (Spain)	#4
0.11	90	29.05	(Muhammad et al. 2011)	Health risk assessment of heavy metals and their source apportionment in drinking water of Kohistan region, northern Pakistan	#3
0.11	43	24.59	(Khan et al. 2008)	Health risks of heavy metals in contaminated soils and food crops irrigated with wastewater in Beijing, China.	#2
0.09	130	4.63	(Xiao et al. 2015)	Assessment of heavy metal pollution and human health risk in urban soils of steel industrial city (Anshan), Liaoning, Northeast China	#5
0.08	144	4.00	(Liu et al. 2013)	Human health risk assessment of heavy metals in soil-vegetable system: A multi-medium analysis	#5
0.08	92	0.05	(Yang et al. 2018)	A review of soil heavy metal pollution from industrial and agricultural regions in China: Pollution and risk assessment	#0
0.08	73	0.05	(Shaheen et al. 2016)	Presence of heavy metals in fruits and vegetables: Health risk implications in Bangladesh	#6
0.08	69	21.65	(Hu et al. 2011)	Bioaccessibility and health risk of arsenic, mercury and other metals in urban street dusts from a mega-city, Nanjing, China	#4

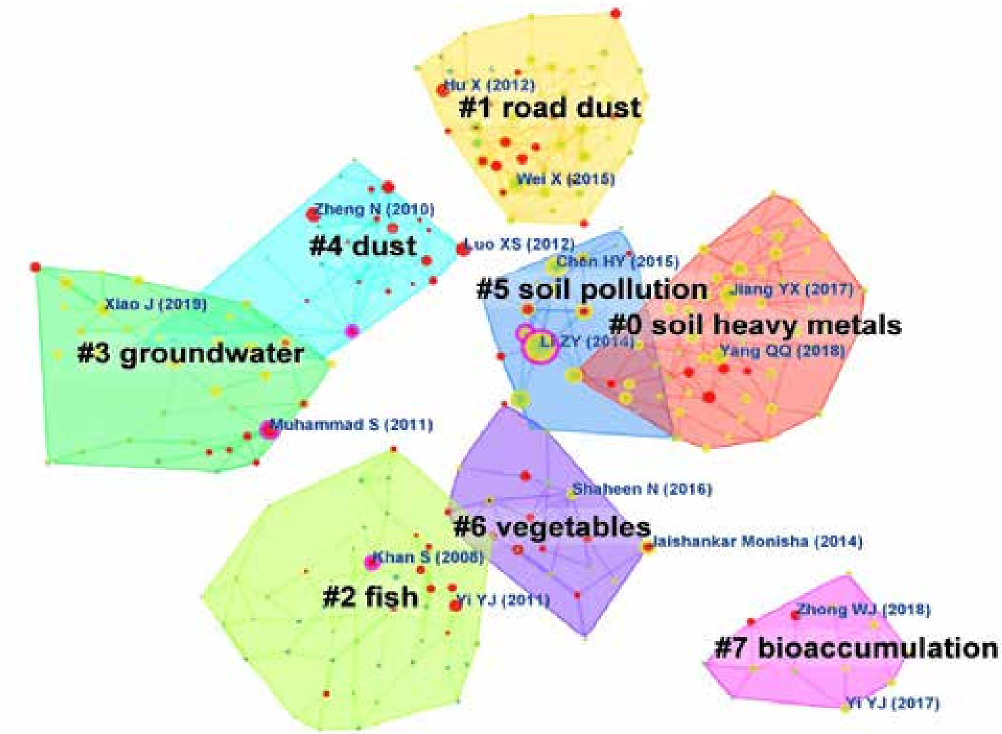

Figure 5. Cluster diagram of co-cited references on health risk assessment of heavy metals from 2000 to 2022.

discussing soil source apportionment and spatial distribution. The clustering results of LLR show that the literature in this cluster is also related to 'source apportionment', 'spatial distribution', 'PMF', and 'land use types'.

Cluster #1, the second-largest cluster labeled as 'road dust', comprises 49 articles posted circa 2015. The similarity silhouette is 0.845, indicating a high homogeneity among the referenced papers. Wei et al. (2015) is the most frequently cited reference in this cluster. The study focuses on examining the distribution, accumulation, and health risk assessment of heavy metals found in road dust from areas of high traffic density, educational institutions, residential dwellings, and tourist destinations located within Beijing, China. According to the results of the LLR algorithm, this cluster encompasses not only studies on 'road dust' but also 'street dust', 'urban dust', and 'indoor dust'.

Cluster #2, the third-largest cluster with 47 articles published around 2008, is highly consistent among references, achieving a silhouette score of 0.885 and is labeled as 'fish'. Within this cluster, the top-cited article is by Yi et al. (2011). This study examined the levels of As, Hg, Cd, Cr, Cu, Pb, and Zn in water bodies, sediments, and fish. It also investigated the health risks of fish in the middle and lower reaches of the Yangtze River. Additionally, the cluster also includes studies related to 'daily source intake', 'apportionment', and 'bioaccumulation'.

Cluster #3, identified as the fourth largest cluster labeled as 'groundwater', includes 35 articles published circa 2015 and achieves the highest silhouette score of 0.987. The study by Muhammad et al. (2011) is the most frequently cited reference in this cluster. The researchers analyzed the levels of heavy metals such as Cd, Pb, Zn, Cr, Ni, Cu Mn, and Co in groundwater and surface water in the Kohistan region of northern Pakistan and evaluated the potential health risks of the local residents. This cluster also includes other research articles related to 'water quality', 'water quality index', 'surface water', and 'drinking water' based on the LLR algorithm.

Cluster #4 contains 30 articles published around 2008, labeled as 'dust', and ranks as fifth with a 0.936 silhouette score. The article with the most citations in this cluster is Zheng et al. (2010). This article studies the spatial distribution of heavy metals (Hg, Cd, Pb, Cu, and Zn) in street dust from the metal smelting industry in the industrial area of Huludao City, and evaluates the non-cancer and cancer effects of exposure to street dust on both children and adults. In addition to 'dust', this cluster also includes literature related to 'bioavailability', 'street dust', 'source apportionment', and 'Beijing'.

