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ARTICLE

PHYTOREMEDIATION OF HEAVY METAL POLLUTION IN SOIL: A BIBLIOMETRIC ANALYSIS

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ABSTRACT

Soil heavy metal pollution poses a significant threat to global ecological integrity and human health. Phytoremediation has emerged as a research focal point due to its eco-friendly nature and advantages in in-situ remediation. Based on the Web of Science Core Collection, this study retrieved 1,536 English-language articles published between 2010 and 2020 and performed a bibliometric analysis using CiteSpace and Excel. The analysis elucidates the current status and evolutionary trends in the field by examining publication volume, collaborative networks (authors, institutions, and countries), keyword dynamics (co-occurrence, clustering, and bursts), and highly cited literature. The results indicate that: (1) The annual number of publications has exhibited a consistent upward trend over the past 11 years. (2) China holds a dominant position in this field, with a robust institutional cooperation network centered around the Chinese Academy of Sciences, the University of Science and Technology of China, and Northwest A&F University. While author collaborations remain relatively decentralized, localized cohesive networks have formed, notably those led by Lebrun and Khalid. (3) Research frontiers are dynamically evolving, with a primary focus on remediation mechanisms, technological innovation, and efficacy evaluation. The research is increasingly advancing toward systematization, multifunctionality, and sustainability. (4) Highly cited publications consist predominantly of comprehensive reviews that systematically synthesize the conceptual frameworks and mechanisms of action in phytoremediation.

KEYWORDS

Soil, heavy metal, phytoremediation, bibliometrics

1. INTRODUCTION

Heavy metal pollution represents a critical global environmental challenge. These contaminants are released into the biosphere primarily through ore extraction and subsequent industrial processing [1]. Driven by accelerating industrialization and the disruption of natural biogeochemical cycles, heavy metal pollution has intensified significantly. Unlike organic pollutants, heavy metals are non-biodegradable, leading to their persistent accumulation in environmental matrices [2,3]. Their presence in soil and water systems poses severe risks to both ecological integrity and human health. Through bioaccumulation and biomagnification, these elements increase in concentration across trophic levels, ultimately threatening apex predators and humans [4]. In soil ecosystems, heavy metals exert toxicological pressures on microbial communities, often reducing their abundance, diversity, and metabolic activity [5,6]. For China—a nation supporting 22% of the global population with only 7% of the world's arable land—the remediation of heavy metal-contaminated soils is a matter of urgent national and food security importance.

Phytoremediation has emerged as a sustainable and promising solution. In contrast to conventional physical and chemical methods, this "green" technology offers an eco-friendly, in-situ approach characterized by minimal soil disturbance and a lower risk of secondary pollution. Its high cost-effectiveness for large-scale applications has garnered significant global research interest. Mechanistically, phytoremediation leverages plant–microbe interactions within the rhizosphere to sequester, degrade, or stabilize heavy metals, providing a resilient strategy for diverse contaminated environments [7-11].

Bibliometrics, a branch of information science, utilizes mathematical and statistical tools to quantify, evaluate, and forecast the evolution of specific scientific fields [12]. A prominent tool in this domain is CiteSpace, developed by Professor Chaomei Chen. Grounded in Kuhn's theory of "scientific revolutions" and document co-citation analysis, CiteSpace facilitates deep data mining and the construction of knowledge maps [13]. By interpreting these visualizations, researchers can identify current research hotspots and emerging frontiers. In this study, we employed CiteSpace to perform a comprehensive bibliometric analysis of phytoremediation literature from the Web of Science (WoS) database (2010–2020). By examining publication outputs, institutional networks, author collaborations, and keyword dynamics, this paper delineated the global and domestic research landscape, aiming to provide a roadmap for future developments in soil phytoremediation.

2. RESEARCH METHODS

2.1 Data sources

The literature for this study was retrieved from the WoS Core Collection database. The search query was formulated as: TS=(Phytoremediation) AND (heavy metal*) AND (soil pollution*), where the asterisk (*) serves as a wildcard to include all term variations. The timespan was set from 2010 to 2020, yielding a total of 1,536 valid documents. These records were then exported in plain text file format for subsequent analysis.

