Environmental Dynamics and Risk: Bibliometric Insights into Soil Heavy Metal Accumulation Under Environmental Stressors

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Under environmental stress, the migration and accumulation of heavy metals in soil profoundly affect ecosystem dynamics and environmental risks. This study applied CiteSpace bibliometric methods to visually analyze 1,768 publications from 2000 to 2024, based on the Web of Science Core Collection. The analysis included publication trends, keyword frequencies, international collaboration, core authors, and institutions. Results show a shift in focus from pollution identification and mechanisms to health risk assessment and material-based remediation. Notably, increasing attention has been given to lignocellulose-derived amendments such as humic acid and biochar for their potential in stabilizing soils under compound environmental stressors. Leading institutions such as the Chinese Academy of Sciences and U.S. research bodies have played prominent roles, while high-impact journals, including the *Journal of Biogeography*, reflect strong academic output. Keyword clustering and burst analysis highlight emerging cores like "speciation," "health risk," and "biochar," showing a phase-based evolution of research themes. The field's short citation half-life, frequent keyword bursts, and multidisciplinary integration confirm its status as a research frontier. This study provides a comprehensive knowledge map and valuable insight into the dynamic behavior of soil heavy metals under environmental stress.

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INTRODUCTION

Soil, as a critical natural resource that is essential for human survival, plays a fundamental role in maintaining ecological balance. Under environmental stress, the migration, transformation, and accumulation of heavy metals in soil exhibit heightened complexity and dynamism (Xu *et al*. 2020; Liu *et al*. 2021). Extreme environmental conditions – such as acid rain, extreme temperatures, high salinity, high pressure, and hypoxia – can significantly alter soil physicochemical properties and microbial community structures, thereby affecting the speciation and bioavailability of heavy metals. However, unsustainable industrial development has accelerated soil degradation, leading to a growing trend of heavy metal pollution on a global scale (Li *et al*. 2018). In China, a typical example, approximately one-fifth of arable land is affected by heavy metal contamination, primarily involving cadmium, nickel, copper, mercury, and lead (Chen *et al*. 2017). In response, the Chinese government has elevated soil pollution control to a national strategic priority through the implementation of the Soil Pollution Prevention and Control Action Plan (2016) (Yue *et al*. 2024).

In recent years, lignocellulose-based materials have received increasing attention due to their abundance, renewability, and multifunctionality in soil remediation. Humic acid, as a terminal product of lignin and cellulose biodegradation, is rich in carboxyl and phenolic hydroxyl groups, enabling the formation of stable complexes with heavy metals, thereby effectively reducing their mobility and bioavailability (Zhang *et al*. 2023). As a typical lignocellulose-derived product, biochar possesses a high specific surface area and porous structure, which not only facilitates the immobilization of heavy metals but also modulates plant antioxidant enzyme activity and nitrogen metabolism, ultimately enhancing crop tolerance to heavy metal stress (Lei *et al*. 2022). In addition, the combination of biochar with nanoscale zero-valent iron has shown synergistic effects, significantly improving the removal efficiency of both organic and inorganic pollutants in contaminated soils (Li *et al*. 2020). El-Mahrouk *et al*. (2020) confirmed that *Populus nigra* exhibited significant phytoremediation capacity for cadmium, copper, and lead. Collectively, these findings underscore the potential of lignocellulose-based materials as key components in the development of sustainable and multifunctional soil remediation technologies.

Under extreme environmental stress conditions, remediation systems constructed with lignocellulose-based materials continue to exhibit high adaptability and functional synergy. The combined application of humic acid and biochar forms a dynamic "desorption-immobilization" remediation pathway, whereby heavy metals previously adsorbed are partially released to enhance plant uptake, while the stabilizing effect simultaneously inhibits excessive migration, thereby mitigating ecological risks. Under high-salinity conditions, Naheed *et al*. (2022) found that moderate salinity (150 mM NaCl) enhanced plant tolerance to nickel, while the humic acid-biochar system buffered oxidative stress induced by higher salinity levels (300 mM NaCl). Similarly, Jampasri *et al*. (2020) demonstrated that under salt stress, bioremediation using *Micrococcus luteus* significantly affected the uptake and accumulation of lead, while having minimal impact on the degradation rate of total hydrocarbons, thereby highlighting the potential of this plant–microbe system in mildly saline-alkaline soils. Under high-temperature conditions, temperature was shown to influence the affinity between alkaline phosphatase (ALP) and cadmium in soil: as temperature increased from 17 to 47 °C, both the reaction rate constant and the maximum reaction rate of ALP increased linearly, suggesting that elevated temperatures exacerbate the toxic effects of cadmium (Tan *et al*. 2018). Additionally, Bogacz *et al*. (2011) found that post-fire high temperatures significantly increased the concentration of heavy metals in organic soils, particularly in surface and sludge layers. Changes in soil color also indicated an increase in iron oxide content, collectively pointing to substantial shifts in heavy metal dynamics under high-temperature conditions. Under high-pressure conditions, Reza *et al*. (2015) found that soil contamination with cadmium (Cd) and lead (Pb) in the coal mining areas of Assam, India, was closely linked to mining activities. Similarly, studies by Mishra *et al*. (2008) and Pandey *et al*. (2016) demonstrated that coal extraction leads to the enrichment of heavy metals in soils, often exceeding environmental safety thresholds. Ou *et al*. (2018) reported that cadmium and chromium posed potential ecological risks in waterlogged subsidence zones caused by coal mining.

Sundaray *et al*. (2011) further indicated that under conditions of reduced redox potential, lowered pH, or oxygen deficiency, heavy metals are more likely to shift from reduced forms to exchangeable forms, thereby increasing the risk of contamination. Acid rain significantly reduces soil pH, inducing the leaching and migration of elements such as Cd (Cheng *et al*. 2023). Song *et al*. (2014) compared three acidification treatments – direct sulfuric acid application (T1), ammonium sulfate-simulated fertilization (T2), and simulated acid rain (T3) – under equal pH reduction conditions and examined their effects on copper speciation in two contaminated soil types (fluvo-aquic soil and yellow brown soil). Results showed that simulated acid rain was the most significant factor promoting heavy metal activation in soil. Through soil column leaching experiments, Liu *et al*. (2017) found that under acid rain conditions, pH changes were most pronounced in the surface layer of red mud, while changes in the deeper layers were relatively limited due to stronger soil buffering capacity. This highlights the differential migration and activation behavior of heavy metals across soil horizons. These phenomena indicate that under the interaction of multiple environmental stressors, lignocellulose-based materials not only exhibit structural stability but they also adapt to the complex dynamics at the soil-pollutant-plant interface, thereby supporting sustainable remediation strategies.