Cluster #5, which is labeled as 'soil pollution' and contains 21 articles published around 2013, ranks as the sixth largest cluster with a silhouette score of 0.843. Li et al. (2014) is the most frequently cited work in this field and has the highest reference coverage in this cluster. Articles in this cluster are also related to 'ecological risk assessment', 'water quality', and 'radionuclide'.

Cluster #6 is labeled as 'vegetables' and ranks seventh with a silhouette score of 0.772. It contains 20 articles published around 2013. Jaishankar et al. (2014), the most cited article in this cluster, provided a comprehensive overview of the toxicity mechanisms and effects of As, Pb, Hg, Cd, Cr, Al, and Fe on the environment and organisms (mainly humans). The articles in this cluster are also associated with 'transfer factor', 'THQ', 'fruits', and 'ICP-OES'.

Cluster #7 is labeled as 'bioaccumulation', including 14 articles published around 2016. It ranks eighth in the cluster with a silhouette score of 0.968. The most frequently cited paper investigated the potential health risks and distribution of As, Pb, Cd, Cr, Cu, Zn, Ni, and Mn in wild and cultured fish and water samples from 16 freshwater systems in central and

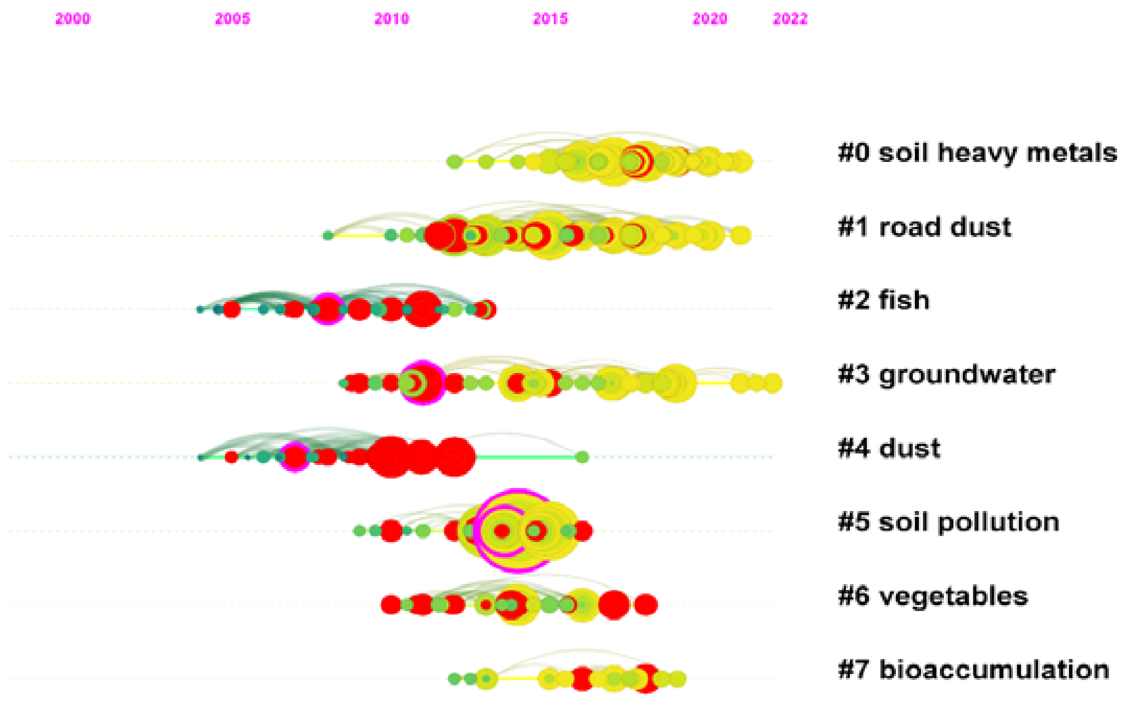

Figure 6. Timeline co-occurrence diagram

eastern North China (Zhong et al. 2018). Based on the LLR clustering results, the articles included in this cluster are also associated with 'fish', 'metals', 'aquaculture pond', and 'fish caught by anglers'.

Through the analysis of the aforementioned eight clusters, a conclusion can be drawn that research on health risk assessment of heavy metals is mainly concentrated in developing countries, with the main research areas in the past two decades being heavy metal research in soil, dust, drinking water, vegetables, and fish, and researchers are also most concerned about bioaccumulation, bioavailability, source apportionment and spatial distribution of heavy metals.

Timeline analysis of clustering

Through a comprehensive analysis of the co-occurrence timeline of the clusters identified by the LLR algorithm mentioned above (Fig. 6), we observed that some groups not only have similarities in content, but also exhibit a sense of temporal inheritance. For example, both cluster #0 (soil heavy metals) and #5 (soil pollution) are associated with heavy metal pollution in soil. Heavy metal pollution in soil was a research hotspot around 2013, mainly focusing on the issues such as ecological risk assessment.

By around 2018, researchers became increasingly interested in the sources, spatial distribution, and improvement of research methods concerning heavy metal contaminants in soil. For cluster #1 (road dust) and #4 (dust), the dust research field experienced a strong burst in 2008 and showed positive research trends. Later, around 2012, researchers began conducting extensive research on road dust, making it a new core research focus. For cluster #2 (fish) and #7 (bioaccumulation), they are interconnected and integrated with each other in terms of content. Specifically, clusters #2 and #7 share the same research area, demonstrating that researchers continue to pay attention to the health hazards and bioavailability of fish consumption. It can be reasonably inferred that this may be the result of the development and innovation of the discipline. Together with other research hotspots, these research hotspots have evolved with the development of health risk assessment research, showing the development of this field over the past two decades.