2.2 Analysis methods

Bibliometric analysis was conducted on the 1,536 retrieved English documents using the analytical tools inherent in the WoS database and CiteSpace (Version 6.1.6R1). The analysis encompassed publication trends, geographical distribution, institutional affiliations, author collaborations, keyword dynamics, and co-citation networks. By delineating the current research landscape and academic hotspots in the phytoremediation of heavy metal-contaminated soils, this study aims to address the existing gap in bibliometric reviews and provide a theoretical foundation for future research in this domain.

3. RESULTS AND DISCUSSION

3.1 Analysis of publication volume and temporal trends

Figure 1 illustrates the annual publication trends regarding the phytoremediation of heavy metal-contaminated soils from 2010 to 2020. This trajectory reflects the correlation between research output and time, as well as the field's evolving theoretical maturity and developmental pace, providing insights into its overall research progress [14,15]. As depicted in Figure 1, the annual volume of publications has exhibited a consistent upward trend over the past 10 years, with a pronounced surge following 2018, peaking at 151 articles in 2020. This growth can be largely attributed to the global implementation of stringent soil environmental protection policies, which mandate the rigorous monitoring, assessment, and remediation of contaminated sites. For instance, China's "Action Plan for Soil Pollution Prevention and Control" (the "Soil Ten Articles"), promulgated in 2016, established clear objectives and provided robust policy and financial frameworks that catalyzed phytoremediation research [16]. Concurrently, the integration of emerging technologies, such as transgenic breeding, nanomaterials, biochar, and high-throughput sequencing, has equipped researchers with high-precision tools, further accelerating research productivity [17-19]. In summary, the phytoremediation of heavy metal-contaminated soil has garnered intensified global attention.

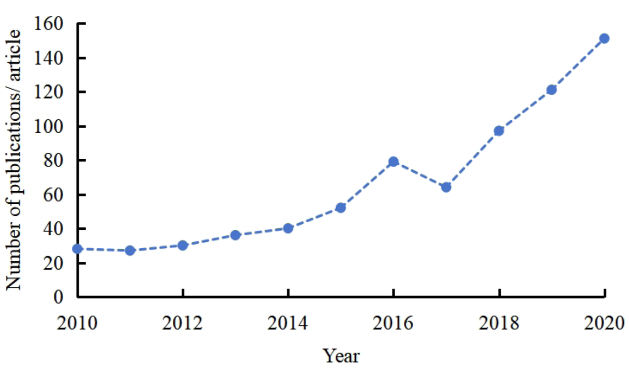

Figure 1. Number of English literature publications from 2010 to 2020

3.2 Analysis of scientific cooperation in phytoremediation of heavy metal- contaminated soil

3.2.1 Analysis of publishing authors

Core authors are defined as prominent scholars with a substantial number of publications and high citation rates within a specific discipline. Analyzing these key contributors is essential for grasping the developmental dynamics and emerging trends of a research field. According to Price's Law, the minimum threshold for the number of publications required to identify a core author is calculated as follows:

$$M\ P = 0.749\sqrt{N_{\max}} \tag{1}$$

In this formula, N_{max} denotes the maximum number of publications by a single author within the field, while *MP* represents the minimum publication threshold for core authorship, typically rounded to the nearest integer. According to Price's Law, a research field is considered to have established a stable and influential core author group when its collective output accounts for more than 50% of the total publications in that field. Based on the CiteSpace analysis, the most prolific author in the field of soil heavy metal phytoremediation is Jie Luo, with 10 publications. Substituting this value into the formula yielded an *MP* of approximately 2.36. Consequently, scholars with three or more publications were identified as core authors in this study.

Statistical analysis via CiteSpace reveals that core authors contributed 193 publications, accounting for approximately 12.57% of the total dataset. Figure 1 remains significantly below the 50% threshold established by Price's Law, suggesting that research in this field is fragmented across a broad range of authors rather than being concentrated within a highly influential core group [20].