Although extensive empirical studies have been conducted on material mechanisms and environmental impacts, a systematic review of the knowledge structure, developmental evolution, and research trends in this field remains insufficient. As a research tool characterized by objectivity, quantifiability, and structural visualization, bibliometric analysis offers support for identifying research frontiers and emerging hotspots. By integrating both qualitative and quantitative approaches, this study employed CiteSpace to construct scientific knowledge maps and conducted a comprehensive bibliometric analysis of soil heavy metal remediation research from 2000 to 2024. The goal was to uncover the evolutionary trends, knowledge clustering patterns, and future directions of research on heavy metal pollution under extreme environmental conditions.

EXPERIMENTAL

Data Acquisition

The data for this study were sourced from the Web of Science (WoS) Core Collection. Due to its comprehensive and multidisciplinary citation data, WoS has become a primary source of bibliometric analysis among various databases (Li *et al*. 2020). It allows researchers and scholars to access a vast array of bibliographic data from reputable and credible journals. A search was conducted within the framework of the study, using the following search query: TS=(Extreme environments Soil heavy metals* OR Extreme Environment Cropland Heavy Metals* OR Extreme Environment Farmland Heavy Metals* OR Extreme environments Agricultural land heavy metals* OR Extreme environments Agricultural soil heavy metals* OR acid rain Soil heavy metals* OR extremal temperature Soil heavy metals* OR high salt Soil heavy metals* OR High Pressure Environmental Soil Heavy Metals* OR radiate Soil heavy metals* OR anoxic Soil heavy metals), with language restricted to English, and document types to Articles and Reviews. The timeframe covered was from 2000 to 2024, with the search executed on August 5, 2024. After removing duplicates, a total of 1,768 publications were retrieved. The bibliometric data encompassed crucial information including paper details, keywords, author affiliations, and citations, all of which are essential for bibliometric analysis.

Research Methods

Rigorous data collection and analytical methods underpin the generation of reliable and insightful research findings. The bibliometric analysis tool, CiteSpace, devised by Chen (2017), is extensively employed to uncover emerging trends and dynamic patterns within the scientific corpus. This study utilized the bibliometric software CiteSpace (6.3.R3) combined with the Web of Science (WoS) database for visual analysis of the retrieved literature. Through the capabilities of CiteSpace, it was possible to gain an in-depth understanding of the content of the literature. A comprehensive bibliometric analysis led to conclusions about the accumulation of heavy metals in soil under extreme environments and provided insights into future environmental research.

RESULTS AND DISCUSSION

Basic Literature Characterization

Annual publication trend

The volume of scientific papers directly reflects changes in the amount of scientific knowledge and research trends within a theme or field. The degree of change in publication volume and citation frequency over time represents the research trends and academic activity of the discipline or field (Yang *et al*. 2021). Based on the Web of Science (WoS) database up to the retrieval date (August 5, 2024), the total number of publications stands at 1,768. An analysis of the annual distribution of literature on soil heavy metals under extreme environments from 2000 to 2024 is illustrated in Fig. 1, showing a maximum annual publication volume of 183 papers and a minimum of 23 papers. From 23 papers in 2000 to 183 papers in 2022, there has been an increase of approximately 8 times. Between 2000 and 2024, the average annual publication volume of English-language literature was 70.7 papers. Overall, the publication data reveals that research on soil heavy metals under extreme environments has rapidly emerged as a hot topic in academic research since 2000, with the number of published papers showing a sharp upward trend. The number of publications has been increasing, with publications in the last decade accounting for 69.6% of the total. In summary, these data indicate that the field of research on soil heavy metals under extreme environments has developed rapidly over the past 24 years and has achieved significant results.

As shown in Fig. 1, the annual distribution of literature on soil heavy metals under extreme environments from 2000 to 2024 indicates that the maximum number of publications reached 183, while the minimum was 23. From 23 publications in 2000 to 183 in 2022, the number increased by 7.96 times. As of the retrieval date (August 5, 2024), the total number of publications amounted to 1,768. Collectively, these figures demonstrate that the field of soil heavy metals research under extreme environments has developed rapidly over the past 24 years, achieving significant outcomes. The number of publications has shown a significant upward trend since 2000, reaching a peak in 2022. The decline in publication volume in 2023 may be attributed to the rapid growth in research driven by heightened attention to environmental risks and climate events in previous years, followed by a phase of stabilization or saturation. Additionally, the decrease may also result from researchers increasingly opting for more specific or updated terminology to replace the keyword “extreme,” leading to a reduction in search results based on this term.

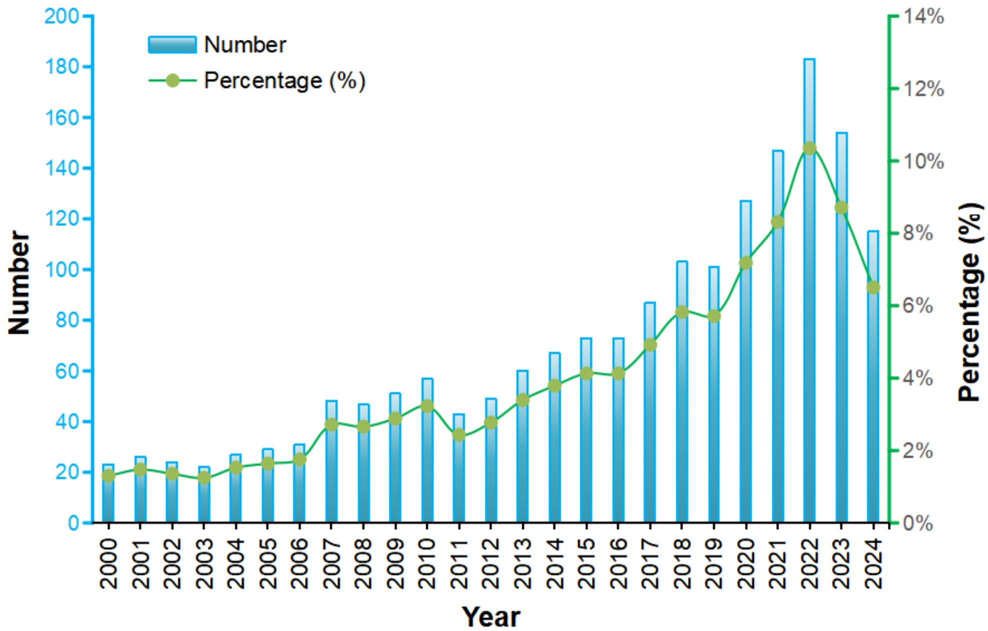

Fig. 1. Trend in the annual publication of literature on soil heavy metals under extreme environments from 2000 to 2024

Subject distribution

The intersection and integration of multiple disciplines have become a trend, with understanding the convergence of content and the evolution of knowledge across disciplines providing further reference for disciplinary development (Yang *et al*. 2018). Based on the publication year, Table 1 lists the top ten disciplines closely related to the field of soil heavy metals under extreme environments over the past 24 years, with publication volumes in each discipline increasing annually, and the average publication volume from 2019 to 2024 being five times that of 2000 to 2005. From a disciplinary perspective, the field of soil heavy metals research under extreme environments exhibits a trend of multidisciplinary intersection and integration.