Keyword analysis

Keyword co-occurrence analysis

Keywords are words or phrases that accurately reflect the primary content of the article and the evolution of the research topic (Liu et al. 2015, Yang and Meng 2019). Keyword co-occurrence analysis knowledge mapping is a technique that utilizes high-frequency keywords to detect hot research fields (Sabe et al. 2022). Fig. 7 depicts the network mapping of keyword co-occurrence. Terminology such as 'heavy metal contamination' and 'heavy metal pollution', 'heavy metals' and 'heavy metal', 'Pb' and 'lead', 'Cd' and 'cadmium', and 'pollution' and 'contamination' have been standardized and merged. Finally, the analysis involves 257 keywords obtained from co-occurring author keywords (DE) and keywords plus (ID). Bigger nodes correspond to a higher frequency of keyword occurrence, and nodes with a purple outer ring are highly centrality nodes (> 0.1). Since 'heavy metal' and 'health risk assessment' are used as the main search terms, their high frequency is expected. After excluding these two keywords, the top ten co-occurring keywords based on frequency, are 'pollution' (1360), 'trace element' (847), 'health risk' (690), 'lead' (567), 'soil' (564), 'cadmium' (551), 'exposure' (536), 'risk assessment' (531), 'source apportionment' (484), and 'sediment' (436). Additionally, the top ten co-occurring keywords with high centrality are 'cadmium' (1.17), 'human health risk assessment' (0.79), 'accumulation' (0.59),

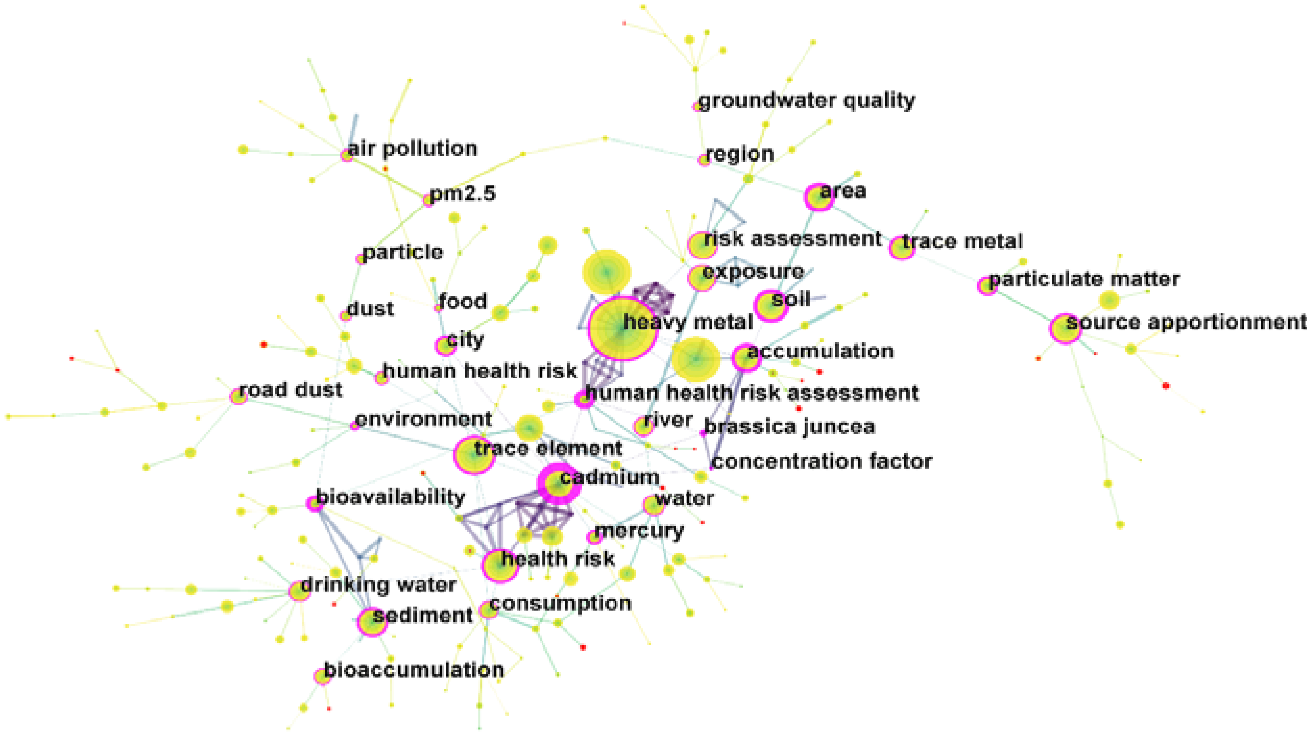

Figure 7. Network diagram of co-occurrence keyword (Larger nodes indicate larger keyword frequency; The outermost purple ring denotes the level of centrality (>0.1), and a red circle represents frequency bursts; The color range in nodes and links indicates the year in which the keywords appear; The dark purple color signifies early keywords, while the yellow color symbolizes the latest keywords).

'bioavailability' (0.54), 'soil' (0.43), 'area' (0.43), 'heavy metal' (0.38), 'health risk' (0.28), 'trace metal' (0.28), and 'trace element' (0.26). By analyzing Fig. 5 and the co-occurring keywords with high frequency and centrality, we can conclude that in the past two decades, the most popular research topics in the field of heavy metal health risk assessment have mainly focused on the investigation of media, including soil, sediment, drinking water, dust, and particulate matter. The heavy metals studied mainly include lead, cadmium, mercury, and zinc. Meanwhile, the research has been mainly focused on cities and regions, source apportionment, accumulation, and bioavailability.

Strong-burst keyword Analysis

The burst detection of co-occurring keywords can identify burst keywords, which can serve as an indicator of emerging trends (Chen et al. 2014). Table 8 presents the top twenty keywords with the strongest citation bursts. Based on these burst keywords, the research trends in the field of heavy metal health risk assessment over the last two decades can be roughly divided into two stages: the first stage, approximately from 2002 to 2015, focuses on health risk assessment of soil heavy metals, such as 'soil', 'risk assessment', 'heavy metals', 'lead', 'mercury', and 'exposure'; the second stage, approximately from 2010 to 2022, marks the transition to studying heavy metals in urban environments, manifested in the study of 'wastewater', 'vicinities', 'population', and 'different functional areas'. The focus has shifted to more commonly occurring types of heavy metals, such as copper and zinc. Furthermore, researchers are increasingly paying attention to human exposure and the bioavailability of heavy metals.

