

ORIGINAL RESEARCH ARTICLE

Bamboo-based remediation of heavy metal-contaminated soils: A bibliometric visualization analysis

Qiao Wu¹, Saihong Ru², Xiaoyu Zheng², Ming Zeng², Maoqing Fan², and Chengyou Sun^{3*}¹Department of Pharmacy, Changsha Health Vocational College, Changsha, Hunan, China²Hunan Changsha Ecological Environment Monitoring Center, Changsha, Hunan, China³Key Laboratory of National Forestry and Grassland Administration on Bamboo & Rattan, International Centre for Bamboo and Rattan, Beijing, China

Abstract

Bamboo and its rhizosphere microorganisms have attracted increasing research attention as an effective strategy for remediating heavy metal-contaminated soils. To map the development trajectory of this field and identify emerging priorities, this study used CiteSpace software to conduct a bibliometric visualization analysis of 210 relevant articles included in the Web of Science Core Collection from 2006 to 2025. The analysis covered annual publication trends, national and institutional collaboration networks, journal distribution, keyword co-occurrence, and cluster analysis. The results show that the development of this field can be divided into three stages: the nascent stage (2006–2012), the stable growth stage (2013–2019), and the rapid expansion stage (2020–2025). China is a major contributor in this field, accounting for 68.5% of the total publications, and maintains close collaborations with Pakistan and the United States. Zhejiang A&F University and Nanjing Forestry University are leading institutions in this field. Core research themes identified through keyword cluster analysis include phytoremediation, adsorption, bamboo species, and remediation efficiency. Notably, relatively few studies explicitly exploring the synergistic remediation of bamboo and microorganisms were found in the retrieved literature, indicating a significant research gap that should be prioritized in future work. This study provides a quantitative overview of bamboo-based heavy metal remediation research and proposes specific directions for mechanistic studies and field applications.

***Corresponding author:**
Chengyou Sun
(chengyou98@163.com)

Citation: Wu Q, Ru S, Zheng X, Zeng M, Fan M, Sun C. Bamboo-based remediation of heavy metal-contaminated soils: A bibliometric visualization analysis. *Asian J Water Environ Pollut.* 2026;23(5):026270186. doi: 10.36922/AJWEP026270186

Received: July 2, 2026

Revised: July 14, 2026

Accepted: July 21, 2026

Published online: August 12, 2026

Copyright: © 2026 Author(s). This is an Open-Access article distributed under the terms of the Creative Commons Attribution License, permitting distribution, and reproduction in any medium, provided the original work is properly cited.

Publisher's Note: AccScience Publishing remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Keywords: Bamboo; Rhizosphere microbiome; Heavy metal pollution; Forest soil remediation; Bibliometrics; CiteSpace

1. Introduction

Bamboo, a perennial herbaceous plant of the Bambusoideae subfamily (Poaceae family), possesses multiple characteristics making it ideal for soil remediation. Species such as moso bamboo (*Phyllostachys edulis*) and early-maturing bamboo (*Phyllostachys praecox*) exhibit high adaptability to diverse soil conditions, growing from acidic red soils in southern China to temperate neutral loam.¹ Their rapid growth (some varieties

elongate 1–2 meters per day) and high annual biomass yield (moso bamboo: 15–30 tons/hectare) enable effective heavy metal enrichment, while their well-developed fibrous root systems (reaching 1.5 meters depth in 3-year-old forests) maximize contact with polluted soil.² Many bamboo species demonstrate inherent heavy metal tolerance: in lightly polluted soils (cadmium content 5–10 mg/kg), the cadmium accumulation coefficient of *P. edulis* reaches 1.23; lead accumulation in *P. praecox* root tissue reaches 89.7 mg/kg, effectively immobilizing lead in the rhizosphere.^{3,4} Bamboo rhizosphere exudates—complex mixtures of organic acids (citric acid, oxalic acid), amino acids (glutamic acid), and polysaccharides (mucilage)—alter soil pH, chelate free metal ions, and convert stable residues into bioavailable forms for plant uptake (e.g., exchangeable cadmium).⁵

The bamboo rhizosphere microbial community (bacteria, fungi, actinomycetes) further regulates heavy metal behavior through multiple mechanisms.⁶ *Pseudomonas* species secrete chromate reductase, reducing toxic soluble hexavalent chromium to insoluble, less toxic trivalent chromium and decreasing bioavailability by 60%–80%. Arbuscular mycorrhizal fungi, such as *Rhizophagus irregularis*, form symbiotic relationships with bamboo roots, expanding the absorption range 2–3-fold and enhancing copper tolerance by chelating copper with glomalin-related soil proteins while restricting translocation to aboveground parts.^{2,7} Actinomycetes such as *Streptomyces* produce siderophores that bind iron and heavy metals (zinc, lead), increasing nutrient uptake while reducing toxicity. This synergistic “rhizosphere effect” is based on the high secretion rate of bamboo roots (up to 15% of photosynthetic carbon), which provides nutrients for microbial growth, while microorganisms regulate nutrient availability and metal speciation to promote bamboo growth. In cadmium-contaminated soil, *P. edulis* secretes oxalic acid to activate cadmium and stimulate *Bacillus* to produce cadmium-chelating peptides, forming complexes that are absorbed by roots and prevent cadmium entry into sensitive cell compartments.^{8,9} This mutualistic relationship explains why field trials show bamboo-microorganism combinations achieve 30%–50% higher metal removal rates than bamboo alone.¹⁰

With the rapid expansion of industry and mining, intensification of agriculture (e.g., overuse of metal-containing pesticides and fertilizers), and long-term atmospheric deposition of anthropogenic emissions (e.g., smelter flue gas and vehicle exhaust), soil heavy metal pollution (cadmium, lead, copper, chromium, arsenic) has become an urgent global environmental problem.¹¹ Forest soils, which support biodiversity, regulate biogeochemical

cycles, and maintain ecological stability, are particularly susceptible to heavy metal enrichment that disrupts their multifunctional integrity.¹² Elevated heavy metal concentrations reduce soil organic matter content, inhibit key soil enzymes (urease, phosphatase, dehydrogenase), and alter microbial community structure, thereby impairing nutrient cycling and soil fertility.¹³ Heavy metals also accumulate in forest plants and animals, transferring to humans through the food chain and causing serious public health risks (e.g., kidney damage from chronic cadmium poisoning, neurodevelopmental disorders from lead poisoning). Forest soil ecosystems exhibit greater complexity than farmland soils, featuring heterogeneous spatial structures (litter layer, humus layer, mineral layer), rich biodiversity, and irreplaceable ecological functions such as carbon sequestration and water retention.

Remediation strategies for heavy metal-contaminated forest soils must therefore balance pollution control with ecological integrity protection—a critical constraint limiting traditional physicochemical remediation technologies.¹⁴ For large forest areas, soil replacement incurs prohibitive costs (up to USD 200–\$500 per cubic meter in temperate regions), while chemical washing (e.g., using ethylenediaminetetraacetic acid or citric acid) damages soil structure, causes loss of essential nutrients (nitrogen, phosphorus, potassium), and risks secondary pollution from chelating agent residues.¹⁵ These limitations have prompted the search for sustainable remediation methods, with the combination of phytoremediation and microbial remediation emerging as a promising alternative due to its environmental friendliness, cost-effectiveness, and strong ecological compatibility.¹⁶ Phytoremediation is the use of living plants to extract, stabilize, transform, or degrade contaminants in soil, water, or sediments. In this study, the term is restricted to remediation mediated by intact living plants and excludes amendments or plant-derived materials such as biochar.¹⁷ Among candidate plants for phytoremediation, bamboo has attracted considerable attention for its unique adaptability to heavy metal-contaminated environments.

Despite growing interest in bamboo-based remediation of heavy metal-contaminated soils, the field currently lacks systematic bibliometric analysis to summarize its development trajectory, core research strengths, and emerging directions. Research output has increased rapidly over the past decade, with publications on bamboo phytoremediation rising from fewer than 20 papers annually before 2010 to over 150 papers annually after 2020, yet knowledge remains fragmented across scattered case studies without comprehensive synthesis of mechanistic insights, technological innovations, or

cross-disciplinary synergies—particularly regarding bamboo–microbe interactions. Combining bibliometrics with knowledge graph visualization technology enables quantitative analysis of disciplinary evolution and cutting-edge directions based on large-scale literature datasets.¹⁸ CiteSpace software, employing co-occurrence analysis, co-citation analysis, and burst detection, is widely used to visualize knowledge networks and evolutionary paths in research fields.^{19,20} This study uses CiteSpace to conduct bibliometric analysis of bamboo-based heavy metal-contaminated soil remediation research, with a focus on the role of rhizosphere microorganisms. Research objectives include: (i) identifying publication trends and core dissemination channels; (ii) mapping the global distribution of research strengths and collaborative network patterns; (iii) delineating the knowledge base and highly cited literature; and (iv) revealing current research hotspots and future research directions. This analysis aims to identify under-researched topics—especially bamboo–microbe synergistic remediation mechanisms, field-scale application barriers, and integration with emerging technologies (e.g., genetic engineering, nanomaterials)—and provide a quantitative framework for theoretical innovation and technological advancement in this field.