To further explore these interpersonal dynamics, an author collaboration network map was generated (Figure 2). The map illustrates a decentralized and sparse collaborative structure. Most researchers operate independently or in isolated small clusters, with a noticeable lack of large-scale, cross-institutional cooperation. This fragmentation may be attributed to the diverse research orientations among scholars, which hinders the formation of integrated collaborative networks. Regarding small-scale clusters, the research groups led by Lebrun and Khalid exhibit relatively high connectivity. Lebrun's team focuses on mining soil remediation using various amendments. Their investigations into the immobilization effects of biochar, activated carbon, and red mud demonstrated that while amendments significantly alter soil physicochemical properties and metal stabilization, certain additives may inadvertently promote As mobility [17]. Furthermore, they reported that the co-application of biochar and compost markedly enhances Pb immobilization and inhibits its translocation in plants, providing a robust strategy for phytoremediation management [18]. Conversely, Khalid's research centers on the accumulation capacity and potential evaluation of plants for heavy metal mitigation. For instance, this group investigated Cd uptake by *Parthenium hysterophorus* and *Ricinus communis* with and without ethylenediaminetetraacetic acid (EDTA) supplementation [21,22], offering significant insights into chelator-assisted phytoremediation.

3.2.2 Analysis of publishing institutions

CiteSpace facilitates the quantification of institutional collaboration through metrics such as linkages, betweenness centrality, and network density [12]. These indicators evaluate an institution's engagement in a specific field and provide strategic insights for future partnerships. This study analyzed institutional publication outputs and summarized the top 10 most productive institutions in the field of soil heavy metal phytoremediation (Table 1).

As shown in Table 1, universities and research institutes constitute the majority of the leading institutions. The Chinese Academy of Sciences (CAS) leads with the highest output (109 publications), followed by the University of Science and Technology of China (35). Northwest A&F University, King Saud University, and Zhejiang University also emerged as major contributors. Notably, the betweenness centrality of CAS reached 0.21, exceeding the critical threshold of 0.10, which identifies it as a pivotal "bridge" node in the knowledge network. This suggested

Figure 2. Map of co-occurrence of publication authors

Table 1. Publication statistics of the top 10 institutions

Institution	Frequency	Betweenness centrality
Chinese Academy of Sciences	109	0.21
University of Science and Technology of China	35	0.04
Northwest A&F University	27	0.04
King Saud University	26	0.04
Zhejiang University	23	0.02
Hunan Agricultural University	22	0.02
Chinese Academy of Forestry	14	0.02
Government College University	14	0.02
Taif University	11	0.02
China University of Geosciences (Beijing)	11	0.02

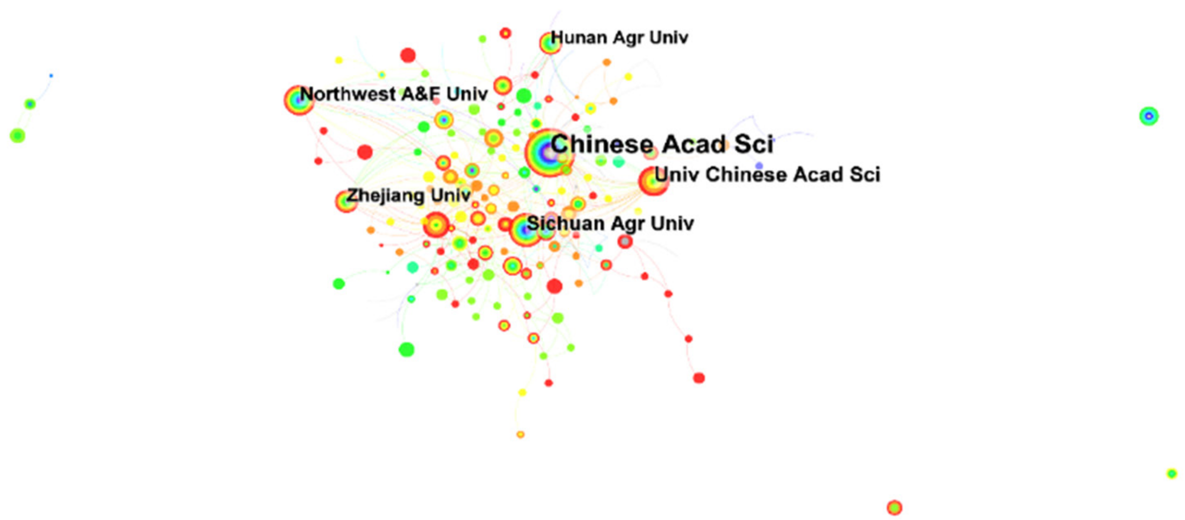

Figure 3. Institutional cooperation network map

that an institutional cooperation framework is gradually coalescing, dominated by CAS, University of Science and Technology of China (USTC), and Northwest A&F University (NWAFU).