Among these keywords, the term 'China' has the strongest burst (20.64), spanning from 2013 to 2018. This suggests a surge of interest among researchers in the field of heavy metal health risk assessment during this period. With the rapid development of industrialization since the 20th century, China's environmental pollution problem has become increasingly prominent (Li et al. 2014). A series of subsequent government environmental protection policies, such as the Environmental Protection Law of the People's Republic of China revised in 2014 (https://www.gov.cn), have garnered significant attention from relevant environmental scholars in China and triggered a research boom. Furthermore, the term 'different functional area' has emerged in the last three years, indicating its recent popularity as a research topic. Urbanization has led to functional differentiation in urban areas, with varying risks of heavy metal pollution caused by human activities in different functional areas (Fan et al. 2022). Therefore, more attention should be paid to the impact of human activities in order to better protect residents' health and environmental quality, and maintain the sustainable development of the entire ecosystem.

Conclusions

This paper utilizes the scientific information visualization software CiteSpace based on the WoS database to explore the publication characteristics, scientific collaborations, hot topics, and research trends in the field of heavy metal health risk assessment from 2000 to 2022, and reveal the research status and trends in this field from a more comprehensive perspective. Since 2010, research on heavy metal health risk assessment has developed rapidly, with an increasing number

Table 8. Top 10 Keywords with the strongest citation bursts.

Phase	Keywords	Strength	Begin	End	2000 - 2022
Phase-1	heavy metal	9.66	2002	2011	
	lead	14.33	2005	2015	
	soil	13.14	2005	2015	
	risk assessment	7.8	2007	2013	
	exposure	8.22	2008	2012	
	mercury	5.87	2009	2013	
Phase-2	bioavailability	8.6	2010	2015	
	china	20.64	2013	2018	
	dietary intake	7.16	2013	2016	
	waste water	11.14	2014	2018	
	bioaccessibility	7.42	2014	2015	
	vicinity	6.64	2014	2019	
	copper	5.22	2014	2015	
	zinc	7.75	2015	2017	
	environment	5.27	2015	2017	
	human exposure	5.24	2015	2016	
	population	7.76	2017	2019	
	health risk index	5.18	2017	2020	
	exposure assessment	6.74	2018	2020	
	different functional area	5.77	2020	2022	

of annual publications. Fakhri, Yadolah from Iran is the most published scholar, the Chinese Academy of Sciences is the most published research institution, and China is the most published country. Published literature indicates that although developing countries have a larger number of publications, developed countries have a higher centrality and burst strength. For the co-cited authors, the citation rates of US Environmental Protection Agency and the World Health Organization are very high. The journals with the highest number of citations in this field typically have multiple scopes and high impact factors related to the environment. In addition, the top ten highly co-cited publications are all published by Chinese authors.

Combining co-citation clustering and high-frequency co-occurrence keyword analysis, it can be seen that the main research fields and hotspots in heavy metal health risk assessment in the past two decades have mainly focused on heavy metal research in media, such as soil, dust, drinking water, vegetables, fish, and sediment. The main types of heavy metals studied are mainly lead, cadmium, mercury, zinc, and copper. The research mainly focuses on the bioaccumulation, bioavailability, source apportionment and spatial distribution of heavy metals. In the future, research trends in heavy metal health risk assessment may focus more on the impact of heavy metals on population exposure in urban areas and the health risks in different functional areas of the city.

Acknowledgments

The National Natural Science Foundation of China provided Grants (42277487) for this research.

References

Alam, A., Chaudhry, M. N., Ahmad, S. R., Batool, A., Mahmood, A. & Al-Ghamdi, H. A. (2021). Application of EASEWASTE model for assessing environmental impacts from solid waste landfilling. *Archives of Environmental Protection*. 47 (4), pp. 84–92, DOI:10.24425/aep.2021.139504

Ali, H., Khan, E. & Ilahi, I. (2019). Environmental chemistry and ecotoxicology of hazardous heavy metals: environmental persistence, toxicity, and bioaccumulation. *Journal of Chemistry*, 6730305. DOI: 10.1155/2019/6730305

Antoniadis, V., Shaheen, S. M., Boersch, J., Frohne, T., Laing, G. D. & Rinklebe, J. (2017). Bioavailability and risk assessment of potentially toxic elements in garden edible vegetables and soils around a highly contaminated former mining area in Germany. *Journal of Environmental Management*, 186, pp. 192–200. DOI: 10.1016/j.jenvman.2016.04.036

Aoshima, K. (2012). Itai-itai disease: cadmium-induced renal tubular osteomalacia-current situations and future perspectives. *Japanese Journal of Hygiene*, 67, pp. 455–463. DOI: 10.1265/jjh.67.455

Börner, K., Chen, C. & Boyack K. W. (2003). Visualizing knowledge domains. *Annual Review of Information Science and Technology*, 37, pp. 179–255. DOI:10.1002/aris.1440370106

Cai, M., An, C. & Guy, C. (2021). A scientometric analysis and review of biogenic volatile organic compound emissions: Research hotspots, new frontiers, and environmental impliations. *Renewable and Sustainable Energy Reviews*, 149, 111317. DOI:10.1016/j.rser.2021.111317

Cao, S., Duan, X., Zhao, X., Ma, J., Dong, T., Huang, N., Sun, C., He, B. & Wei, F. (2014). Health risks from the exposure of children to As, Se, Pb and other heavy metals near the largest coking plant in China. *Science of the Total Environment*, 472, pp. 1001–1009. DOI:10.1016/j.scitotenv.2013.11.124

Chen, C. (2005). The centrality of pivotal points in the evolution of scientific networks. In Proceedings of the 10th international conference on Intelligent user interfaces (IUI '05). Association for Computing Machinery, New York, USA, pp. 98–105. DOI:10.1145/1040830.1040859

Chen, C. (2006). CiteSpace II: Detecting and visualizing emerging trends and transient patterns in scientific literature. *Journal of the American Society for Information Science and Technology*, 57 (3), pp. 359–377. DOI:10.1002/asi.20317

Chen, C., Ibekwe-SanJuan F. & Hou J. (2010). The structure and dynamics of cocitation clusters: A multiple-perspective cocitation analysis. *Journal of the American Society for Information Science and Technology*, 61 (7), pp. 1386–1409. DOI:10.1002/asi.21309