Table 1. Top Ten Disciplines in the Field of Soil Heavy Metals Research under Extreme Environments and their Publication Volumes

NO.	Discipline	NOP (Number of Papers)				
		2000-2005	2006-2011	2012-2017	2018-2024	Total (Proportion/%)
1	Environmental Sciences	77	151	224	556	1008(57.01%)
2	Engineering Environmental	16	25	34	95	170(9.62%)
3	Soil Science	24	48	40	49	161(9.11%)
4	Water Resources	18	24	52	67	161(9.11%)
5	Plant Sciences	16	21	24	90	151(8.54%)
6	Ecology	5	21	21	27	74(4.19%)
7	Toxicology	4	6	10	52	72(4.07%)
8	Microbiology	2	15	15	38	70(3.96%)
9	Geosciences Multidisciplinary	7	10	29	20	66(3.73%)
10	Agronomy	10	10	10	35	65(3.68%)

Journal analysis

The introduction of the journal self-citation rate ($R_{RSC-ing}$), with values greater than 20% considered indicative of excessive self-citation and a high-risk journal status (Li *et al*. 2013), serves as a metric to assess the health of journals. Table 2 lists the top ten journals by publication volume in the field of soil heavy metals research under extreme environments over the past 24 years. Journals such as "Environmental Science and Pollution Research", "Science of the Total Environment", and "Chemosphere" each have published more than 60 articles, with "Environmental Science and Pollution Research" leading the field with 93 publications (accounting for 5.26% of the total), surpassing the second-ranked "Science of the Total Environment" (89 publications, accounting for 5.03%). The "Journal of Biogeography" boasts the highest average citation frequency per article, indicating high article quality within this field. From an impact factor (IF) analysis, the "Journal of Hazardous Materials" ranks highest with an IF of 12.2, while the "Journal of Soils and Sediments" has the lowest at 2.8. Furthermore, none of the journals exceed a 20% self-citation rate, suggesting a generally healthy state across the publications in this field.

The rate of self-citing (Fangfang *et al*. 2019) was defined by Eq. 1.

$$R_{RSC-ing} = \frac{a}{a+b} \qquad (1)$$

Author analysis

The concept of "small peers" has promoted the analysis and research of authors' publications in the same field, and also provided convenience for literature readers to search (Tang *et al*. 2021). In the past 24 years, the number of scholars engaged in research on soil heavy metals in extreme environments has shown an upward trend. Table 3 lists the top 10 WOS publications, with Abdelly Chedly from Tunisia having the highest number of publications (9). The most frequently cited and single article cited is Ali Shafaqat from Govt Coll Univ, (447 times) and the highest single article (245 times) were both cited with a frequency of 74.50 and an H-index of 6. The above-mentioned author has made sustained research contributions in this field. Exploring the core author group is of great significance in distinguishing experts in the field and analyzing the forefront of research (Yang *et al*. 2021). At the same time, the Price law provides a measure of the academic output of authors and analyzes whether they are core authors in the field (Price *et al*. 1963). According to this, it can be seen that if the number of publications is higher than 2, then one can be considered a core author in the field of soil heavy metal research in extreme environments, with a total of 185 core authors. The research field of heavy metals in soil under extreme environments is a hot topic. The Price law is shown in Eq. 2 (Price *et al*. 1963).

$$M \approx 0.749 \times \sqrt{N_{\max}} \qquad (2)$$

The *H*-index is a metric that measures the productivity and citation impact of the publications of a scientist or scholar (Hirsch *et al*. 2005). It is defined as the maximum value of *H* such that the individual has published h papers that have each been cited at least *h* times. Here, *i* is the rank of a paper when sorted in descending order by citation count, and C_i is the number of citations for the *i*-th paper. The function max(*i*) determines the highest rank at which the citation count of a paper is at least equal to its rank. The *H*-index is shown in Eq. 3 (Hirsch *et al*. 2005).

$$H = \max(i) \text{ such that } C_i \geqslant i \qquad (3)$$

Table 2. Top 10 Journals by Publication Volume in the Field of Soil Heavy Metals Research under Extreme Environments

NO.	Journal	NOP	PR (%)	CF	ACF	RRSC−ing(%)	HI	IF	JCR-P
1	Environmental Science and Pollution Research	93	5.26	1,857	19.97	N/A	22	N/A	Q1
2	Science of The Total Environment	89	5.03	3,842	43.17	11	32	8.2	Q1
3	Chemosphere	60	3.39	3,259	54.32	2.5	31	8.1	Q1
4	Environmental Pollution	53	3.00	3,083	58.17	5.3	26	7.6	Q1
5	Water Air and Soil Pollution	47	2.66	979	20.83	5.3	18	3.8	Q1
6	Journal of Soils and Sediments	40	2.26	773	19.33	3.6	18	2.8	Q2
7	Environmental Monitoring and Assessment	39	2.21	676	17.33	10.3	15	2.9	Q3
8	Ecotoxicology and Environmental Safety	38	2.15	1,227	32.29	4.8	20	6.2	Q1
9	Journal of Hazardous Materials	37	2.09	1,603	43.32	6.6	19	12.2	Q1
10	Journal of Environmental Management	26	1.47	878	33.77	5	15	8.0	Q1

*IF, JCR-P data source: Journal Citation Reports ™ 2023. NOP, number of papers; PR, published ratio; CF, citation frequency; ACF, average citation frequency; RRSC− ing, rate of self-citing; HI, h-index; IF, impact factors; JCR-P, JCR partition.

Table 3. Top 10 Authors by Publication Volume in the Field of Soil Heavy Metals Research under Extreme Environments (WoS)

NO.	Author	NOP	CF	ACF	HI
1	Abdelly, Chedly	9	236	26.22	6
2	Idaszkin, Yanina L	7	92	13.14	6
3	Ali, Shafaqat	6	447	74.50	6
4	Du, Yan-Jun	6	434	72.33	6
5	Zeng, Guangming	6	353	58.83	5
6	Mandzhieva, Saglara S	5	47	9.40	4
7	Li, Yuan	5	67	11.17	4
8	Tsang, Daniel C W	5	183	36.6	5
9	Luo, Dinggui	5	178	35.60	5
10	Perez-Lopez, Rafael	5	120	24.00	5

Published institution

Analysis of the WoS database shows that a total of 1,705 institutions worldwide have conducted research in the field of soil heavy metals under extreme environments during the study period. As indicated in Table 4, the Chinese Academy of Sciences has the highest publication volume (118 publications, accounting for 6.67% of the total). It also leads in terms of citation frequency (4,281 citations) and average citations per paper (36.28 citations), and has the highest *H*-index. Among the top ten publishing institutions, Chinese institutions appear five times, highlighting China's significant influence in this field, with the Chinese Academy of Sciences being the most influential research institution in this area.