Furthermore, the institutional collaboration map (Figure 3) was analyzed. The concentric rings of each node represent the temporal distribution of publications; more rings indicate an earlier involvement in the field. While the number of nodes (443) reflects widespread global interest, the relatively low number of linkages (563) and a sparse network density (0.0036) indicated that deep cross-institutional communication remains insufficient. These results suggested that although numerous institutions are active in phytoremediation research, a robust and well-integrated cooperative network has yet to be fully established.

3.2.3 Analysis of publishing countries

A country collaboration map facilitates the exploration of cross-border academic partnerships, providing insights into the global dynamics and collaborative trends within a specific field. Table 2 summarizes the publication outputs of the top 10 most productive countries.

As indicated, China leads the field with 686 publications, representing 44.66% of the total dataset. This significant share underscores China's intense research focus and substantial scholarly contributions to the phytoremediation of heavy metal-contaminated soils. India and Pakistan rank second and third, with 119 and 89 publications, respectively, highlighting their pivotal roles in this domain. Furthermore, the majority of the top 10 countries possess advanced industrial and technological infrastructures, suggesting that research progress in this area is primarily driven by both scientific capacity and socioeconomic demand [12].

Furthermore, the international collaboration network for soil heavy metal phytoremediation was mapped and analyzed using CiteSpace (Figure 4). The network demonstrates relatively extensive international cooperation, with China exhibiting the highest betweenness centrality (0.41). This identifies China as a pivotal bridge and a core node for global information exchange in this field [23]. This central role is primarily driven by the long-standing challenges of soil heavy metal pollution within China, which has garnered sustained academic attention [16]. Moreover, China's diverse ecological conditions and abundant phytogenetic resources provide a robust foundation for large-scale research. Other nations with betweenness centrality values exceeding the 0.10 threshold include Spain, Saudi Arabia, Italy, the United States, and Egypt. These countries are geographically dispersed across multiple continents, establishing a solid framework for global collaborative efforts.

3.3 Keyword co-occurrence analysis

Keywords serve as succinct distillations of research themes and effectively mirror the hotspots and evolutionary trends within a specific academic field. By quantifying keyword frequencies, CiteSpace provides a robust analytical dimension for identifying core research focuses. To explore the thematic landscape of soil heavy metal phytoremediation,

Table 2. Publication statistics of the top 10 countries

Country	Frequency	Betweenness centrality
China	686	0.41
India	119	0.08
Pakistan	89	0.04
Spain	78	0.23
Saudi Arabia	73	0.28
Iran	72	0.02
Italy	70	0.15
United States	67	0.17
China	62	0.02
India	51	0.10

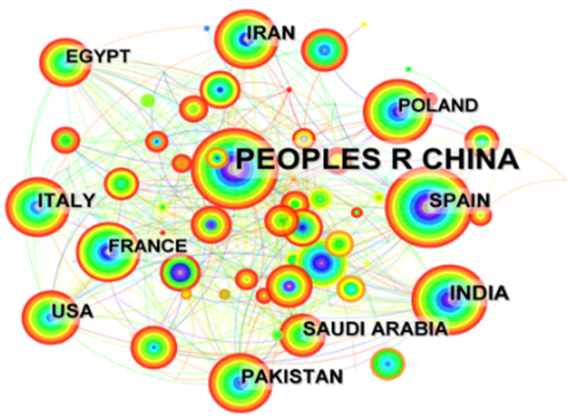

Figure 4. National cooperation co-occurrence map

this study utilized the "Keyword" function in CiteSpace to construct a co-occurrence network based on the WoS Core Collection database (2010-2020, Figure 5). In this visualization, each node represents a keyword, with its size proportional to its occurrence frequency [17].

The network comprises 619 nodes and 4,992 linkages, with a network density of 0.0261. This suggests that while research topics are diverse and highly interconnected, they lack a high degree of thematic centralization. Dominant nodes such as "trace element", "contamination", "bioremediation", "mine tailing", "phytoextraction", and "rhizosphere" constitute the primary research subjects in this domain.