Chen, C., Hu, Z., Liu, S. & Tseng, H. (2012). Emerging trends in regenerative medicine: a scientometric analysis in CiteSpace. *Expert Opinion on Biological Therapy*, 12 (5), pp. 593–608. DO I:10.1517/14712598.2012.674507

Chen, C., Dubin, R. & Kim, M. C. (2014). Orphan drugs and rare diseases: a scientometric review (2000–2014). *Expert Opinion on Orphan Drugs*, 2 (7), pp. 709–724. DOI:10.1517/21678707 .2014.920251

Chen, H., Zheng, C., Tu, C. & Zhu, Y. (1999). Heavy metal pollution in soils in China: status and countermeasures. *Ambio*, 28 (2), pp. 130–134. DOI:10.1080/027868299304679

Chen, H., Teng, Y., Lu, S., Wang, Y. & Wang, J. (2015). Contamination features and health risk of soil heavy metals in China. *Science of the Total Environment*, 512–513, pp. 143–153. DOI:10.1016/j. scitotenv.2015.01.025

Chen, X., Li, F., Zhang, J., Liu, S., Ou, C., Yan, J. & Sun, T. (2021). Status, fuzzy integrated risk assessment, and hierarchical risk management of soil heavy metals across China: a systematic review. *Science of the Total Environment*, 785, 147180. DOI:10.1016/j.scitotenv.2021.147180

Cui, Y., Mou, J. & Liu, Y. (2018). Knowledge mapping of social commerce research: a visual analysis using CiteSpace. *Electronic Commerce Research*, 18, pp. 837–868. DOI:10.1007/s10660-018-9288-9

De Miguel, E., Iribarren, I., Chacón, E., Ordoñez, A. & Charlesworth, S. (2007). Risk-based evaluation of the exposure of children to trace elements in playgrounds in Madrid (Spain). *Chemosphere*, 66, pp. 505–513. DOI: 0.1016/j.chemosphere.2006.05.065

De Rosa, E., Montuori, P., Sarnacchiaro, P., Di Duca, F., Giovinetti, M. C., Provvisiero, D. P., Cavicchia, C. & Triassi, M. (2022). Spatiotemporal estimation of heavy metals pollution in the Mediterranean Sea from Volturno River, southern Italy: distribution, risk assessment and loads. *Chemistry and Ecology*, 38 (4), pp. 327-355. DOI:10.1080/02757540.2022.2047950

Dhital, S., Rupakheti, D., Rupakheti, M., Yin, X., Liu, Y., Mafiana, J. J., Alareqi, M. M., Mohamednour, H. & Zhang, B. (2022). A scientometric analysis of indoor air pollution research during 1990–2019. *Journal of Environmental Management*, 320, 115736. DOI:10.1016/j.jenvman.2022.115736

Egghe, L. (2006). Theory and practise of the g-index. *Scientometrics*, 69, pp. 131–152. DOI:10.1007/s11192-006-0144-7

Ellegaard, O. & Wallin, J. A. (2015). The bibliometric analysis of scholarly production: How great is the impact?. *Scientometrics*, 105, pp. 1809–1831. DOI:10.1007/s11192-015-1645-z

Eslami, H., Esmaeili, A., Razaeian, M., Salari, M., Hosseini, A. N., Mobini, M. & Barani, A. (2022). Potentially toxic metal concentration, spatial distribution, and health risk assessment in drinking groundwater resources of southeast Iran. *Geoscience Frontiers*, 13, 101276. DOI:10.1016/j.gsf.2021.101276

European Parliament and Council of the European Union (2003). Directive 2002/95/EC of the European Parliament and of the Council of 27 January 2003 on the restriction of the use of certain hazardous substances in electrical and electronic equipment. *Official Journal of the European Union*, pp. 19–23.

Fakhri, Y., Daraei, H., Hoseinvandtabar, S., Mehri, F., Mahmudiono, T. & Khaneghah, A. M. (2022). The concentration of the potentially toxic element (PTEs) in black tea (*Camellia sinensis*) consumed in Iran: a systematic review, meta-analysis, and probabilistic risk assessment study. *International Journal of Environmental Analytical Chemistry*, DOI:10.1080/03067319.2022.2118596.

Fan, P., Lu, X., Yu, B., Fan, X., Wang, L., Lei, K., Yang, Y., Zuo, L. & Rinklebe, J. (2022). Spatial distribution, risk estimation and source apportionment of potentially toxic metal (loid)s in resuspended megacity street dust. *Environment International*, 160, 107073. DOI:10.1016/j.envint.2021.107073

Fathabad, A. E., Shariatifar, N., Moazzen, M., Nazmara, S., Fakhri, Y., Alimohammadi, M., Azari, A. & Khaneghah, A. M. (2018). Determination of heavy metal content of processed fruit products from Tehran's market using ICP- OES: A risk assessment study. *Food and Chemical Toxicology*, 115, pp. 436–446. DOI:10.1016/j.fct.2018.03.044

Fei, X., Lou, Z., Xiao, R., Lv, X. & Christakos, G. (2023). Contamination and health risk assessment of heavy metal pollution in soils developed from different soil parent materials. *Exposure and Health*, 15, pp. 395–408. DOI:10.1007/s12403-022-00498-w

Ferreira-Baptista, L. & De Miguel, E. (2005). Geochemistry and risk assessment of street dust in Luanda, Angola: A tropical urban environment. *Atmospheric Environment*, 39, pp. 4501–4512. DOI:10.1016/j.atmosenv.2005.03.026

Freeman, L. C. (1977). A set of measures of centrality based on betweenness. *Sociometry*, 40 (1), pp. 35–41. DOI: 10.2307/3033543

Geng, Y., Zhu, R. & Maimaituerxun, M. (2022). Bibliometric review of carbon neutrality with CiteSpace: evolution, trends, and framework. *Environmental Science and Pollution Research*, 29, pp. 76668–76686. DOI:10.1007/s11356-022-23283-3