2. Data and methods

2.1. Data

To ensure the comprehensiveness and authority of the literature, this study selected the Web of Science (WoS) Core Collection as the data source. The search query for the WoS Core Collection was “(bamboo OR *Phyllostachys*) AND (heavy metal OR cadmium OR lead OR chromium OR arsenic) AND (remediation OR restoration OR phytoremediation),” with a search period from 2006 to 2025 (search date: November 20, 2025). The document type was limited to “articles” and “reviews,” the language to English, and the subject categories to “environmental science,” “forestry engineering,” “plant science,” and “microbiology.” The retrieved literature underwent manual screening: conference abstracts, patents, and news reports (non-academic sources) were excluded; literature that did not meet the subject criteria (e.g., literature only concerning bamboo cultivation or heavy metal detection without mentioning remediation measures) was also removed. A total of 212 valid articles were obtained for subsequent quantitative analysis. The research method is shown in Figure 1.

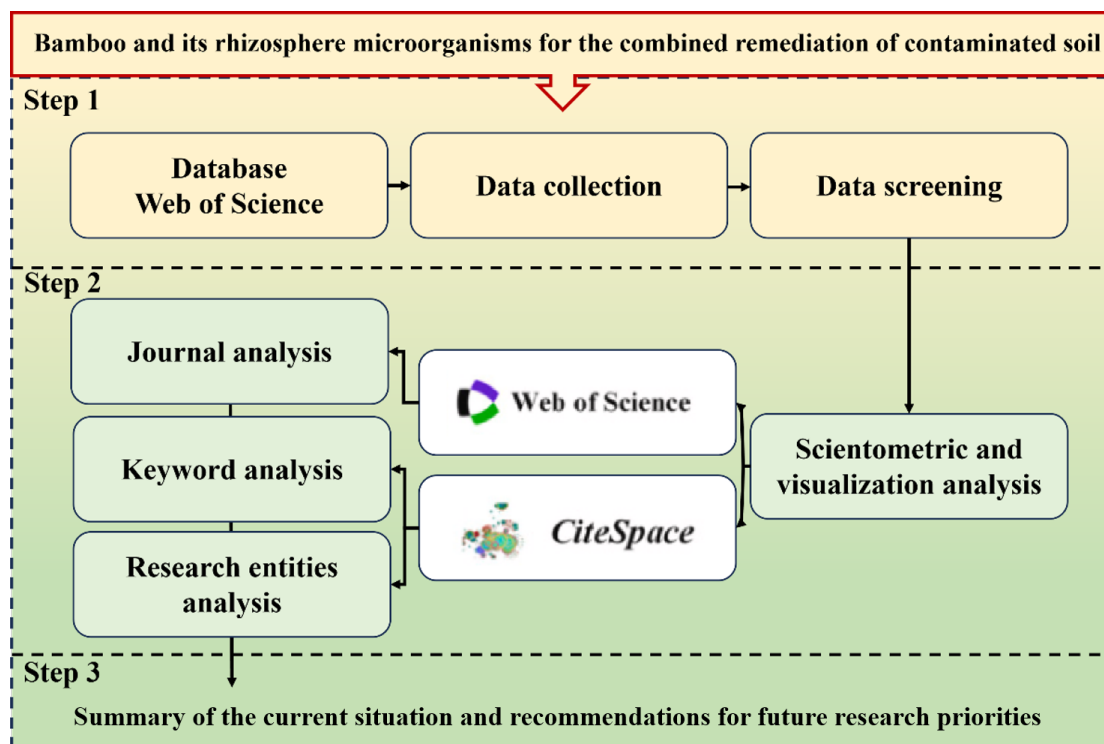


Figure 1. Methodology framework

2.2. Methods

This study used CiteSpace 6.3.R1 software for visualization analysis. First, Excel 2021 was used to perform statistical analysis on basic information such as publication year, country/region, and institution to summarize the characteristics of academic output. Then, CiteSpace was used to perform collaborative network analysis on research entities (country/region, institution, author), as well as keyword co-occurrence, cluster, and document co-citation analyses. The parameter configuration is as follows: (i) time period: 2006–2025, with a two-year interval; (ii) node type was set to “country,” “institution,” “author,” “keyword,” and “reference;” (iii) threshold was set to the 30 nodes with the highest frequency in each time period to ensure the core connectivity and simplicity of the network; and (iv) pathfinder and pruning algorithms were used to prune the slice network to eliminate redundant connections; all other parameters were kept at default settings.

3. Results

3.1. Characteristics of the literature

3.1.1. Changes in the number of publications

Figure 2A shows that the development of research literature on the synergistic remediation of heavy metal-contaminated soil by bamboo and its rhizosphere microorganisms from 2006 to 2025 exhibits a clear three-stage trajectory. This pattern vividly reflects the discipline’s journey from initial exploration to rapid development. The period from 2006 to 2012 was the nascent stage of this field, with the average number of published papers per year consistently below five, indicating a relatively limited research scale. At present, the academic community’s understanding of bamboo’s remediation potential is still limited. Research mainly focuses on basic studies of heavy metal tolerance in different bamboo species, such as analyzing the accumulation characteristics and patterns of lead in moso bamboo.^{21,22} The role of rhizosphere microorganisms in soil remediation has not yet become a research focus, and related explorations are almost non-existent. From 2013 to 2019, this field entered a period of stable growth, with the number of papers published annually gradually increasing from 5 to 12 (example study: Ref.²³). A total of 60 papers were published during these seven years, indicating that research activities remained active. With advances in microbial ecology theory and innovations in research methods, scholars began to break through the limitations of single bamboo species research.²⁴ The research focus shifted to the rhizosphere microbial ecosystem of bamboo, concentrating on the community structure, diversity dynamics and growth

correlation of rhizosphere bacteria and fungi.²⁵ This laid a crucial foundation for subsequent comprehensive restoration studies.²⁶ It experienced explosive growth from 2020 to 2025, with particularly rapid development. As of November 2025, 29 papers were published in 2025 alone, accounting for 13.7% of the total number of publications. Between 2020 and 2025, a total of 149 papers were published, accounting for 70.3% of the total. This explosive growth is mainly attributed to the widespread application of advanced molecular technologies such as high-throughput sequencing and metagenomics. These technologies have broken through traditional research bottlenecks, enabling scholars to conduct in-depth research on the synergistic repair mechanisms between bamboo and rhizosphere microorganisms—including core scientific questions such as functional microbial screening and metabolic pathway regulation—thereby driving the field toward precision and depth.²⁷ To date, this research direction has shown the potential to become a cutting-edge research hotspot in ecological restoration. Figure 2B shows the proportion of articles of each type, with more than 90% of the research concentrated in the “articles” (original research papers) category, while review articles account for only 7.1%. This indicates that the field is still in its early stages, and although a large number of original papers have driven in-depth research, the data available for comprehensive reviews is very limited.^{26,28} Figure 2C shows the top eight categories in the WoS database. The majority of publications belong to environmental science (142 articles; 67.0%), followed by environmental engineering (30 articles; 14.1%), forestry (22 articles; 10.4%), and toxicology (18 articles; 8.5%). This distribution reflects the multidisciplinary nature of the field, with environmental science and engineering accounting for a higher proportion, while microbiology (12 articles; 5.7%) and plant science (9 articles; 4.3%) have a lower proportion (example study: Ref.²⁹). Overall, the literature indicates that research in this field is currently very active. Future research should focus on analyzing synergistic effects, remediation mechanisms, soil biocommunity evolution, and the interaction mechanisms among these elements (for example, Ref.³⁰).