Country of publication of literature

Globally, 109 countries or regions have conducted research in the field of soil heavy metals under extreme environments. As shown in Table 5, China has the highest publication volume with 497 papers, accounting for 28.11% of the total, and the highest number of citations at 14,807, along with the highest *H*-index at 62. India has the highest average citations per paper at 44.52. Among the top 10 countries by publication volume, aside from China and India, the rest are from Europe and North America, indicating that these regions hold a leading position in research within this field.

Academic Layout Analysis

Keywords represent a condensation of the content and research ideas of authors, embodying the directions, scope, and hotspots of a research field (Yang *et al*. 2021). Keyword clustering analysis is employed to delineate the academic landscape of soil heavy metals research under extreme environments. The settings for this analysis included a Time slicing from January 2000 to August 2024, with Years Per Slice set at 1 year, Node Types as Keywords, and Pruning options selected as Pathfinder and Pruning Sliced Networks. The calculation method chosen was "LLR", with all other settings at default. The results are as follows: the analysis revealed 651 nodes and 3,059 links, forming 9 clusters (Fig. 2). The modularity value Q of 0.4015 > 0.3 indicates a significant cluster structure, and the average silhouette S of 0.7024 > 0.5 suggests that the clustering results are reliable.

It is noteworthy that clusters #3 and #4 have similar names but are not technically duplicates. Clustering algorithms generate clusters based on different sets of literature or slightly different contextual keywords, even if the themes appear similar. This can be attributed to subtle differences in keywords, where singular and plural forms of a keyword (such as "metal" and "metals") may point to different research focuses or scopes of literature. The clusters are identified as follows: #0, speciation; #1, air pollution; #2, abiotic stress; #3, heavy metals; #4, heavy metal; #5, stabilization; #6, serpentine; #7, pH; #8, chromate reduction. According to Table 6, these clusters are categorized into four main themes.

Theme One focuses on heavy metal pollution and bioremediation, encompassing studies on the detection of heavy metal pollution, bioavailability, and the use of biotechnological approaches for remediation. Cluster#0 focuses on the speciation and bioavailability of heavy metals. Cluster#3 examines plant remediation and extraction of heavy metals, particularly lead. Cluster#4 explores bioremediation techniques, especially the role of microbial communities in heavy metal contamination. Cluster#6 is concerned with the environmental behavior and adsorption competition of heavy metals in serpentine areas.

Table 4. Top 10 Institutions by Publication Volume in the Field of Soil Heavy Metals Research under Extreme Environments (WoS)

NO.	Institution	Country	NOP	PR (%)	CF	ACF	HI
1	Chinese Academy of Sciences	China	118	6.67%	4,281	36.28	31
2	University of Chinese Academy of Sciences	China	45	2.55%	1,539	34.20	20
3	Centre National de la Recherche Scientifique (CNRS)	France	38	2.15%	1,233	32.45	18
4	University of Agriculture Faisalabad	Pakistan	30	1.70%	800	26.67	15
5	Consejo Superior de Investigaciones Cientificas (CSIC)	Spain	29	1.64%	716	24.69	16
6	Zhejiang University	China	28	1.58%	1,072	38.29	10
7	Egyptian Knowledge Bank (EKB)	Egypt	27	1.53%	530	19.63	14
8	Ministry of Agriculture & Rural Affairs	China	27	1.53%	1,334	49.41	13
9	Russian Academy of Sciences	Russia	25	1.41%	269	10.75	10
10	Nanjing Institute of Soil Science	China	23	1.30%	1,106	48.09	15

*IF, JCR-P data source: Journal Citation Reports ™ 2023. NOP, number of papers; PR, published ratio; CF, citation frequency; ACF, average citation frequency; HI, h-index

Table 5. Top 10 Countries by Publication Volume in the Field of Soil Heavy Metals Research under Extreme Environments

NO.	Country	NOP	PR (%)	CF	ACF	HI
1	China	497	28.11	14,807	29.79	62
2	America	211	11.93	8,423	39.92	47
3	Spain	130	7.35	4,077	31.36	37
4	India	104	5.88	4,630	44.52	36
5	Pakistan	93	5.26	2,285	24.57	25
6	Germany	88	4.98	3,901	44.33	30
7	Poland	87	4.92	1,418	16.3	20
8	Italy	85	4.81	2,397	28.2	25
9	Australia	79	4.47	3,059	38.72	30
10	France	74	4.19	2,516	34.00	28

Table 6. Keyword Clusters in the Field of Soil Heavy Metals Research under Extreme Environments

ClusterID	size	LLR	Keyword
#0	96	speciation	trace metals; sequential extraction; bioavailability; fractionation
#1	93	air pollution	roadside soils; risk assessment; pollution; particulate matter
#2	83	abiotic stress	antioxidants; oxidative stress; soil salinity; salinity
#3	81	heavy metals	lead; phytoremediation; EDTA; phytoextraction
#4	75	heavy metal	bioremediation; microbial community; diversity; PGPR
#5	71	stabilization	geopolymer; management; zeolite; organic matter
#6	44	serpentine	heavy metals; heavy metal(loid)s; extreme environment; competitive adsorption
#7	41	ph	soil properties; contaminated soils; bioremediation; aging;
#8	20	chromate reduction	contaminated soil; food safety; metal mobility; purple non-sulfur bacteria

Moharami *et al*. (2015) investigated the effects of simulated acid rain at different pH values on the distribution of heavy metals (Cd, Cu, Fe, Mn, Ni, Pb, Zn) and major elements (K, Na, Ca, Mg) in contaminated calcareous soils, discovering that acid rain altered the chemical forms of some metals and major elements, potentially affecting their mobility in soil. Zhang *et al*. (2023) explored microbially induced carbonate precipitation (MICP) as a sustainable, eco-friendly, and energy-efficient bioremediation method for stabilizing heavy metals in the environment. The study analyzed its mechanisms, implementation strategies, and technological challenges, offering prospects for future developments. In addition to conventional adsorptive materials and microbial regulation strategies, Moslemi *et al*. (2022) demonstrated that the incorporation of 1% natural lignocellulosic pulp (such as softwood pulp and wheat straw pulp) can significantly enhance the structural stability and shear strength of sandy soils, while effectively reducing pore water pressure. The improvement in soil physical stability suggests a potential for retaining heavy metals under rainfall or irrigation-driven conditions, thereby offering auxiliary value in ecological remediation.

Theme Two focuses on soil pollution assessment and management, centering on the evaluation of pollutants in the soil environment, risk analysis, and management strategies. Cluster#1 addresses the impact of air pollution on roadside soils and its risk assessment. Cluster#7 examines the influence of soil pH on the bioremediation of contaminated soils. Cluster#8 explores the role of chromate reduction in contaminated soils and its impact on food safety. The research of Guo *et al*. (2021) analyzed the seasonal variations, sources, and health risks of 24 metal elements in PM2.5 in a central city of Liaoning Province, China, in 2018, identifying major sources including coal combustion, industry, traffic emissions, and soil dust, and noting that chromium, arsenic, and cadmium pose potential carcinogenic risks to both adults and children. Hu *et al*. (2009) conducted field experiments to study the effects of soil acidification on the availability of copper (Cu) and lead (Pb) and their migration in the soil vertical profile, finding that simulated acid rain significantly reduced soil pH, increased the availability of Cu and Pb, with Cu tending to migrate deeper into the soil layers, whereas Pb was relatively immobile in the soil (Hu *et al*. 2009).