Gong, Y., Zhao, D. & Wang, Q. (2018). An overview of field-scale studies on remediation of soil contaminated with heavy metals and metalloids: Technical progress over the last decade. *Water Research*, 147, pp. 440–460. DOI:10.1016/j.watres.2018.10.024

Grochowska, J. K., Tandyrak, R., Augustyniak, R., Łopata, M., Popielarczyk, D. & Templin, T. (2021). How we can disrupt ecosystem of urban lakes – pollutants of bottom sediment in two shallow water bodies. *Archives of Environmental Protection*, 47 (4), pp. 40–54, DOI:10.24425/aep.2021.139501

Guo, K., Liu, Y.F., Zeng, C., Chen, Y.Y. & Wei, X.J. (2014). Global research on soil contamination from 1999 to 2012: A bibliometric analysis. *Acta Agriculturae Scandinavica, Section B—Soil & Plant Science*, 64 (5), pp. 377–391. DOI:10.1080/09064710.2014.913679

Håkanson, L. (1980). An ecological risk index for aquatic pollution control: a sedimentological approach. *Water Research*, 14, pp. 975–1001. DOI:10.1016/0043-1354 (80)90143-8

Han, M., Yang, F. & Sun, H. (2021). A bibliometric and visualized analysis of research progress and frontiers on health effects caused by $PM_{2.5}$. *Environmental Science and Pollution Research*, 28, pp. 30595–30612. DOI:10.1007/s11356-021-14086-z

Hossini, H., Shafie, B., Niri, A. D., Nazari, M., Esfahlan, A. J., Ahmadpour, M., Nazmara, Z., Ahmadimanesh, M., Makhdoumi, P., Mirzaei N. & Hoseinzadeh, E. (2022). A comprehensive review on human health effects of chromium: insights on induced toxicity. *Environmental Science and Pollution Research*, 29, pp. 70686–70705. DOI:10.1007/s11356-022-22705-6

Hu, X., Zhang, Y., Ding, Z., Wang, T., Lian, H., Sun, Y. & Wu, J. (2012). Bioaccessibility and health risk of arsenic and heavy metals (Cd, Co, Cr, Cu, Ni, Pb, Zn and Mn) in TSP and PM2.5 in Nanjing, China. *Atmospheric Environment*, 57, pp. 146–152. DOI:10.1016/j.atmosenv.2012.04.056

Hu, X., Zhang, Y., Luo, J., Wang, T., Lian, H. & Ding, Z. (2011). Bioaccessibility and health risk of arsenic, mercury and other metals in urban street dusts from a mega-city, Nanjing, China. *Environmental Pollution*, 159, pp. 1215–1221. DOI:10.1016/j.envpol.2011.01.037

Huang, J., Guo, S., Zeng, G., Li, F., Gu, Y., Shi, Y., Shi, L., Liu, W. & Peng, S. (2018). A new exploration of health risk assessment quantification from sources of soil heavy metals under different land use. *Environmental Pollution*, 243, pp. 49–58. DOI:10.1016/j.envpol.2018.08.038

Ivaneev, A. I., Brzhezinskiy, A. S., Karandashev, V. K., Ermolin, M. S. & Fedotov, P. S. (2023). Assessment of sources, environmental, ecological, and health risks of potentially toxic elements in urban dust of Moscow megacity, Russia. *Chemosphere*, 321, 138142. DOI:10.1016/j.chemosphere.2023.138142

Jaishankar, M., Tseten, T., Anbalagan, N., Mathew, B.B. & Beeregowda, K.N. (2014). Toxicity, mechanism and health effects of some heavy metals. *Interdisciplinary Toxicology*, 7 (2), pp. 60–72. DOI:10.2478/intox-2014-0009

Järup, L. (2003). Hazards of heavy metal contamination. *British Medical Bulletin*, 68, pp. 167–182. DOI:10.1093/bmb/ldg032

Ji, A., Wang, F., Luo, W., Yang, R., Chen, J. & Cai, T. (2011). Lead poisoning in China: a nightmare from industrialisation. *Lancet*, 377 (9776), pp. 1474–1476. DOI:10.1016/S0140-6736 (10)60623-X

Jiang, Y., Chao, S., Liu, J., Yang, Y., Chen, Y., Zhang, A. & Cao, H. (2017). Source apportionment and health risk assessment of heavy metals in soil for a township in Jiangsu Province, China. *Chemosphere*, 168, pp. 1658–1668. DOI:10.1016/j.chemosphere.2016.11.088

Khan, D. A., Qayyum, S., Saleem, S., Ansari, W. M. & Khan, F. A. (2010). Lead exposure and its adverse health effects among occupational worker's children. *Toxicology and Industrial Health*, 26 (8), pp. 497 –504. DOI:10.1177/0748233710373085

Khan, S., Cao, Q., Zheng, Y. M., Huang, Y. Z. & Zhu, Y. G. (2008). Health risks of heavy metals in contaminated soils and food crops irrigated with wastewater in Beijing, China. *Environmental Pollution*, 152, pp. 686–692. DOI:10.1016/j.envpol.2007.06.056

Kleinberg, J. (2003). Bursty and hierarchical structure in streams. *Data Mining and Knowledge Discovery*, 7, pp. 373–397. DOI:10.1023/A:1024940629314

Komárek, M., Ettler, V., Chrastný, V. & Mihaljevič, M. (2008). Lead isotopes in environmental sciences: A review. *Environment International*, 34, pp. 562–577. DOI:10.1016/j.envint.2007.10.005

Kumari, M. & Bhattacharya, T. (2023). A review on bioaccessibility and the associated health risks due to heavy metal pollution in coal mines: Content and trend analysis. *Environmental Development*, 46, 100859. DOI:10.1016/j.envdev.2023.100859

Li, F., Yan, J., Wei, Y., Zeng, J., Wang, X., Chen, X., Zhang, C., Li, W., Chen, M. & Lv, G. (2020). PM2.5-bound heavy metals from the major cities in China: Spatiotemporal distribution, fuzzy exposure assessment and health risk management. *Journal of Cleaner Production*, 286, 124967. DOI:10.1016/j.jclepro.2020.124967