3.1.2. Analysis of representative journals

These 212 papers were published in 151 journals. Table 1 lists the top 10 journals by the number of papers published. *Environmental Science and Pollution Research* published the most papers (13; 6.2%), including some highly cited papers, such as Liu D *et al.*³¹’s research on zinc toxicity in *Phyllostachys pubescens* (8 citations) and Tang *et al.*³²’s research on biochar-mediated cadmium immobilization (15 citations); other examples include Li *et al.*³³ and Wang *et al.*³⁴ *Chemosphere* (10 papers; 4.8%), *Ecotoxicology and*

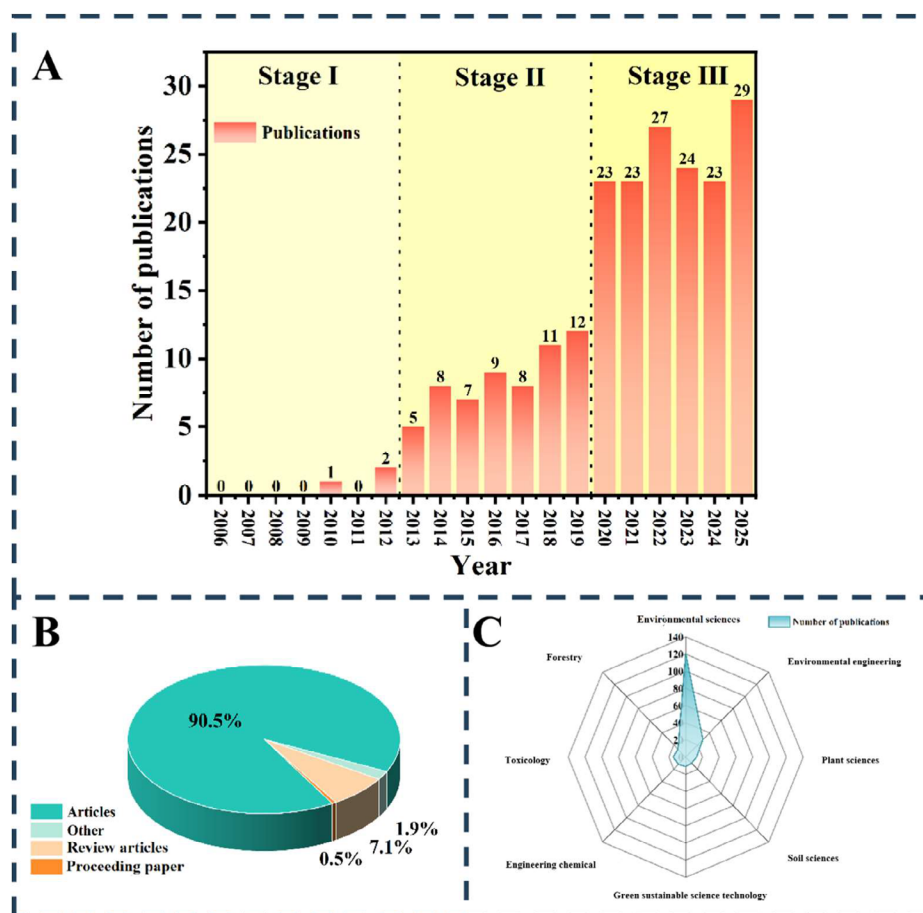


Figure 2. Research trends on bamboo and its rhizosphere microbial community for remediation of heavy metal-contaminated soil. (A) Publications from 2006 to 2025, (B) document types, and (C) the top eight categories of Web of Science.

Environmental Safety (8 papers; 3.8%), and *Journal of Environmental Management* (8 papers; 3.8%) also published a large number of papers. These journals collectively constitute the main channels for disseminating research findings on bamboo–microbe synergistic remediation mechanisms and their efficacy assessment.

From a disciplinary perspective, the core journals covered environmental science (4 journals), soil science (3 journals), microbiology (2 journals), and botany (1 journal), demonstrating significant multidisciplinary integration. Furthermore, Chinese scholars in these journals primarily focus on the remediation applications of native bamboo species (e.g., *Phyllostachys pubescens* and *Phyllostachys aurea* in heavy metal-contaminated forests in southern China).³⁵ Scholars from other countries also mainly focus on studying their own bamboo varieties, suggesting that there is still room to strengthen regional cooperation.^{36,37}

In terms of journal impact dynamics, the *Journal of Environmental Management* and *Environmental Science and Pollution Research* saw average annual citation growth rates of 28.6% and 32.1%, respectively, over the past five years (2020–2025), significantly higher than other journals. This indicates that their influence in the field is rapidly increasing. Although the *Journal of Hazardous Materials* was established early in this field (the first article was published in 2010), its five-year growth rate remained at 26.3%, maintaining its authoritative position in the field; examples of articles include.^{38,39}

3.2. Research capability analysis

3.2.1. Country/Region analysis

A multidimensional analysis based on the CiteSpace network graph revealed the unique distribution patterns and evolutionary trajectories of national/regional

Table 1. Top 10 core journals by publication

Journals	Publications	Initial year	<i>h</i> -index	Impact factor
<i>Environmental Science and Pollution Research</i>	13	2014	82	5.19
Chemosphere	10	2016	212	8.1
Ecotoxicology and Environmental Safety	8	2017	110	6.1
Journal of Environmental Management	8	2016	146	8.4
Journal of Hazardous Materials	7	2010	210	11.3
Environmental Research	5	2020	170	8.3
International Journal of Phytoremediation	5	2018	110	4.18
Science of the Total Environment	5	2019	234	8.0
Toxics	5	2021	86	5.0
Biochar	4	2021	45	6.8

cooperation networks in this field. From a data foundation perspective, the graph used the WoS Core Collection as its data source, covering the period from 2006 to 2025, as shown in Figure 3. Through co-occurrence analysis of countries/regions, a network with 50 nodes and 114 edges was constructed, with a network density of 0.0931 and a node label coverage rate of 1.0%. This network fully reflects the overall pattern and intensity of international cooperation in this field. In terms of node size and distribution, China (People's Republic of China) holds an absolute dominant position, with the largest node size. Its multi-colored ring structure (transitioning from blue in 2006–2007 to red in 2024–2025) visually demonstrates continuous growth in research output, closely related to China's research investment and needs in the field of environmental governance. The United States and India also have large node sizes, reflecting their dynamism in technological innovation and regional environmental research (for example, Refs.^{40,41}). The nodes representing countries such as Pakistan indicate that developing countries are involved in this field

From a cooperation perspective, China maintains close ties with many countries, including the United States, India, Indonesia, and Malaysia, forming a cross-regional cooperation network (for example, Ref³¹). The United States also collaborates with Japan and Thailand on research, while India maintains connections with Southeast Asian countries such as Malaysia and Indonesia. This model of cooperation is influenced by both geographical factors and the common environmental challenges these countries

face. Regional cooperation in this field is expected to show three major trends in the future. First, the leadership of core countries will be strengthened (for example, Ref.⁴²). It is expected that China will further utilize international cooperation platforms such as the Belt and Road Initiative to deepen scientific cooperation with Pakistan and Southeast Asian countries (such as Malaysia and Indonesia) and promote joint research and practical application of environmental governance technologies. Second, the cooperation network is diversifying.⁴³ Countries such as the United States and India can strengthen their interaction with European countries (such as the Netherlands and Italy) and introduce advanced analytical techniques and theoretical frameworks to promote research innovation and internationalization (example of collaborator: Ref.⁴⁴). Third, deepen regional collaborative research. For regions with prominent pollution problems, such as South Asia and Southeast Asia, a regional research alliance centered on India and Pakistan can be established.⁴⁵ The alliance will work together to address common environmental challenges through joint research efforts.⁴⁶ By leveraging China's technological and financial advantages, we can achieve an integrated development model of "technology export-localization-regional governance," thereby improving the fairness and effectiveness of global environmental governance.^{47,48}

3.2.2. Institutional analysis

As shown in Figure 4, this study analyzed 210 papers published by 188 research institutions worldwide on soil

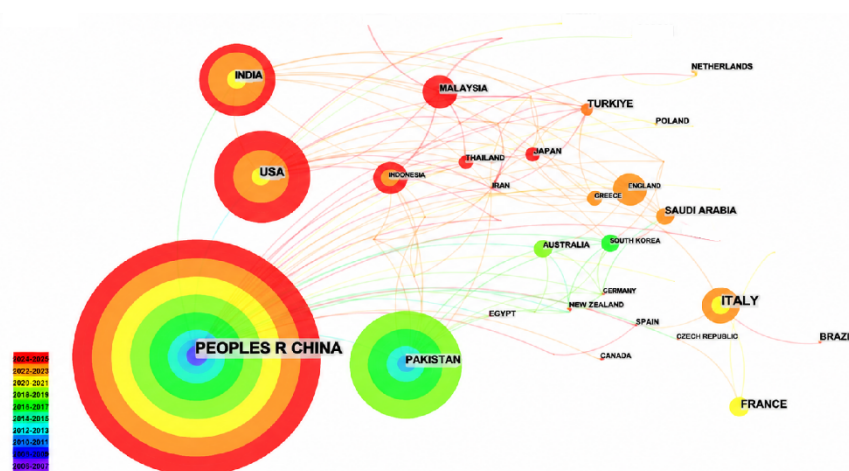


Figure 3. National/Regional cooperation network

remediation using bamboo and its rhizosphere microbial community. Among them, Zhejiang A & F University (29 papers), Nanjing Forestry University (16 papers), and Sichuan Agricultural University (16 papers) have made particularly significant contributions and generated considerable impact in this field. It is worth noting that Zhejiang A & F University has established collaborative relationships with numerous institutions, indicating that it possesses a well-developed cooperation framework in this field (international partners include Florida Atlantic University, etc.). As an important participant in this field, Nanjing Forestry University also maintains a close cooperative relationship with Zhejiang A & F University.⁴⁹ The Bamboo Research and Development Center of the Chinese Academy of Forestry (8 papers) is one of the most professional research institutions in this field and has a considerable influence on the application of bamboo in environmental restoration (example study: Ref.⁵⁰). Overall, a close collaborative network has been formed, centered on Zhejiang A & F University and encompassing institutions such as Nanjing Forestry University, Sichuan Agricultural University, the Bamboo Research and Development Center of the Chinese Academy of Forestry, and the Chinese Academy of Sciences.