Theme Three focuses on environmental stress and plant responses, particularly examining how plants respond to salinity stress and related biochemical adaptation mechanisms. Cluster#2 deals with plants' antioxidant and physiological responses under salinity stress. Naheed *et al*. (2022) conducted experimental research on the combined effects of salinity and nickel (Ni) on the growth and physiological characteristics of quinoa (*Chenopodium quinoa* Willd.). The findings indicated that moderate salinity (150 mM NaCl) can improve quinoa's growth and physiological responses in nickel-contaminated soil, whereas higher salinity (300 mM NaCl) exacerbated the plant's oxidative stress, suggesting that quinoa has the potential for nickel phytostabilization under salinity stress.

Theme Four focuses on soil stabilization and remediation techniques, exploring the use of various materials and technologies to stabilize and improve contaminated soils. Cluster#5 investigates the application of geopolymers, zeolites, and other materials in soil stabilization. Peng *et al*. (2018) conducted a study using column leaching over 100 days to assess the reuse possibilities of heavy metal-contaminated sediments under simulated acid rain conditions using modified zeolites and biochar. The findings indicated that NaCl-modified zeolite performed better than biochar in stabilizing Cu, Cd, and Pb, thereby ensuring the environmentally safe reuse of sediments in land applications. However, Li *et al*. (2018) found that the aging of biochar in soil significantly reduces its retention capacity for acetochlor, leading to increased accumulation and bioavailability of the herbicide in maize plants. Pesticides initially adsorbed by biochar may be re-desorbed during the aging process, remaining in the soil over the long term and thereby increasing the risk of phytotoxicity to subsequent crops. Aging also promotes the enrichment of oxygen-containing functional groups on the biochar surface, elevates the O/C ratio, enhances its polarity, and lowers its pH, consequently altering its physicochemical properties and interactions within the soil–plant system. Wei *et al*. (2025) reported that the combined application of biochar and *Trichoderma viride* enhances soil nutrient retention capacity, where the large specific surface area of biochar plays a key role in nutrient adsorption and prolonged availability, thus facilitating sustained and efficient uptake by cucumber plants. However, excessive application was found to disrupt the balance of vegetative growth, thereby limiting nutrient accumulation and normal plant development.

These clusters encompass various aspects from heavy metal pollution and bioremediation to specific remediation techniques and soil management strategies. Each theme offers different research perspectives, facilitating a comprehensive understanding of soil heavy metal pollution issues and their solutions, and providing direction for further research.

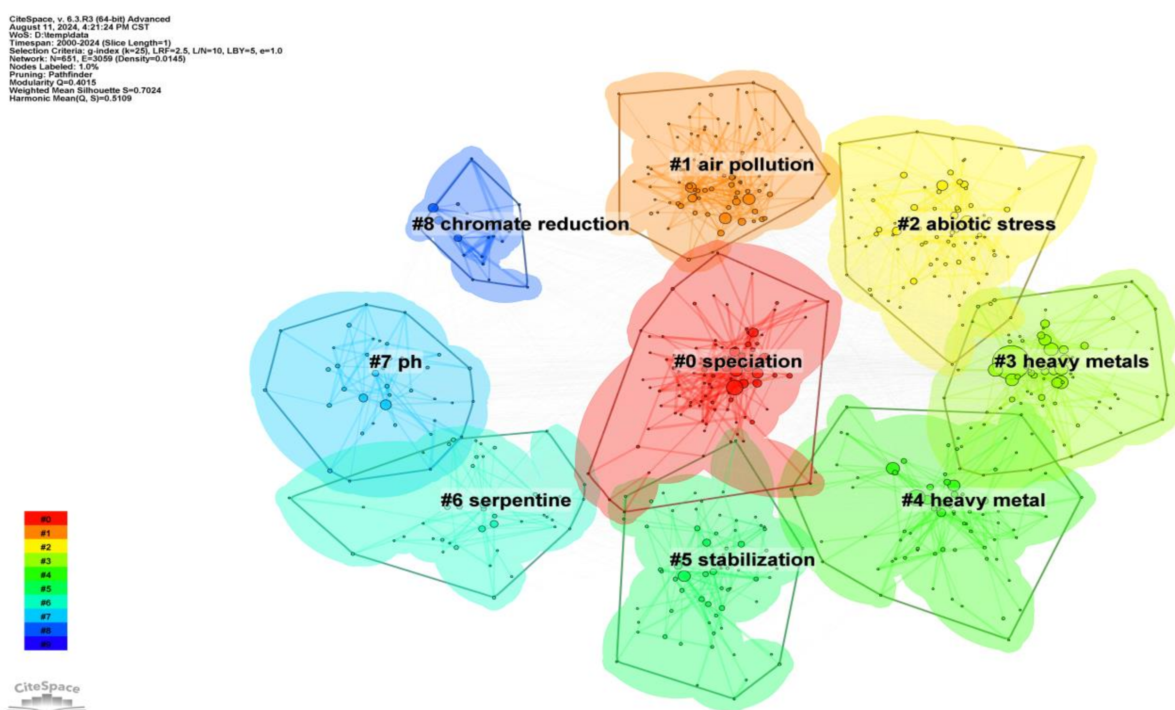

Fig. 2. Keyword clustering network map (WoS)

Research Hotspots and Frontier Analysis

Research hotspots analysis

To gain a more intuitive understanding of keyword trends within a specific timeframe, the Timezone View in CiteSpace was used for analysis. The WoS database (Fig. 3) saw many new keywords emerge from 2000-2004, with the number of new keywords gradually decreasing and then increasing over the years. Concurrently, based on the Keyword Timezone Map (Fig. 3), research hotspots can be roughly divided into two phases. The first phase (2000-2010) marks a period of rapid development and flourishing in the field of soil heavy metals under extreme environments, focusing on the formation and changing mechanisms of this field from the perspective of soil heavy metals. The most frequently occurring keywords during this phase include “heavy metals” (1104 occurrences), “soil” (241 occurrences), “accumulation” (203 occurrences), “cadmium” (167 occurrences), and “growth” (135 occurrences), along with terms such as “phytoextraction”, “climate change”, and “municipal solid waste”, which indicate the penetration of this research into other fields or disciplines. The second phase (2012-2021) represents a period of continued development in the field, focusing on deeper investigations into the impact mechanisms of soil heavy metals and specifically around issues such as the influence of soil heavy metals on food safety and the characteristics of heavy metal risk studies. Additionally, there was a shift towards using various materials and technologies for the stabilization and improvement of contaminated soils. The most frequently occurring keywords during this phase include “risk assessment” (60 occurrences), “spatial distribution” (31 occurrences), “water quality” (24 occurrences), “health risk” (24 occurrences), “source apportionment” (20 occurrences), and “surface sediments” (18 occurrences).