Li, M., Wang, Y., Xue, H., Wu, L., Wang, Y., Wang, C., Gao, X., Li, Z., Zhang, X., Hasan, M., Alruqi, M., Bokhari, A. & Han, N. (2022). Scientometric analysis and scientific trends on microplastics research. *Chemosphere*, 304, 135337. DOI:10.1016/j.chemosphere.2022.135337

Li, Z., Ma, Z., van der Kuijp, T. J., Yuan, Z. & Huang, L. (2014). A review of soil heavy metal pollution from mines in China: Pollution and health risk assessment. *Science of the Total Environment*, 468–469, pp. 843–853. DOI:10.1016/j.scitotenv.2013.08.090

Liu, X., Song, Q., Tang, Y., Li, W., Xu, J., Wu, J., Wang, F. & Brookes, P. C. (2013). Human health risk assessment of heavy metals in soil–vegetable system: A multi-medium analysis. *Science of the Total Environment*, 463–464, pp. 530–540. DOI:10.1016/j.scitotenv.2013.06.064

Liu, Z., Yin, Y., Liu, W. & Dunford, M. (2015). Visualizing the intellectual structure and evolution of innovation systems research: a bibliometric analysis. *Scientometrics*, 103, pp. 135–158. DOI:10.1007/s11192-014-1517-y

López, L. A., Arce, G., Kronenberg, T. & Rodrigues, J. F. D. (2018). Trade from resource-rich countries avoids the existence of a global pollution haven hypothesis. *Journal of Cleaner Production*, 175, pp. 599–611. DOI:10.1016/j.jclepro.2017.12.056

Lu, X., Zhang, X., Li, L.Y. & Chen, H. (2014). Assessment of metals pollution and health risk in dust from nursery schools in Xi'an, China. *Environmental Research*, 128, pp. 27–34. DOI:10.1016/j.envres.2013.11.007

Luo, H., Wang, Q., Guan, Q., Ma, Y., Ni, F., Yang, E. & Zhang, J. (2022). Heavy metal pollution levels, source apportionment and risk assessment in dust storms in key cities in Northwest China. *Journal of Hazardous Materials*, 422, 126878. DOI:10.1016/j.jhazmat.2021.126878

Mahmood, A. & Malik, R. N. (2014). Human health risk assessment of heavy metals via consumption of contaminated vegetables collected from different irrigation sources in Lahore, Pakistan. *Arabian Journal of Chemistry*, 7, pp. 91–99. DOI:10.1016/j.arabjc.2013.07.002

Mahmudiono, T., Fakhri, Y., Adiban, M., Sarafraz, M. & Mohamadi, S. (2023). Concentration of potential toxic elements in canned tuna fish: systematic review and health risk assessment. *International Journal of Environmental Health Research*, DOI:10.1080/09603123.2023.2264205

Masri, S., LeBrón, A. M. W., Logue, M. D., Valencia, E., Ruiz, A., Reyes, A. & Wu, J. (2021). Risk assessment of soil heavy metal contamination at the census tract level in the city of Santa Ana, CA: implications for health and environmental justice. *Environmental Science: Processes & Impacts*, 23, pp. 812–830. DOI:10.1039/d1em00007a

Men, C., Liu, R., Xu, F., Wang, Q., Guo, L. & Shen, Z. (2018). Pollution characteristics, risk assessment, and source apportionment of heavy metals in road dust in Beijing, China. *Science of the Total Environment*, 612, pp. 138–147. DOI:10.1016/j.scitotenv.2017.08.123

Merigó, J. M. & Yang, J.-B. (2017). A bibliometric analysis of operations research and management science. *Omega*, 73, pp. 37–48. DOI:10.1016/j.omega.2016.12.004

Muhammad, S., Shah, M.T. & Khan, S. (2011). Health risk assessment of heavy metals and their source apportionment in drinking water of Kohistan region, northern Pakistan. *Microchemical Journal*, 98, pp. 334–343. DOI:10.1016/j.microc.2011.03.003

Peng, J., Zhang, S., Han, Y., Bate, B., Ke, H. & Chen, Y. (2022). Soil heavy metal pollution of industrial legacies in China and health risk assessment. *Science of the Total Environment*, 816, 151632. DOI:10.1016/j.scitotenv.2021.151632

Qin, F., Li, J., Zhang, C., Zeng, G., Huang, D., Tan, X., Qin, D. & Tan, H. (2022). Biochar in the 21st century: a data-driven visualization of collaboration, frontier identification, and future trend. *Science of the Total Environment*, 818, 151774. DOI:10.1016/j.scitotenv.2021.151774

Rai, P. K., Lee, S. S., Zhang, M., Tsang, Y. F. & Kim, K.-H. (2019). Heavy metals in food crops: Health risks, fate, mechanisms, and management. *Environment International*, 125, pp. 365–385. DOI:10.1016/j.envint.2019.01.067

Sabe, M., Pillinger, T., Kaiser, S., Chen, C., Taipale, H., Tanskanen, A., Tiihonen, J., Leucht, S., Correll, C. U. & Solmi, M. (2022). Half a century of research on antipsychotics and schizophrenia: A scientometric study of hotspots, nodes, bursts, and trends. *Neuroscience and Biobehavioral Reviews*, 136, 104608. DOI:10.1016/j.neubiorev.2022.104608

Saha, K. C. (2003). Review of arsenicosis in West Bengal, India—a clinical perspective. *Critical Reviews in Environmental Science and Technology*, 33 (2), pp. 127–163. DOI:10.1080/10643380390814514

Shahab, A., Hui, Z., Rad, S., Xiao, H., Siddique, J., Huang, L. L., Ullah, H., Rashid, A., Taha, M. R. & Zada, N. (2023). A comprehensive review on pollution status and associated health risk assessment of human exposure to selected heavy metals in road dust across different cities of the world. *Environmental Geochemistry and Health*, 45, pp. 585–606. DOI:10.1007/s10653-022-01255-3

Shaheen, N., Irfan, N. M., Khan, I. N., Islam, S., Islam, M. S. & Ahmed, M. K. (2016). Presence of heavy metals in fruits and vegetables: Health risk implications in Bangladesh. *Chemosphere*, 152, pp. 431–438. DOI:10.1016/j.chemosphere.2016.02.060