To further evaluate the structural significance of these terms, Table 3 summarizes the frequency and betweenness centrality of major keywords. The most frequent keyword is "accumulation" (521 occurrences), followed by "plant" (369), "soil" (359), and "cadmium" (357). Notably, the betweenness centrality for all major keywords remained below the 0.10 threshold, indicating that although multiple hotspots attract scholarly attention, a singular, dominant core node has yet to be established.

Table 3. High-frequency keywords

Keyword	Frequency	Betweenness centrality
Accumulation	521	0.01
Plant	369	0.02
Soil	359	0.04
Cadmium	357	0.03
Contaminated soil	265	0.03
Growth	247	0.06
Pollution	230	0.02
Phytoextraction	195	0.04
Tolerance	182	0.06
Toxicity	160	0.05

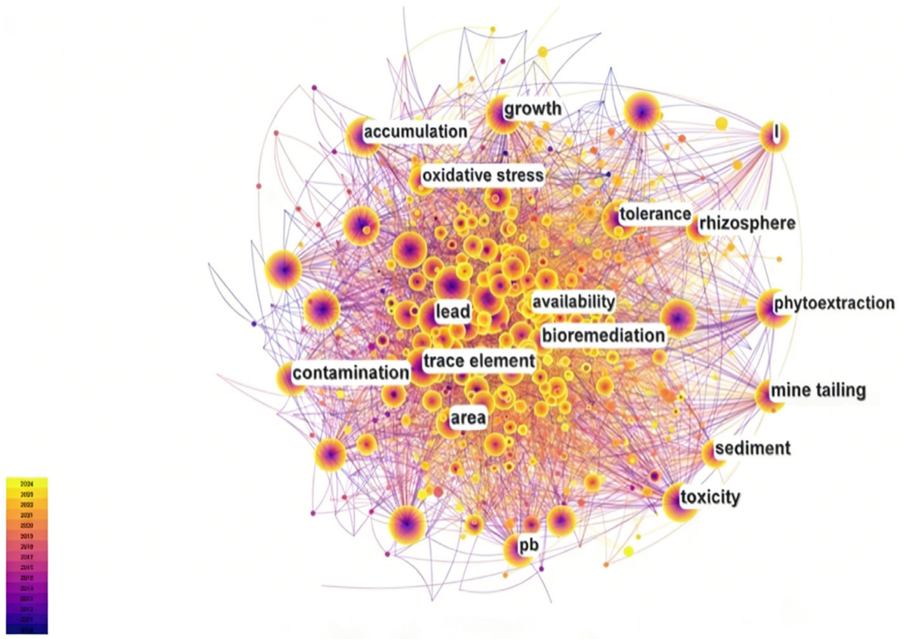

Figure 5. Keyword co-occurrence map

3.4 Keyword cluster analysis

Building upon the keyword co-occurrence network, a cluster analysis was conducted using CiteSpace, with each cluster named after its most frequent keyword. This method effectively identifies the core research themes within the field of soil heavy metal phytoremediation. The resulting cluster map is presented in Figure 6, where the prefix "#" denotes the cluster ID and distinct color blocks represent individual clusters. The network parameters are as follows: nodes = 619, edges = 4,992, and density = 0.0261. To evaluate the clustering quality, CiteSpace employs two metrics: modularity (Q) and mean silhouette (S). A higher Q value indicates a well-defined community structure, while a larger S value reflects higher homogeneity within clusters and greater reliability of the results [24]. As shown in Figure 6, the modularity Q = 0.3279 (> 0.3) confirms a significant clustering structure, and the mean silhouette S = 0.6172 (> 0.5) demonstrates that the clustering results are highly credible and reasonable.