The density and strength of the connections between these institutions indicate that they frequently collaborate on projects or jointly publish papers, thus forming a core research team in the field. In addition, the bright yellow areas around the nodes of Zhejiang A & F University, Sichuan Agricultural University, Chinese Academy of Sciences, and Nanjing Forestry University indicate that these institutions have been conducting high-output, high-intensity research in recent years, making them

global pillars in the field of bamboo-based environmental remediation research (for example: the study by Chen *et al.*⁵¹). Only a few international organizations appeared in the network diagram. These organizations have relatively small node sizes and sparse connections with domestic entities. This indicates that international cooperation in this field is still in its early stages, but the potential for future cooperation is enormous. Furthermore, Zhejiang Urban Landscape Planning and Design Institute Co., Ltd. is one of the few companies in this field with considerable influence. Its close cooperation with numerous universities and research institutions indicates a mature industry–academia–research collaboration model. Future work should actively seek more such collaborations to strengthen the transformation of theoretical achievements into practical applications, thereby paving the way for the large-scale implementation of theoretical achievements, such as the study by Zhang *et al.*⁵²

3.2.3. Author analysis

Authors and their teams are the core force driving progress in a research field. Co-occurrence analysis of authors and their collaborators can identify closely collaborating and frequently exchanging teams within a specific field, thus helping to examine their literature and grasp the latest academic trends. Simultaneously, co-citation analysis of authors and their collaborators can reveal the most influential and authoritative academic groups in the field—the pioneering forces leading the research frontier.^{53–55}

In Figure 5A, each node represents an author, and the lines connecting the nodes represent collaborations. Node size is proportional to the author's centrality and activity. The circular structure and line colors represent

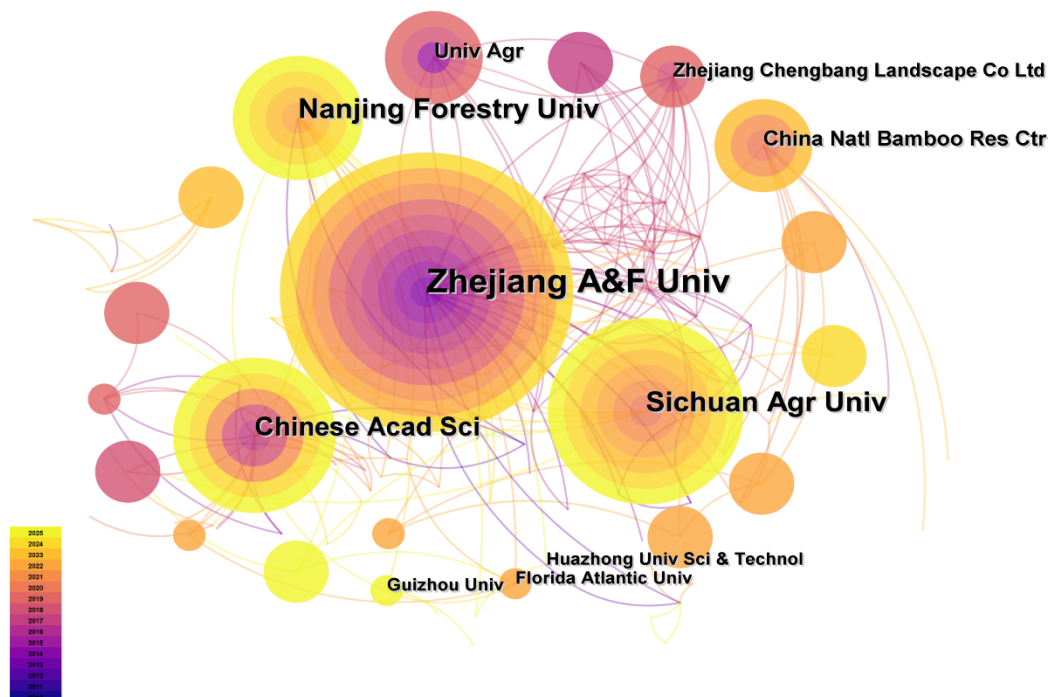


Figure 4. Institutional cooperation network

the publication year, and the timeline in the lower left corner covers the period from 2010 to 2025, with different colors representing different time periods.^{47,48} Several representative research teams can be identified in the figure. These teams have made significant contributions in their respective fields thanks to their abundant academic achievements and close collaborative networks. Among them, the team led by Liu Dan (for example, Ref.⁵⁶) brings together scholars such as Ye Zhengqian, Wu Jiasen, Li Song, Yan Wenbo, Peng Danli, Chen Junren, and Wang Ying, forming a broad collaborative network. This team has maintained stable research output over a long period, demonstrating the continuity and depth of its research work; for example, Ref.⁵⁶ The team centered around Luo Zhenghua (for example, Ref.⁵⁷) includes Liao Jiarong, Yang Yixiong, Chen Qibing, and Jiang Mingyan. Although the team's influence and activity are relatively low, its research activities increased significantly between 2024 and 2025, indicating that its research focus is on specific contemporary research hotspots and that it maintains a highly close cooperative relationship; example articles include Refs.^{46,57} Zhang Xiaoping's team, including Bian Fangyuan⁵⁸, Zhong Zheke, and Li Qiaoling, has also established close cooperation in this field and carried out research with certain unique characteristics.⁵⁸ Furthermore, the team led by Singh Lal, in collaboration with scholars such as

Ranieri Ada Cristina, D'Onghia Gianfranco, Ranieri Ezio, and Ranieri Francesca, and the team led by Emamvadian Abolghasem, have all demonstrated significant research dynamism in their respective fields (such as Ref.⁵⁹). Notably, the close connections between internationally renowned scholars such as Mohammad Shafi⁶⁰, Ejazul Islam¹³, and Chinese scholars indicate a vibrant international research network in this field.

Co-citation analysis profoundly reflects a scholar's academic contributions and the scope of their influence in a specific field. In this network graph, the size of a node is directly related to the author's citation frequency. Larger nodes indicate that the author's literature is cited more frequently in the field, symbolizing higher academic authority and influence.^{61,62}

For example, Liu D's node stands out prominently in the graph, indicating that his research has garnered widespread attention and citations within the field. He is likely a leading expert in this area, and his research direction or theoretical contributions have become foundational references for many scholars. Similarly, Guo Jia's node is also quite large. Considering the active period of his research team (2024–2025), it can be inferred that his recent research is highly innovative, sparking extensive discussion and citations within the industry (for example, see Ref.⁶⁰). Furthermore,

the nodes of scholars who closely collaborate with Liu D (such as Ye Zhengqian) are also quite large. This reflects the collective academic influence of the research team; their collaborative achievements have generated a cluster citation effect within the industry, further solidifying the team's authoritative position.

From the perspective of co-citation networks, connections between highly cited authors also imply academic associations. These connections not only reflect collaborative relationships but also reveal potential theoretical or methodological continuity and resonance in the literature they co-cite. Such co-citation relationships are key clues for tracing the inheritance and innovation of academic discourse in this field. Meanwhile, connections between highly cited authors from different teams reveal the degree of cross-fertilization between different research directions. Cross-team connections indicate overlapping or mutual influence across research fields, reflecting academic exchange and integration within the field. The citation burst data in Figure 5B identify core influential authors. Jessie Park had the highest citation burst intensity between 2016 and 2019 (6.11), indicating that this period was a crucial stage in the development of his academic influence; Islam Ejazul (4.28; 2014–2015) ranked second, reflecting the iteration and changes of key contributors over time. Notably, the explosive growth of Bian Fangyuan, Liang Zhao (3.3, 2021–2022), Amanullah Mahar (3.3, 2021–2022), and Jian Zhang (2023–2025) indicates the emergence of new research focuses after 2020 (example: Refs.^{63,64}). This coincides with the previously inferred inflection point and may be related to disciplinary hotspots.

In summary, the author collaboration network in this field exhibits characteristics of multi-team parallel operation and cross-regional cooperation. Research activities vary across different teams and time periods, reflecting dynamic changes in research focus. Co-citation analysis further highlights the leading role of core scholars and teams, whose research results constitute the knowledge base for the field's development. Looking ahead, the research directions of these core teams are likely to represent the field's future trajectory. Continuously monitoring their latest research findings helps to grasp cutting-edge developments and promote innovation and breakthroughs in related research. Simultaneously, examining the academic connections among highly cited authors can provide important insights for identifying research gaps and potential intersections in the field.