Shen, Z., Wu, H., Chen, Z., Hu, J., Pan, J., Kong, J. & Lin, T. (2022). The global research of artificial intelligence on prostate cancer: A 22-year bibliometric analysis. *Frontiers in Oncology*, 12, 843735. DOI:10.3389/fonc.2022.843735

Small, H. (1973). Co-citation in the scientific literature: A new measure of the relationship between two documents. *Journal of the American Society and Information Science*, 24, pp. 265–269. DOI:10.1002/asi.4630240406

Smith, A. H., Lingas, E. O. & Rahman, M. (2000). Contamination of drinking-water by arsenic in Bangladesh: a public health emergency. *Bulletin of the World Health Organization*, 78, pp. 1093–1103. DOI:10.1146/annurev.publhealth.21.1.659

Sultana, Z., Rehman, M. Y. A., Khan, H. K. & Malik, R. N. (2023). Health risk assessment associated with heavy metals through fractioned dust from coal and chromite mines in Pakistan. *Environmental Geochemistry and Health*, 45, pp. 1617–1633. DOI:10.1007/s10653-022-01285-x

Trujillo-González, J. M., Torres-Mora, M. A., Keesstra, S., Brevik, E. C. & Jiménez-Ballesta, R. (2016). Heavy metal accumulation related to population density in road dust samples taken from urban sites under different land uses. *Science of the Total Environment*, 553, pp. 636–642. DOI:10.1016/j.scitotenv.2016.02.101

Urbano, T., Verzelloni, P., Malavolti, M., Sucato, S., Polledri, E., Agnoli, C., Sieri, S., Natalini, N., Marchesi, C., Fustinoni, S., Vinceti, M. & Filippini, T. (2023). Influence of dietary patterns on urinary excretion of cadmium in an Italian population: A cross-sectional study. *Journal of Trace Elements in Medicine and Biology*, 80, 127298. DOI:10.1016/j.jtemb.2023.127298

USEPA (United States Environmental protection Agency). (1989). Risk Assessment Guidance for Superfund (RAGS): Volume I. Human Health Evaluation Manual (HHEM)–Part A, Baseline Risk Assessment. Office of Emergency and Remedial Response, Washington DC [EPA/540/1-89/002].

USEPA (2008). Overview: Office of pollution prevention and Toxics laws and programs.

Wang, J., Cai, Y., Yang, J. & Zhao, X. (2021). Research trends and frontiers on source appointment of soil heavy metal: a scientometric review (2000–2020). *Environmental Science and Pollution Research*, 28, pp. 52764–52779. DOI:10.1007/s11356-021-16151-z

Wei, X., Gao, B., Wang, P., Zhou, H. & Lu, J. (2015). Pollution characteristics and health risk assessment of heavy metals in street dusts from different functional areas in Beijing, China. *Ecotoxicology and Environmental Safety*, 112, pp. 186–192. DOI:10.1016/j.ecoenv.2014.11.005

WHO (2011). Guidelines for Drinking-water Quality, fourth ed. World Health Organization, Geneva.

Wu, Q., Hu, W., Wang, H., Liu, P., Wang, X. & Huang, B. (2021). Spatial distribution, ecological risk and sources of heavy metals in soils from a typical economic development area, Southeastern China. *Science of the Total Environment,* 780, 146557. DOI:10.1016/j.scitotenv.2021.146557

Xiao, F., Li, C., Sun, J. & Zhang, L. (2017). Knowledge domain and emerging trends in organic photovoltaic technology: A scientometric review based on CiteSpace analysis. *Frontiers in Chemistry*, 5, 67. DOI:10.3389/fchem.2017.00067

Xiao, Q., Zong, Y. & Lu, S. (2015). Assessment of heavy metal pollution and human health risk in urban soils of steel industrial city (Anshan), Liaoning, Northeast China. *Ecotoxicology and Environmental Safety*, 120, pp. 377–385. DOI:10.1016/j.ecoenv.2015.06.019

Yan, J., Qu, Z., Li, F. & Li, H. (2021). Heavy metals in the water environment of Yangtze River Economic Belt: status, fuzzy environmental risk assessment and management. *Urban Climate*, 40, 100981. DOI:10.1016/j.uclim.2021.100981

Yang, Q., Li, Z., Lu, X., Duan, Q., Huang, L. & Bi, J. (2018). A review of soil heavy metal pollution from industrial and agricultural regions in China: Pollution and risk assessment. *Science of the Total Environment*, 642, pp. 690–700. DOI:10.1016/j.scitotenv.2018.06.068

Yang, Y. & Meng, G. (2019). A bibliometric analysis of comparative research on the evolution of international and Chinese ecological footprint research hotspots and frontiers since 2000. *Ecological Indicators*, 102, pp. 650–665. DOI:10.1016/j.ecolind.2019.03.031

Yi, Y., Yang, Z. & Zhang, S. (2011). Ecological risk assessment of heavy metals in sediment and human health risk assessment of heavy metals in fishes in the middle and lower reaches of the Yangtze River basin. *Environmental Pollution*, 159, pp. 2575–2585. DOI:10.1016/j.envpol.2011.06.011

Zhang, J., Jiang, L., Liu, Z., Li, Y., Liu, K., Fang, R., Li, H., Qu, Z., Liu, C. & Li, F. (2021). A bibliometric and visual analysis of indoor occupation environmental health risks: Development, hotspots and trend directions. *Journal of Cleaner Production*, 300, 126824. DOI:10.1016/j.jclepro.2021.126824

Zheng, N., Liu, J., Wang, Q. & Liang, Z. (2010). Health risk assessment of heavy metal exposure to street dust in the zinc smelting district, Northeast of China. *Science of the Total Environment*, 408, pp. 726–733. DOI:10.1016/j.scitotenv.2009.10.075

Zhong, W., Zhang, Y., Wu, Z., Yang, R., Chen, X., Yang, J. & Zhu, L. (2018). Health risk assessment of heavy metals in freshwater fish in the central and eastern North China. *Ecotoxicology and Environmental Safety*, 157, pp. 343–349. DOI:10.1016/j.ecoenv.2018.03.048