Between 2010 and 2024, seven major clusters were identified within the network. Ordered by size, these include: #0 *Phragmites australis*,

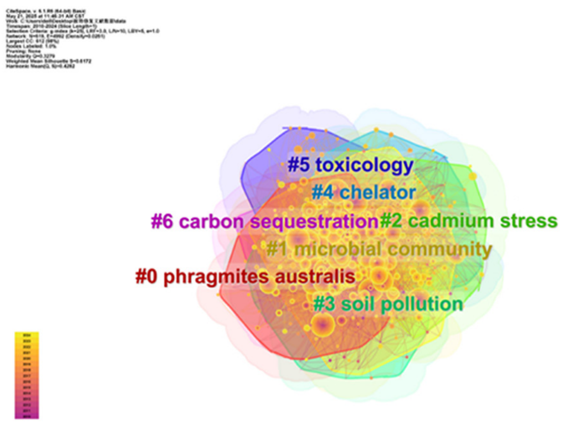

Figure 6. Keyword cluster network map

#1 microbial community, #2 cadmium stress, #3 soil pollution, #4 chelator, #5 toxicology, and #6 carbon sequestration. Cluster #0 is the largest, representing the most prevalent research theme. Clusters #0, #1, and #4-focusing on *Phragmites australis*, microbial communities, and chelators, respectively-delineate the core mechanisms of soil heavy metal phytoremediation. As a well-known pollution-tolerant species, *Phragmites australis* is extensively utilized in wetland restoration, particularly for mitigating heavy metal contamination in hydromorphic soils and aquatic environments [25,26]. It exhibits a robust capacity for the uptake, immobilization, and translocation of metals such as Cd, Pb, and Zn [26]. For instance, Castaldi et al. [27] demonstrated that while *Phragmites australis* experienced slight nutrient imbalances when exposed to varying As (V) concentrations (0.5-10 mg/L) in hydroponic systems, it maintained high root accumulation without symptomatic toxicity. Given that arsenic was primarily sequestered in the roots with minimal shoot translocation, *Phragmites australis* serves as an ideal candidate for rhizofiltration and phytostabilization.

Microbial communities act as critical synergists in phytoremediation, enhancing efficiency by bolstering plant tolerance and altering metal speciation [28,29]. Key functional taxa, including Proteobacteria, Actinobacteria, and Firmicutes, have been identified as pivotal for pollutant removal due to their dual resistance to heavy metals and antibiotics [29]. Furthermore, chelating agents (e.g., EDTA, citric acid) are employed to enhance metal bioavailability, thereby facilitating plant uptake [30]. Wang et al. [31] observed that multi-chelator combinations outperformed individual applications in mobilizing Cd and promoting its translocation within plant tissues. However, the use of chelators carries the risk of metal leaching into deeper soil profiles or groundwater if plant uptake is not immediate [32]. To address this, Luo et al. [33] found that electric field-assisted phytoremediation could double the efficiency compared to chelator application alone. Notably, the emergence of cluster #6 indicates an interdisciplinary alignment with global climate change mitigation, exploring the dual benefits of pollution remediation and ecosystem carbon sink functions. Collectively, research in this field is progressively advancing toward systematization, multifunctionality, and sustainability.

3.5 Keyword burst analysis

Keyword bursts refer to terms that experience a rapid increase in frequency over a short duration, reflecting the evolution of research hotspots and frontiers at specific stages [9]. In this study, burst detection was performed using CiteSpace, with the top 20 keywords by burst strength visualized in Figure 7. “Strength” denotes the magnitude of the burst, “Begin” and “End” demarcate its temporal boundaries, and