3.3. Research hotspots and trends analysis

3.3.1. Keyword outbreak analysis

Figure 6A shows the temporal distribution of these

keywords in the field of “bamboo–microbe co-remediation of heavy metal-contaminated soil.” Figure 6B shows the 20 most representative keywords in this field. This analysis, based on data from the 20 keywords with the largest increases in citations in soil remediation and related research between 2006 and 2025, reveals the development trends and research hotspots in this field over the past two decades. The increase in citation intensity reflects the academic attention and research enthusiasm received by the keywords during a specific period; a higher value indicates greater research intensity.⁶⁵ From a temporal perspective, the research hotspots exhibit distinct phased characteristics: In the early stage (2012–2015), the focus was mainly on basic research on materials and pollutants. This is reflected in the emergence of keywords such as bamboo charcoal (keyword intensities of 1.63 and 1.9 in 2012 and 2013, respectively), cadmium (1.85 in 2014), ecotype (1.64 in 2014 and 2.56 in 2015, respectively), and bioavailability (1.78 in 2015). These keywords mainly focus on the interaction between specific materials and heavy metal pollutants and their environmental behavior. In the mid-term (2016–2019), the research objects and technologies continued to deepen.

The research focus has shifted from single materials to the application of phytoremediation technologies, as well as the expansion of heavy metal research categories (including lead). Recent trends (2020–2025) show a combination of comprehensive technological application and practical application: contaminated soil (with an outbreak intensity of 38 in 2020, the highest during the entire period) has become a core research focus, accompanied by the rise of key technologies such as phytoremediation (2.18 in 2020), pyrolysis temperature (1.62 in 2018, outbreak in 2020–2023), soil remediation (2021), adsorption (3.17 in 2021, the longest outbreak period from 2021–2025), heavy metal pollution (2.34 in 2010, another outbreak in 2021–2023), biochar (2 in 2018, another outbreak in 2021–2023), hexavalent chromium (1.65 in 2022, another outbreak in 2022–2025), and removal rate (1.57 in 2014, another outbreak in 2023–2025). It is worth noting that the intensity of the outbreaks in contaminated soils was extremely high (38), highlighting the urgency of soil pollution control in practical applications; while the long-term outbreaks of adsorption (2021–2025) and hexavalent chromium (2022–2025) indicate that adsorption technology and the remediation of highly toxic heavy metals (such as hexavalent chromium) are frontier areas of current and future research.⁶⁶ In addition, the repeated appearance of keywords such as biochar, heavy metal pollution, and removal reflects the sustainability of the core research topic, while the appearance of pyrolysis temperature emphasizes the optimization of material

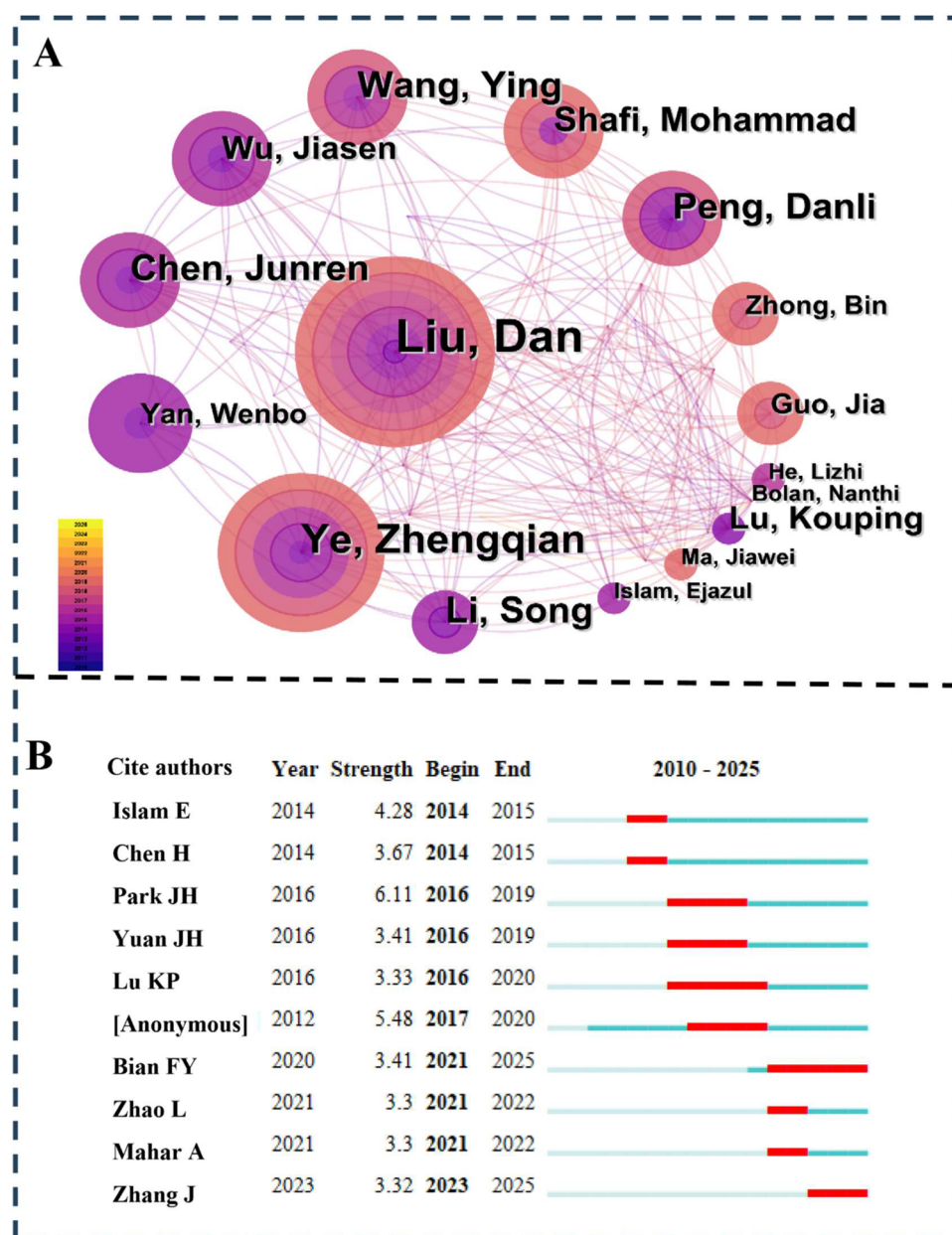


Figure 5. Author analysis. (A) Author collaboration network. (B) Top 10 authors with the most citation surges.

preparation technology in remediation.⁶⁷ Overall, the field has evolved from basic research on materials and pollutants to the integration of remediation technologies, showing a clear shift toward practicality, efficiency, and treatment of highly toxic pollutants. Research focus in the coming years will continue to concentrate on the practical applications of adsorption technologies, hexavalent chromium remediation, and soil remediation technologies.⁶²

3.3.2. Keyword co-occurrence analysis

Keywords embody the essence of the article's theme. Keyword co-occurrence analysis reveals research themes, emerging directions, and hot topics in the academic field. Before analysis, the raw data were preprocessed by merging similar keywords. A keyword co-occurrence network was generated using CiteSpace software to identify research hotspots.

Figure 6C presents the keyword co-occurrence network. Node size represents keyword frequency, line thickness reflects co-occurrence frequency, and node ring color corresponds to the year the keyword appeared.

After pretreatment, “heavy metals” became the most frequently occurring keyword (89 times), occupying a central position and forming the core theme. High-frequency keywords included “remediation” (35 times), “accumulation” (30 times), “cadmium” (28 times), “growth” (28 times), “lead” (26 times), “removal” (24 times), “contaminated soil” (23 times), and “adsorption” (20 times).

Co-occurrence analysis revealed three main research directions: (i) “heavy metals” were closely related to “remediation,” “contaminated soil,” “adsorption,” “cadmium,” and “plants,” reflecting that the research focus was on remediating heavy metal contaminated soil through adsorption and phytoremediation technologies, especially the accumulation, toxicity, and bioavailability of cadmium; (ii) “phytoremediation” co-occurred with “plants,” “growth,” and “accumulation,” highlighting the research on the mechanisms of plant growth and heavy metal accumulation; (iii) “adsorption” was related to “heavy metals,” “aqueous solution,” and “removal,” indicating the adsorption-based aqueous solution heavy metal removal technology.^{37,62}

3.3.3 Keyword cluster analysis

Keyword clustering analysis focuses on the co-occurrence frequency of keywords and uses statistical methods to simplify the co-occurrence network. Clustering analysis is an effective method for identifying research hotspots in a specific field.⁴⁶ This study used the clustering function of CiteSpace for cluster identification and used the log-likelihood ratio weighted algorithm to analyze keyword clustering. The clustering quality was evaluated by the profile index, which ranges from 0 to 1. A value higher than 0.5 indicates that the clustering results are highly reliable and effective. Figure 7 shows the main clustering results: modularity $Q = 0.7522$, weighted average profile value $S = 0.9029$, harmonic mean (Q, S) = 0.8207. These values indicate that the cluster structure is robust and has high internal homogeneity.⁶¹ Based on the clustering labels and research content, the following sequential analysis was performed on the seven clusters (Figure 7).