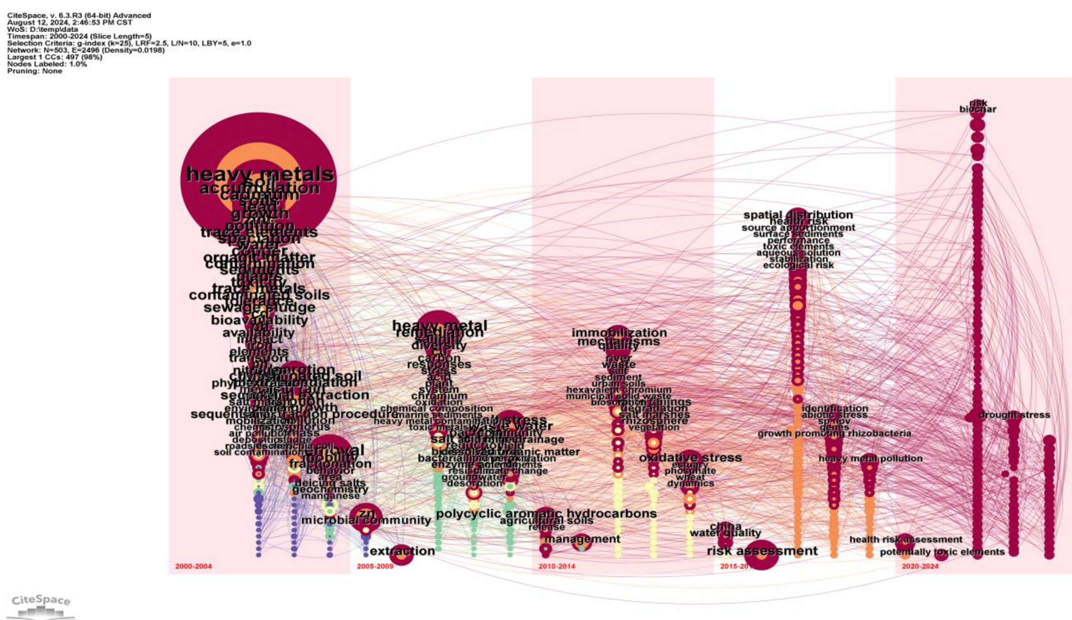

Fig. 3. Keyword Timezone Map (WoS). The map displays keywords that appear ≥15 times; larger fonts or circles indicate a higher frequency of keyword occurrences

Research frontier analysis

Keyword bursts reflect the development trends and frontiers of a research field (Jiang *et al*. 2021). As shown in Fig. 4, keywords such as “zinc”, “soils”, “sewage sludge”, and “trace metals” exhibit higher burst strengths compared to other keywords, indicating that these directions are key themes during this period. Keywords like “sequential extraction procedure”, “chemistry”, “speciation”, and “populations” have longer durations, primarily concentrated between 2000 and 2014, suggesting that they represent foundational research in this field, focusing on the ecological environment and metal extraction techniques related to the impact mechanisms of soil heavy metals.

According to the map (Fig. 4), the research can be divided into two phases. The first phase (2000-2014) primarily focused on soil heavy metals, indicating that research on soil heavy metals rapidly expanded globally during this period, receiving increased attention. This phase emphasized the chemical forms, extraction methods, and solubility studies of soil heavy metals, which are all fundamental areas of soil science. This stage was more about basic research, focusing on changes in chemical forms and the impact of environmental behavior.

The second phase (2015-2024) primarily revolves around studies on health risk assessments and responses to environmental stress, focusing more on how to address pollution issues in soil and water bodies during urbanization processes and further utilizing ecological remediation technologies for resolution. Advanced methods, such as remote sensing technology, have been introduced, reflecting stronger innovation in research approaches and perspectives, with a particular emphasis on effectively mitigating the risks posed by heavy metals and other pollutants in the environment through technological means. Additionally, this period has also concentrated on exploring biodiversity conservation and sustainable development strategies, particularly in the improvement of saline-alkali soils and contaminated lands, demonstrating a deep commitment to environmental sustainability. Keywords such as “drought stress”, “biochar”, “salt tolerance”, “responses”, and “plant growth” have shown high emergence intensity in recent years, representing the cutting-edge research in the field of soil heavy metals under extreme environmental conditions. These terms also likely indicate the future trends in this research area for the coming years.

Studies have shown that the combined application of humic acid and biochar exhibits strong metal complexation and adsorption capabilities in soil, while also significantly influencing the accumulation characteristics of metals within plants. For instance, Park *et al*. (2012) reported that in petroleum hydrocarbon and heavy metal co-contaminated soils, the addition of humic acid reduced the content of exchangeable heavy metals such as Pb, Cu, Cd, and Ni in the soil, yet it markedly increased their plant-available forms. Consequently, the bioconcentration factors of these metals in plant tissues rose substantially, with a maximum increase of up to 265%. These findings highlight the regulatory role of humic acid in the transformation of heavy metal speciation and underscore its potential as a green and sustainable remediation material under extreme environmental stress, such as the co-occurrence of organic and heavy metal pollution. Meanwhile, the application of weathered coal has been shown to significantly reduce the concentration of bioavailable lead in the surface layer of lead-contaminated soils under simulated acid rain leaching conditions (Liu *et al*. 2016). Under high salinity stress, the bioremediation of lead and petroleum co-contaminated soils using the herbaceous plant *Chromolaena odorata* inoculated with *Micrococcus luteus* demonstrated that salt stress notably affected lead uptake and accumulation, while having minimal impact on the degradation rate of total petroleum hydrocarbons. These findings suggest that the plant-microbe system holds potential for application in mildly saline-alkaline soils (Jampasri *et al*. 2020). Relevant studies have also shown that the application of α-tocopherol combined with thermal activation can significantly enhance the antioxidant defense and physiological activity of rapeseed in mercury-contaminated soils, particularly under low-level mercury stress, effectively promoting plant growth and seed germination. This provides a viable strategy for the bioremediation of heavy metal-contaminated soils (Amin *et al*. 2024). In addition, research on the ecological risks and spatial distribution of polycyclic aromatic hydrocarbons (PAHs) in soils has offered important insights for heavy metal pollution control, not only deepening the understanding of PAH behavior in contaminated soils but also suggesting potential pathways for the integrated management of soil heavy metal pollution (Li *et al*. 2019).