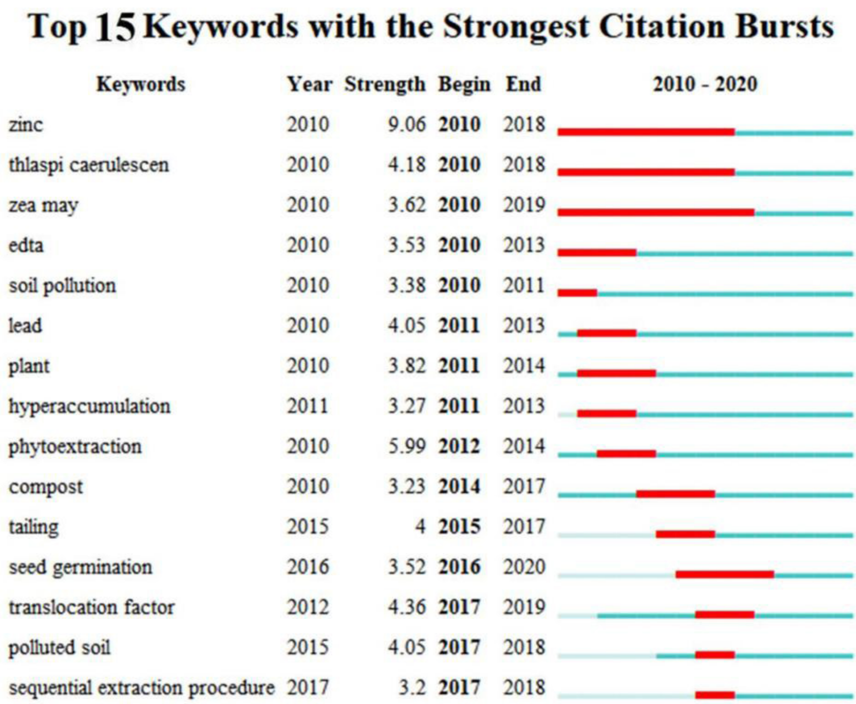

Figure 7. Keyword burst map of phytoremediation of heavy metal-contaminated soil (2010-2020)

the red segments highlight the specific burst duration. As illustrated, keywords with significant burst strength include “zinc” (9.06, 2010–2018), “phytoextraction” (5.99, 2012–2014), “Sedum alfredii” (4.36, 2017–2019), “translocation factor” (4.36, 2017–2019), and “Thlaspi caerulescens” (4.18, 2010–2018). Early research primarily addressed fundamental issues such as heavy metal elements, soil contamination, and model species like *Zea mays* and *Thlaspi caerulescens*.

Subsequently, the emergence of burst keywords such as “compost” and “tailing” signaled the diversification of remediation strategies. For instance, Ogundiran et al. [34] found that *Moringa oleifera* can tolerate Pb concentrations up to 8,600 mg/kg; notably, its combination with compost or rice husk biochar enhanced phytoextraction, while peanut shell biochar improved phytostabilization. Similarly, Roccotiello et al. [35] evaluated dual strategies at an open-pit nickel mine: phytostabilization for alkaline tailings using organic amendments (e.g., vermicompost and biochar) and EDTA-assisted phytoextraction for neutral mining soils. Their results identified vermicompost as the most effective amendment for promoting Lolium perenne growth and reducing Ni availability. The efficacy of such strategies is typically quantified via the bioconcentration factor and translocation factor (TF) [36-38]. A TF > 1 is a hallmark of hyperaccumulators, serving as a critical criterion for selecting species for phytoremediation [39,40].

In recent years, the burst of the keyword “seed germination” (3.52, 2016–2020) indicates a shift toward the precise characterization and efficacy evaluation of remediation plants. By integrating microbial taxonomic identification and functional activity analysis, researchers can optimize remediation protocols [41]. For example, Xu et al. [42] reported that D-gluconate-enhanced colonization of *Enterobacter cloacae* Y16 (a siderophore-producing rhizobacterium) significantly improves Cd phytoextraction in *Solanum nigrum* by mobilizing soil cadmium and optimizing the functional structure of the rhizospheric microbial community.

3.6 Analysis of highly cited literature

Cumulative citation frequency serves as a pivotal metric for evaluating the quality and scholarly impact of research. Articles characterized by both high journal impact factors and significant citation counts are regarded as seminal works that exert a profound influence on the field’s evolution [23]. In this study, the “Reference” module in CiteSpace was employed to conduct a co-citation analysis of the literature related to soil heavy metal phytoremediation retrieved from the WoS Core Collection (2010–2020, Figure 8). The resulting network consists of 845 nodes and 3,293 linkages, with a density of 0.0092. While high citation rates highlight landmark achievements, nodes with elevated centrality typically function as critical hubs bridging diverse research themes [12,24]. The top 5 most frequently cited documents are summarized in Table 4.