The first cluster focuses on plant bioavailability. This cluster focuses on the proportion of heavy metals in the soil that can be absorbed by plants, which directly determines the feasibility and efficiency of phytoremediation. The co-occurrence frequency of keywords was high, and the profile coefficient was close to 0.9. The research mainly

focuses on three dimensions of soil–plant interface mechanisms: soil physicochemical properties, heavy metal speciation, and plant physiology. Soil pH is a key regulator: a decrease in pH can increase the content of exchangeable cadmium and lead by 30%–50%, thereby promoting plant absorption. High organic matter content reduces plant bioavailability by 15%–25% through complexation. A series of extraction studies have shown that exchangeable heavy metals account for 60%–80% of total plant absorption, while residual heavy metals account for only 5%–10%. Root exudates (such as citric acid) can increase the bioavailability of cadmium by more than 40%, while the expression level of transport proteins (such as the heavy metal ATPase family) in hyperaccumulating plants is 2–3 times that of ordinary plants.⁴⁴ Synchrotron radiation X-ray fluorescence imaging showed that cadmium in the leaves of hyperaccumulating plants was mainly distributed in epidermal cells and veins, thereby reducing its toxicity to photosynthetic tissues.⁵⁹ Under high stress, the activity of antioxidant enzymes (superoxide dismutase, peroxidase) increased by 2–4 times, thus ensuring normal plant growth. These findings laid the foundation for screening highly enriched, low-toxicity phytoremediation materials and guided soil remediation strategies (e.g., pH adjustment, chelating agent application).

The second research cluster is closely related to adsorption. This cluster represents technology-driven research with a profile coefficient of 0.85 and an average annual growth rate of 12% in the number of publications over the past five years. Adsorption technology is favored for its ease of operation, cost control, and efficiency. Research focuses on three material systems: biochar, nanomaterials, and clay minerals. Bamboo charcoal and rice husk charcoal have adsorption capacities of 200–300 mg/kg for chromium⁶⁶, which is superior to conventional activated carbon. Biochar prepared at 500 °C–700 °C has a specific surface area of 500–800 m²/g and exhibits the best performance.³⁸ Nano-zero ferric iron removes more than 99% of hexavalent chromium, and its reaction rate is 10–20 times faster than conventional iron.

Metal–organic frameworks have adsorption capacities of more than 500 mg/g for lead and specific surface areas greater than 1,000 m²/g. The adsorption capacity of organically modified montmorillonite for cadmium increased from 50 mg/g to 150 mg/g, while the removal rate of arsenic by kaolinite-iron nanocomposite exceeded 95%. The adsorption characteristics of most materials conformed to the Langmuir model ($R^2 > 0.95$), indicating monolayer adsorption. Kinetic studies showed that their adsorption kinetics conformed to pseudo-second-order kinetics (chemisorption is the rate-determining step).

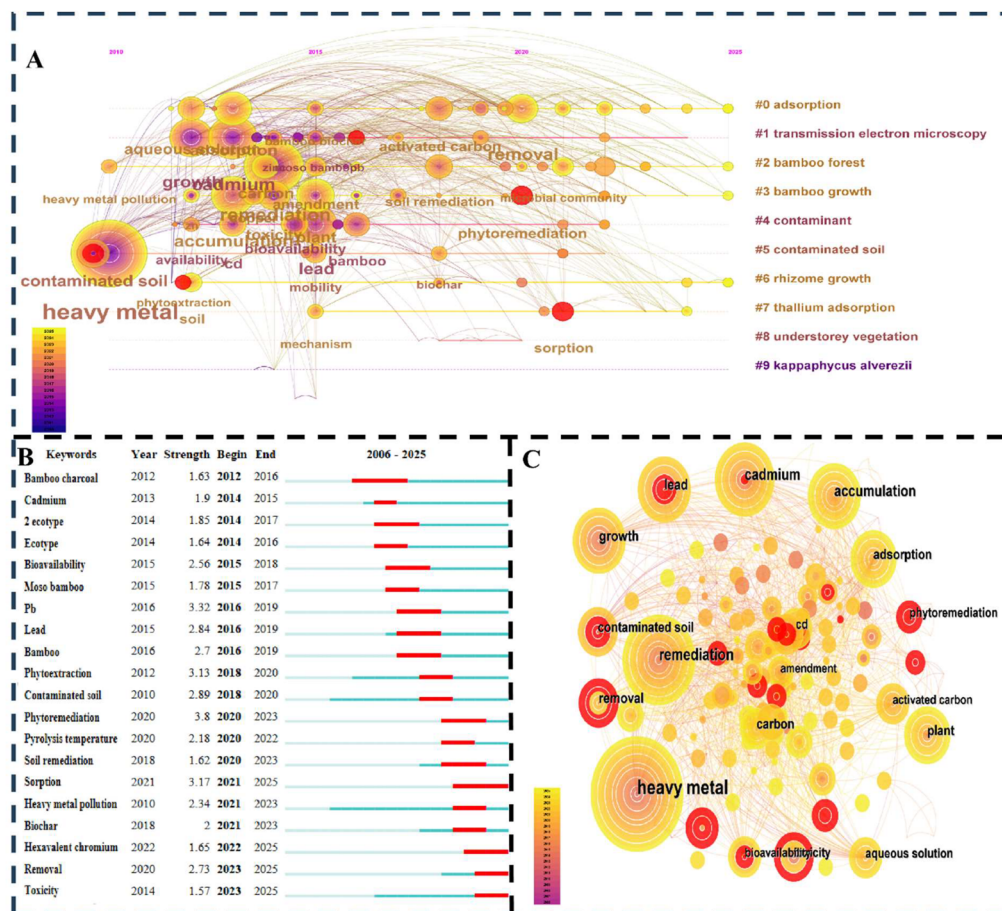


Figure 6. Keyword outbreak analysis. (A) Author collaboration network. (B) Top 20 most cited keywords. (C) Keyword co-occurrence graph.

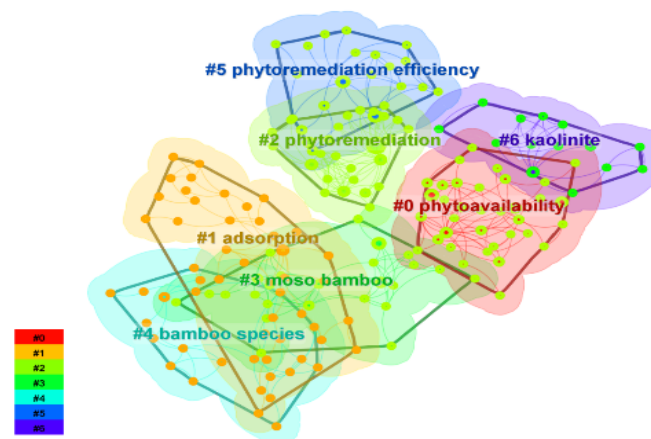


Figure 7. Keyword cluster analysis

X-ray photoelectron spectroscopy and Fourier transform infrared spectroscopy analyses showed that, in addition to ion exchange and electrostatic attraction, coordination bonds between heavy metals and oxygen-containing groups (–OH, –COOH) were the main adsorption mechanism.⁶⁰ Some adsorbents have entered the pilot stage and are expected to be put into industrial-scale application within 3–5 years.

The third cluster is related to phytoremediation. This cluster comprehensively reflects phytoremediation technology, with co-occurring keywords covering multiple dimensions such as plant species, remediation mechanisms, and technology optimization. Its silhouette coefficient is 0.8, indicating rich and extensive research in this field. As a green and sustainable pollution control technology, phytoremediation is increasingly used to remediate heavy metal-contaminated soils, with the proportion of related literature rising from 25% to 35% in the past five years, making it one of the core research directions.