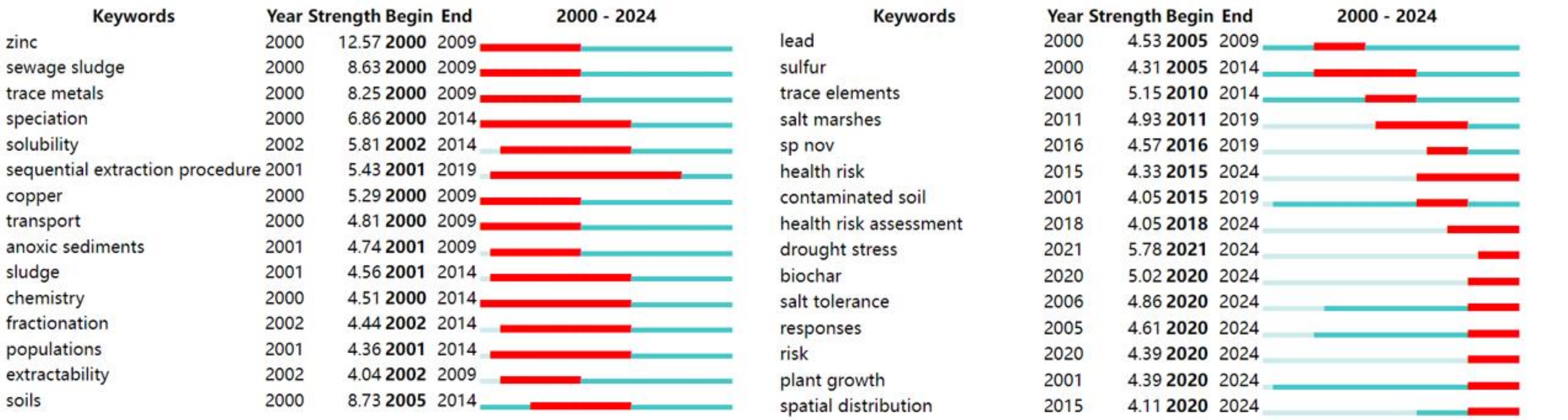

Fig. 4. Top 30 Keywords with High Burst Strength. The red areas represent the duration of the keyword bursts

Table 7. Top 10 Cited References from 2000 to 2024

NO.	Literature	Country	First author	Journal	Year	C-CF	HL
1	Trace metal behaviour in estuarine and riverine floodplain soils and sediments: A review	Belgium	Du Laing G	SCI TOTAL ENVIRON	2009	16	2.5
2	Phytoremediation of heavy metals concepts and applications	Pakistan	Ali H	CHEMOSPHERE	2013	14	3.5
3	Remediation techniques for heavy metal-contaminated soils: Principles and applicability	China	Liu LW	SCI TOTAL ENVIRON	2018	14	2.5
4	Leaching characteristics of heavy metals in tailings and their simultaneous immobilization with triethylenetetramine functioned montmorillonite (TETA-Mt) against simulated acid rain	China	Huang ZY	ENVIRON POLLUT	2020	14	2.5
5	Remediation of heavy metal(loid)s contaminated soils–to mobilize or to immobilize?	Australia	Bolan N	J HAZARD MATER	2014	13	3.5
6	How can we take advantage of halophyte properties to cope with heavy metal toxicity in salt-affected areas?	Belgium	Lutts S	ANN BOT-LONDON	2015	12	3.5
7	Lead Toxicity in Plants	Czech Republic	Küpper H	METAL IONS LIFE SCI	2017	12	0.5
8	Phytoremediation: Environmentally sustainable way for reclamation of heavy metal polluted soils	Pakistan	Ashraf S	ECOTOX ENVIRON SAFE	2019	12	2.5
9	Phytoremediation of heavy metal contaminated saline soils using halophytes: current progress and future perspectives	China	Liang LC	ENVIRON REV	2017	11	2.5
10	A review of soil heavy metal pollution from industrial and agricultural regions in China: Pollution and risk assessment	China	Yang QQ	SCI TOTAL ENVIRON	2018	11	3.5

*C-CF, the frequency of common citations of a certain document among the 1768 documents in the field of Soil Heavy Metals Research under extreme Environments; HL, half-life of literature.

In addition, source-tracking studies of regional soil heavy metal contamination-such as the identification of agricultural and urban wastewater inputs of Cr, Zn, Mn, and Co in the Gohar Rood River basin, and risk assessments of Pb and Cd accumulation in medicinal plants from mining areas-have provided essential data support for precise pollution risk identification and material-based remediation strategies (Ashayeri et al. 2023; Nawab et al. 2023). Although the construction of the Three Gorges Dam has reduced trace metal concentrations in surface waters, sediment in the water-level fluctuation zones-particularly that affected by anthropogenic activities-shows increased levels of Cd, Pb, and Zn. This suggests that while the dam contributes to long-term mitigation of trace metal pollution through sediment filtration and deposition, it also alters the pathways of metal accumulation in riverine systems (Bing et al. 2022). Collectively, these findings reflect a growing concern for the sustainable development of soil environments and highlight the necessity of rigorous heavy metal monitoring prior to the consumption of medicinal plants.
Highly co-cited literature analysis

The co-citation frequency and half-life of research literature can reflect to some extent the academic value of the literature and its contribution to the field. The half-life of a document is commonly used to indicate the degree of its obsolescence (Chen *et al*. 2020), with a longer half-life implying greater value of the literature (Li *et al*. 2016).

The half-life of literature was calculated by Eq. 4 (Burton *et al*. 1960),

$$y = 1 - (a\mathrm{e}^{-x} + b\mathrm{e}^{-2x}) \quad (4)$$
$$a + b = 1$$
$$T_{1/2} = 10\ln\left[a + \sqrt{(a^2 - 2a + 2)}\right]$$

where x represents time (in units of 10 years), y is the total citation rate after time x, and a and b are coefficients. $T_{1/2}$ represents the half-life of the document. This formula uses the B-K equation method for calculation.

As shown in Table 7, the top ten most co-cited documents originate from scholars or teams in Belgium, Pakistan, China, and Australia. Among these, one study explored the leaching characteristics of heavy metals in tailings through batch experiments and successfully synthesized triethylenetetramine functionalized montmorillonite (TETA-Mt). Compared to montmorillonite and TETA alone, TETA-Mt demonstrated high efficiency in stabilizing heavy metals, achieving fixation rates over 90% for Cu(II), Cd(II), Mn(II), and Zn(II), and over 75% for Pb(II). This makes it suitable for the effective stabilization of heavy metals in tailings and the efficient remediation of acidic mine wastewater in acid rain-affected areas (Huang *et al*. 2020). Therefore, remediation strategies should be integrated with pollution source control and include comprehensive evaluations of the long-term stability of the applied materials and their impact on the total heavy metal burden in soils (Sun *et al*. 2024).

Du (2009) highlighted the factors influencing the behavior of trace metals in soils and sediments, emphasizing the significant impact of topography, redox conditions, organic matter, salinity, pH, and plant growth on metal mobility and availability. Ali *et al.* (2013) discussed the accumulation of heavy metals in the environment due to human activities and the subsequent contamination of the food chain, as well as how phytoremediation, as a relatively economical, environmentally friendly, and publicly accepted technique, can be used to reduce the concentration or toxicity of pollutants in the environment. Liu *et al.* (2018) provided an overview of the global contamination of over 20 million hectares of land by heavy metals, exploring various soil remediation technologies including *in-situ* and *ex-situ* treatments. It was noted that *in-situ* remediation is generally more cost-effective than *ex-situ* treatments, and that the selection, cost, and duration of remediation technologies depend on the type, extent, and specific site conditions of contamination.