Notably, all five top-cited documents are comprehensive reviews that delineate the background, technical merits, remediation mechanisms, and emerging trends of phytoremediation. Ali et al. [5] elucidated

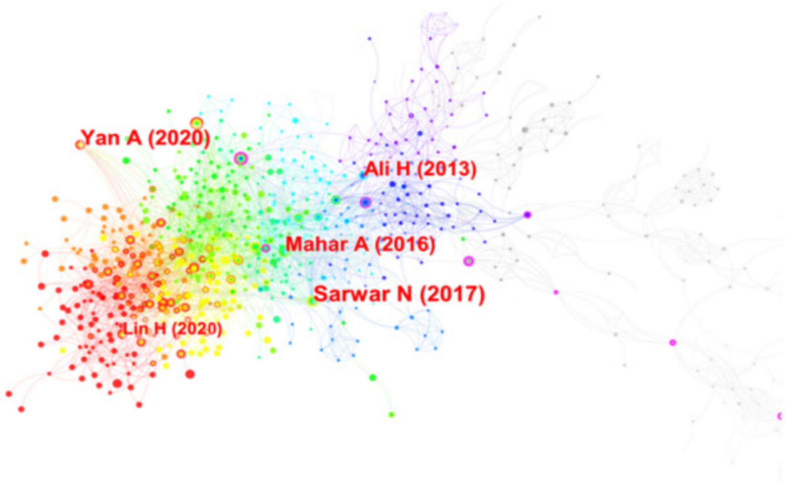

Figure 8. Highly cited literature map of phytoremediation of heavy metal- contaminated soil

Table 4. Top highly cited papers on phytoremediation of heavy metal- contaminated soil (2010–2020)

Citations	Year	First author	Title	Centrality
82	2017	Sarwar N	Phytoremediation strategies for soils contaminated with heavy metals: Modifications and future perspectives	0.09
66	2020	Yang A	Phytoremediation: a promising approach for revegetation of heavy metal-polluted land	0.02
63	2016	Mahar A	Challenges and opportunities in the phytoremediation of heavy metals contaminated soils: A review	0.07
56	2019	Ashraf S	Phytoremediation: Environmentally sustainable way for reclamation of heavy metal polluted soils	0.02
53	2013	Ali H	Phytoremediation of heavy metals—Concepts and applications	0.10

how anthropogenic activities drive heavy metal accumulation in the environment and food chains, posing severe risks to human health, particularly in vulnerable populations such as children. They emphasized the limitations of conventional physicochemical methods, such as exorbitant costs and soil degradation, positioning phytoremediation as a sustainable, cost-effective alternative that leverages plant-microbe synergies. Similarly, Ashraf et al. [10] addressed the environmental challenges posed by global industrialization, systematically reviewing the sources and hazards of toxic metals. They concluded that phytoremediation techniques, such as phytostabilization and phytoextraction, are essential for restoring contaminated lands for agricultural use. Yan et al. [43] synthesized the mechanisms underlying metal uptake, translocation, and detoxification, focusing on enhancing remediation efficiency through genetic engineering, microbial inoculation, and chelator assistance. Despite their high citations, these five articles exhibit centrality values ≤ 0.10, indicating a shared thematic focus: highlighting the severity of heavy metal pollution, promoting green solutions, and identifying technical bottlenecks [43,44]. Collectively, these works provide a foundational roadmap for technological innovation and policy formulation.

4. CONCLUSIONS

This study performed a comprehensive visual analysis of the literature related to soil heavy metal phytoremediation from the WoS Core Collection (2010-2020). The main conclusions are as follows:

(1) The annual volume of publications in this field exhibited a consistent upward trajectory, with a pronounced surge following 2018 and a peak in 2020. This trend underscores the intensifying global focus on phytoremediation technologies.

(2) While Jie Luo emerged as the most prolific author, the overall author collaboration remains fragmented, with no established core research cluster. Universities and research institutes constitute the primary contributors, led by the CAS. However, robust inter-institutional partnerships have yet to be fully realized. China leads in total publication output and serves as a pivotal bridge for international scholarly exchange.

(3) Keyword evolution indicates a shift toward a deeper understanding of remediation mechanisms, technological innovation, and efficacy evaluation. Research is progressively advancing toward systematization, multifunctionality, and sustainability, reflecting increasing academic depth.

(4) Seminal works in this field are predominantly comprehensive reviews rather than empirical studies. These reviews collectively define the field's thematic priorities and developmental trajectories.

Overall, research on soil heavy metal phytoremediation has evolved into a comprehensive and multi-dimensional discipline. While foundational research continues to be consolidated, cutting-edge explorations are expanding in scope. Driven by technological advancements and the increasing precision of analytical instrumentation, this field is poised for rapid development and systematic innovation in the coming years.

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