This research covered three main areas: screening hyperaccumulating plants, analyzing remediation mechanisms, and developing integrated remediation technologies. Significant progress has been made in screening hyperaccumulating plants through surveys of local plant resources, identifying more than 20 hyperaccumulating plants with cadmium accumulation coefficients greater than 1 and translocation coefficients greater than 1 (e.g., *Sedum orientalis* and *Sedum variegatum*).²⁵ In forest soil environments, shade-tolerant hyperaccumulating plants (e.g., *Polygonum cuspidatum*) have been identified, with cadmium accumulation in aboveground biomass exceeding 1,000 mg/kg even under semi-shaded forest conditions.⁶⁸ At the mechanistic analysis level, molecular biology techniques have deepened our understanding of hyperaccumulating plants. Transcriptome sequencing revealed that the expression levels of heavy metal transport-related genes (e.g., *HMA2*, *HMA3*) in hyperaccumulating plants are 5–10 times higher than in ordinary plants.² Metabolomics analysis further revealed that the synthesis of large amounts of organic acids (such as malic acid and citric acid) is a key metabolic response in plant tolerance to heavy metal stress, and their concentration increased by 3–5 times.⁵

Co-remediation technology is a key focus in this research field, with plant–microbe co-remediation being particularly prominent. Plant growth-promoting rhizosphere bacteria promote plant growth by secreting plant hormones and dissolving mineral nutrients, while fixing heavy metals through biosorption and redox processes. Bacterial inoculation can increase plant biomass by 20%–40% and heavy metal accumulation by 15%–30%.¹⁰

Arbuscular mycorrhizal fungi enhance plant tolerance by expanding the rhizosphere absorption area and regulating plant hormone balance. After arbuscular mycorrhizal fungi infection, the amount of lead absorbed by plants can be reduced by 40%–60%, thereby achieving a stable phytoremediation target.²⁹ In addition, the combination of phytoremediation and chemical remediation has also been studied. For example, the application of chelating agents such as ethylenediaminetetraacetic acid can increase the absorption of heavy metals by plants by 2–3 times, but its potential risks to soil ecology deserve consideration.⁴⁹ Field application studies have shown that phytoremediation technology can achieve a remediation cycle of 3–5 years in lightly to moderately polluted soils, with a remediation cost of about RMB 2,000–5,000 per acre, which has good cost-effectiveness.⁶⁹ This laid the foundation for its large-scale application.

The fourth cluster includes *P. edulis*. This cluster focuses primarily on *P. edulis*, the most widely distributed and biomass-rich bamboo species in southern China. The co-occurrence network exhibits significant species specificity, with a silhouette coefficient of 0.88. Over the past five years, literature on *P. edulis* has grown at a rate of 15% annually, making it a core topic in bamboo restoration research.

This study focused on three main aspects: the heavy metal accumulation characteristics of moso bamboo, its physiological responses, and the optimization of remediation techniques. Moso bamboo exhibits significant accumulation capacity for cadmium, lead, and copper, with cadmium accumulation coefficients ranging from 1.5 to 2.0, and cadmium concentrations in the aboveground parts ranging from 50 to 100 mg/kg.⁴⁵ The cadmium concentration in the roots is 3 to 5 times higher than that in the aboveground parts, indicating a strong cadmium retention capacity in the roots. Under heavy metal stress, moso bamboo activates its antioxidant system (superoxide dismutase and peroxidase activities increase by 2 to 3 times) and regulates photosynthesis (net photosynthetic rate decreases by 10% to 20%).¹⁶ Root exudates (oxalic acid and citric acid) significantly increase, thereby improving the bioavailability of heavy metals in the soil.⁶⁴

Optimization strategies include fertilizer management and soil improvement. Applying nitrogen and phosphorus fertilizers can increase biomass by 30% to 50% while promoting the accumulation of heavy metals.²³ Applying quicklime to adjust the soil pH to 6.5–7.5 can reduce the aboveground cadmium content by 20% to 30%, achieving the goal of plant stabilization.⁶¹ Intercropping systems are promising: the intercropping system of moso bamboo and purple-stemmed eupatorium can increase the soil

cadmium removal rate by 15% to 20% while increasing biodiversity.⁴² The utilization of remediation biomass is crucial. Bamboo rich in heavy metals can be pyrolyzed to produce biochar with a cadmium adsorption capacity of 150 to 200 mg/g⁵², realizing a circular “waste to resource” model and providing a way for the development of sustainable remediation technologies.

The fifth cluster, “Bamboo Species,” focuses on the application of bamboo species diversity in the remediation of heavy metal-contaminated soils. The co-occurrence network of related keywords reveals the differences and complementarities among different bamboo species, with a silhouette coefficient of 0.82, reflecting the systematic nature of research in this field.²⁸ There are more than 1,600 species of bamboo worldwide, of which more than 600 are distributed in China. They vary significantly in terms of growth characteristics, heavy metal tolerance, and accumulation capacity. This diversity provides a rich selection of materials for soil remediation. In the past five years, the number of publications on bamboo species screening and comparative studies has increased by 20%, indicating that this field is gradually becoming a research hotspot.

The study included species surveys, tolerance comparisons, and differentiated remediation strategies. More than 200 plant species in southern China were surveyed, of which more than 30 species had high cadmium tolerance (e.g., European larch and hairy larch) and more than 25 species had high lead tolerance (e.g., hairy larch and black larch). Shade-tolerant plants (black larch and European larch) could also grow normally under semi-shade forest conditions. Comparative studies revealed significant differences among different species: the cadmium accumulation coefficient of early-maturing larch was 2.0–2.5, while that of nested larch was only 0.5–1.0.³ The antioxidant enzyme activities (superoxide dismutase, peroxidase) of highly tolerant plants were 2–3 times higher than those of low-tolerant plants, and the cell wall pectin content was higher, which was conducive to heavy metal fixation.⁶³

Differentiation strategies include: (i) using highly enriching plants (such as edible pine) for phytoremediation, which can reduce the cadmium content in moderately polluted soil by more than 50% within 3–5 years; and (ii) using highly tolerant, moderately enriching plants (such as hairy pine) for phytostabilization, which can reduce the bioavailability of heavy metals by 30%–40%. Compared with monoculture, mixed planting systems that utilize niche differences (height, root distribution) can increase the removal rate by 20%–30% and increase forest biomass by 40%–50%.⁷⁰

The sixth cluster is phytoremediation efficiency. This cluster focuses on assessing and improving the effectiveness of phytoremediation, marking a key transition from laboratory research to engineering applications. The co-occurrence network covers influencing factors, technology optimization, and assessment methods, with a silhouette coefficient of 0.86. Over the past five years, research in this area has increased from 15% to 25% of total publications, making it a priority research area.

This study covered three aspects: factors affecting efficiency, optimization of efficiency-improving technologies, and evaluation methods. Soil environmental factors, plant physiology, and management practices collectively influence efficiency: higher soil clay content hinders heavy metal migration, reducing efficiency by 15% to 25%; plant growth rate is significantly positively correlated with efficiency; doubling the growth rate can increase efficiency by 30% to 50%.⁵ Applying nitrogen and phosphorus fertilizers can increase plant biomass by 20% to 40%, while also improving efficiency.⁸ Irrigation management that maintains water balance can increase efficiency by 15% to 20% during the dry season.⁴⁵

Enhancement techniques include genetic engineering, chemical induction, and microbial inoculation. Overexpression of heavy metal transporter genes (e.g., *HMA4*) can increase cadmium accumulation in plants by 2–3 times.²³ Chelating agents such as ethylenediaminetetraacetic acid can increase the bioavailability of heavy metals in soil by 40%–60% while promoting plant uptake.¹⁷ Inoculation with heavy metal-tolerant bacteria can increase efficiency by 20%–30%.²⁵ Assessment methods are no longer limited to traditional heavy metal removal rates. Multi-indicator systems now cover removal efficiency, biomass accumulation, remediation duration, cost-effectiveness, and ecological risk.

Remote sensing and Internet of Things technologies enable real-time monitoring; drone-based biomass data combined with soil sampling helps quickly assess remediation effectiveness. Long-term stability studies have shown that the risk of heavy metal rebound after remediation is low. With appropriate management measures (vegetation cover maintenance, avoidance of disturbance), the remediation effect can be sustained for 5–10 years, ensuring the sustainable application of this technology.

The seventh cluster is kaolinite. This cluster, centered on “kaolinite,” represents typical research on clay minerals in the remediation of heavy metal-contaminated soils. The co-occurrence network reflects the interfacial interactions between clay minerals and heavy metals, with a silhouette

coefficient of 0.89. Kaolinite possesses a large specific surface area (10–30 m²/g) and abundant surface active sites, giving it an advantage in heavy metal adsorption. Related research has grown at a rate of 10% annually over the past five years.

This study focused on the adsorption properties of kaolin, the development of composite materials and their application in soil passivation. The adsorption capacity of kaolin for cadmium, lead and copper is 20–50 mg/g. pH value has a significant effect on adsorption: the adsorption capacity increases significantly in the pH range of 5–7; when the pH value is higher than 7, the hydroxyl complexation reaction dominates.³⁵ X-ray photoelectron spectroscopy analysis shows that the coordination bond between Al–OH and Si–OH surface groups and heavy metals is the main adsorption mechanism.⁷¹ Kinetic studies show that the adsorption process conforms to the pseudo-second-order kinetic model, and chemisorption is the rate-determining step ($R^2 > 0.95$).⁷²

The development of composite materials is one of the key research directions. The adsorption capacity of cadmium by kaolin–biochar composite material is 100–150 mg/g, which is 2–3 times that of pure kaolin.⁷² The arsenic removal rate of kaolin–nano iron composite material exceeds 90%, and the stability is excellent. Soil passivation applications show that 2% (w/w) kaolin can reduce the effective cadmium content in the soil by 30%–40%, and plant absorption is also reduced accordingly.⁷¹ When used in combination with organic fertilizer, the effective cadmium content in the soil can be reduced by 50%–60%.⁷³ Kaolin can also improve soil structure (increase aggregate content by 10%–20%), improve the soil's water and fertilizer retention capacity, promote the growth of remediation plants, and increase biomass by 20%–30%.⁷¹ These studies provide a theoretical basis for the development of kaolin-based remediation materials. At present, various formulations are undergoing field trials and are expected to play an important role in soil passivation and phytoremediation.