As illustrated in Fig. 5, the three aforementioned documents have high citation frequencies, with dense and thick connections around them, indicating that they play a pivotal role in the research field of soil heavy metals under extreme environments. The analysis of the half-lives of these documents reveals that they range between 0.5 and 3.5 years, indicating a rapid pace of literature renewal in the field of heavy metal pollution and remediation. The average half-life of articles in academic journals is relatively short, at approximately 2.85±1.25 years. This demonstrates the swift development of the research field, frequent updates of literature, and reflects the high level of attention researchers place on the latest methods and discoveries.

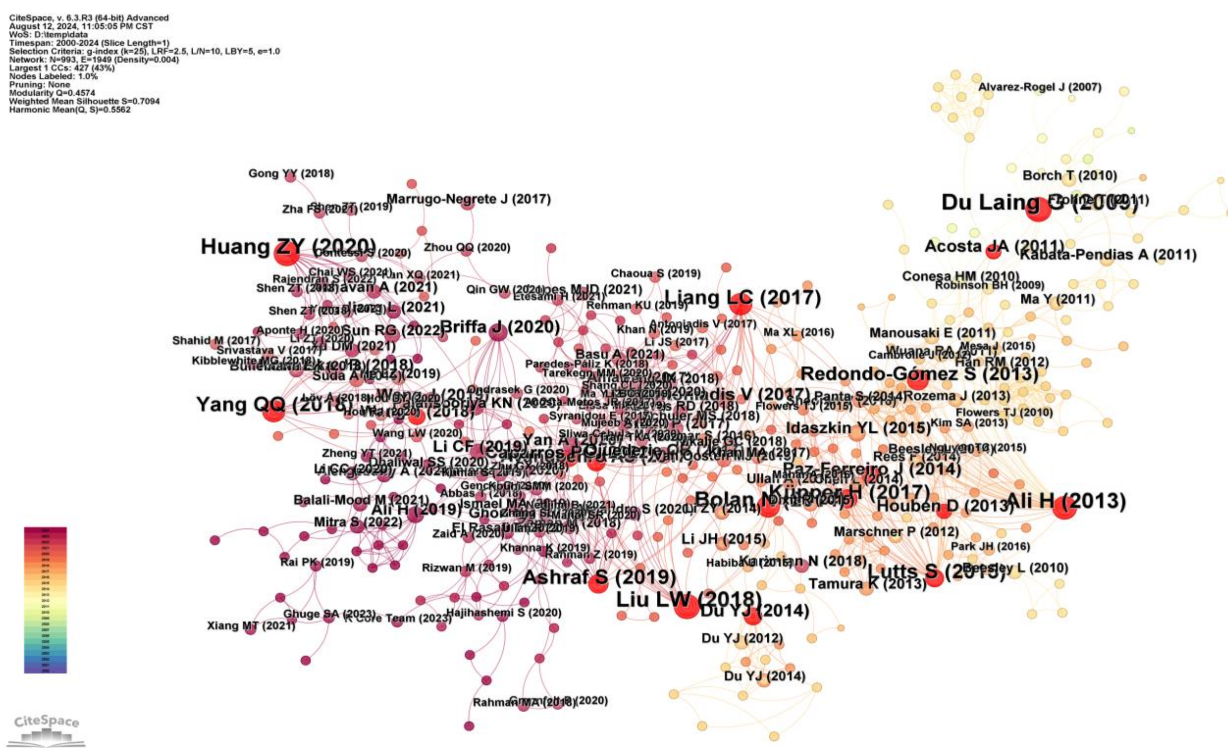

Fig. 5. Co-citation Network Map. Larger nodes or fonts indicate a higher frequency of co-citations among the 1,768 documents

Perspectives

This study has constructed a structured framework based on qualitative analysis, which not only provides theoretical support and clear direction for current scientific discussions on soil heavy metals under extreme environments but also identifies key focal points and future research prospects. The study emphasizes the integration of environmental monitoring with model development by employing advanced technologies such as machine learning, remote sensing, and geographic information systems (GIS) to achieve real-time monitoring and precise prediction of soil heavy metal migration and accumulation under extreme conditions. Simultaneously, it proposes combining environmental remediation with biotechnological applications by leveraging phytoremediation and microbial remediation techniques and developing transgenic plants and microbes through genetic engineering and molecular biology to enhance remediation efficiency under extreme conditions. Moreover, given the global impact of soil heavy metal pollution, the study calls for enhanced international cooperation, the sharing of research findings and technological solutions, and the formulation of scientifically based environmental policies and environmental risk assessments. Through the collaborative efforts of soil environmental worldwide, the goal is to reveal the mechanisms of formation and control of heavy metals and to reinforce the integral role of soil within the entire ecosystem.

CONCLUSIONS

1. This study conducted an in-depth analysis of 1,768 documents on soil heavy metals under extreme environments from 2000 to 2024 using scientific analysis and bibliometric methods. By synthesizing the evolution of the literature over the past 24 years, the research reveals dynamic trends, response mechanisms, and potential future directions, thereby providing new scientific evidence and perspectives for addressing this global issue.
2. In the field of soil heavy metals research, countries including China, the United States, and India play pivotal roles in advancing global scientific efforts. They not only contribute significantly to the literature but have also established robust academic collaborations. Notably, leading institutions in China, such as the Chinese Academy of Sciences, are at the forefront of high-quality research. Influential journals including *Environmental Science and Pollution Research*, *Science of The Total Environment*, and *Chemosphere* continue to push the boundaries of environmental science and pollution research, underscoring the central role of these nations in addressing global soil heavy metal pollution.
3. The integration of environmental science with molecular biology has spurred the precise development of bioremediation strategies and fostered broader scientific communication and technological innovation. Over the past 24 years, research has trended towards multidisciplinary integration-combining environmental science, environmental engineering, and soil science-which enriches both the content and methodologies of the studies. This comprehensive approach provides innovative solutions and a more holistic perspective for tackling complex environmental challenges.
4. Current research focuses on how plants and microorganisms absorb and transform heavy metals, elucidating their bioavailability and bioaccumulation mechanisms. Advanced strategies – such as gene-editing technologies and functional microbial consortia – are increasingly employed to enhance phytoremediation efficiency. In parallel, lignocellulose-derived soil amendments, particularly humic acid and biochar, have attracted growing attention for their ability to modulate metal speciation, reduce leaching risk, and stimulate rhizospheric microbial activity under stress conditions. Their multifunctional roles in stabilizing soils and enhancing remediation efficacy reflect a broader paradigm shift from isolated remediation techniques to integrated, sustainable, and adaptive soil engineering frameworks.

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