4. Discussion

This bibliometric visualization analysis systematically mapped the evolution of bamboo-based heavy metal soil remediation research spanning 2006–2025 based on 210 WoS core papers, offering a quantitative panorama of publication trajectories, global collaborative patterns, core research themes, and disciplinary frontiers. Consistent with the three-stage developmental trajectory identified via annual output statistics, the field has shifted from preliminary single bamboo tolerance tests (2006–2012) to microbial rhizosphere exploration (2013–2019) and

finally entered a high-speed expansion phase driven by multi-omics sequencing after 2020. As the dominant contributor with 68.5% of total publications, China holds unparalleled advantages in bamboo germplasm resources and forest pollution governance demand, while Zhejiang A&F University and Nanjing Forestry University form the backbone domestic research alliance, though cross-border institutional cooperation remains limited and fragmented.

Keyword clustering further confirms that phytoremediation, adsorption materials, moso bamboo cultivation, and remediation efficiency constitute the mainstream research framework, yet a striking research gap emerges: studies explicitly exploring bamboo–microbe synergistic remediation mechanisms remain scarce despite verified 30–50% higher metal removal efficiency of combined systems. Similar views have been expressed in other studies, and researchers generally agree that bamboo is more often utilized in other forms, such as biochar and soil conditioners.^{74, 75}

Several limitations inherent to existing literature are revealed by this knowledge network. First, over 90% of publications are original experimental articles, with few comprehensive reviews to integrate scattered mechanistic data, leading to fragmented theoretical cognition. Second, current investigations are largely confined to laboratory pot trials; long-term field monitoring, ecological risk evaluation and industrialized transformation pathways are insufficiently addressed. Third, international collaboration mainly concentrates on China–Pakistan and China–United States partnerships, lacking joint projects targeting tropical bamboo species and cross-continental pollution scenarios.

Furthermore, it is particularly important to note that the vast majority of existing studies have failed to consider the fate of heavy metals within bamboo after the plant dies. Heavy metals sequestered through bioaccumulation or through the combined action of “bamboo bioaccumulation and root-associated microorganisms” are likely to be released back into the environment after the bamboo dies (whether through natural senescence or due to pests, fires, or other disasters). Although this issue has been raised in some studies, it has yet to be systematically addressed or given due attention.⁷⁶

To guide and facilitate subsequent investigations, this study proposes four prospective research directions. First, integrating multi-omics approaches and synchrotron imaging technology is highly desirable to elucidate the molecular signaling mechanisms underlying the interactions between bamboo root exudates and rhizosphere functional microorganisms, thereby filling existing knowledge gaps in their synergistic regulatory mechanisms. Second, interdisciplinary cooperation across forestry science,

microbiology, and environmental engineering should be strengthened to scale up field demonstration projects and establish a circular utilization system. This system enables the conversion of heavy metal-enriched bamboo biomass into modified biochar adsorbents through pyrolysis treatment. Third, establishing a global research alliance is recommended to systematically compare the phytoremediation capacities of indigenous bamboo species distributed in Asia, Africa, and South America. Such comparative analyses can support the development of region-adaptive, low-cost bamboo-microbe combined remediation strategies to mitigate forest heavy metal pollution on a global scale. Finally, multiple influencing factors, including endogenous natural senescence and exogenous mortality induced by pest infestation and natural disasters, should be comprehensively investigated to clarify the ultimate migration and transformation fate of heavy metals accumulated in residual bamboo tissues. On this basis, targeted management strategies can be formulated to effectively prevent secondary heavy metal pollution.

5. Conclusion

This bibliometric and visual analysis systematically mapped research on bamboo and rhizosphere microbial communities for the remediation of heavy metal-contaminated forest soils during 2006–2025. The field has expanded rapidly, with China emerging as a major contributor because of its extensive bamboo resources and the practical need for pollution control. Nanjing Forestry University and the Chinese Academy of Forestry have played central roles in establishing research frameworks based on native bamboo species. Nevertheless, greater international collaboration, methodological innovation, and high-impact outputs are still needed.

For bamboo researchers, the results highlight the importance of selecting bamboo species not only for biomass production and metal tolerance but also for their capacity to recruit beneficial rhizosphere microorganisms. For phytoremediation researchers, the major research frontier is shifting from plant-based metal accumulation alone toward plant-microbe interactions, including plant growth-promoting rhizobacteria, arbuscular mycorrhizal fungi, and their regulation of metal bioavailability, plant uptake, and soil microecological processes. Future studies should prioritize precise bamboo-microbe matching, mechanistic validation using molecular and multi-omics approaches, and long-term assessments of ecosystem stability and ecological risks following remediation.

For scientometric researchers, this study demonstrates that bibliometric tools, such as CiteSpace and VOSviewer,

can effectively identify influential countries, institutions, collaboration networks, research clusters, and emerging topics. Their combined application, together with transparent database selection, standardized search strategies, and periodic data updates, can improve the reproducibility and interpretability of knowledge mapping in this interdisciplinary field.

The next stage of research should integrate field-scale and long-term trials with molecular mechanisms, ecological risk evaluation, and techno-economic assessment. Strengthening international and interdisciplinary collaboration will be essential for translating bamboo-microbe synergistic remediation from experimental studies into scalable and sustainable management strategies for heavy metal-contaminated forest soils.

Acknowledgments

We would like to thank the Hunan Changsha Ecological Environment Monitoring Center for its technical support. We would also like to thank the Key Laboratory of the National Forestry and Grassland Administration on Bamboo & Rattan for its assistance with the visualization techniques used in this study.

Funding

We would like to thank the Scientific Research Project of the Hunan Provincial Department of Education (Grant No. 25B1178) for its support of this work.

Conflict of interest

The authors declare that they have no competing interests.

Author contributions

Conceptualization: Qiao Wu, Chengyou Sun

Formal analysis: Saihong Ru

Funding acquisition: Maoqing Fan

Investigation: Qiao Wu, Xiaoyu Zheng

Methodology: Ming Zeng

Writing—original draft: Qiao Wu

Writing—review & editing: Qiao Wu

Availability of data

Data will be made available from the corresponding author upon reasonable request.

References

1. Zhang H, Qian Z, Zhuang S. Effects of Soil Temperature, Water Content, Species, and Fertilization on Soil Respiration in Bamboo Forest in Subtropical China. *Forests*. 2020;11(1):99.

- doi: 10.3390/f11010099
2. Bian F, Zhong Z, Zhang X, Yang C. Phytoremediation potential of moso bamboo (*Phyllostachys pubescens*) intercropped with *Sedum plumbizincicola* in metal-contaminated soil. *Environ Sci Pollut Res*. 2017;24(35):27244-27253.
doi: 10.1007/s11356-017-0326-2
 3. Yang F, Li J, Wang S, Zheng Y, Yu X, Shao J. Silicon application reduces cadmium accumulation by suppressing expression of genes involved in cadmium transport in Moso bamboo (*Phyllostachys edulis*). *Industrial Crops and Products*. 2026;247:123504.
doi: 10.1016/j.indcrop.2026.123504
 4. Bian F, Zhong Z, Wu S, Zhang X, Yang C, Xiong X. Comparison of heavy metal phytoremediation in monoculture and intercropping systems of *Phyllostachys praecox* and *Sedum plumbizincicola* in polluted soil. *Int J Phytoremediation*. 2018;20(5):490-498.
doi: 10.1080/15226514.2017.1374339
 5. Bian F, Zhong Z, Li C, *et al.* Intercropping improves heavy metal phytoremediation efficiency through changing properties of rhizosphere soil in bamboo plantation. *J Hazard Mater*. 2021;416:125898.
doi: 10.1016/j.jhazmat.2021.125898
 6. Zhang X, Gai X, Zhong Z, *et al.* Understanding variations in soil properties and microbial communities in bamboo plantation soils along a chromium pollution gradient. *Ecotoxicol Environ Saf*. 2021;222:112507.
doi: 10.1016/j.ecoenv.2021.112507
 7. Bian F, Zhong Z, Zhang X, Li Q, Huang Z. Bamboo-based agroforestry changes phytoremediation efficiency by affecting soil properties in rhizosphere and non-rhizosphere in heavy metal-polluted soil (Cd/Zn/Cu). *J Soils Sediments*. 2023;23(1):368-378.
doi: 10.1007/s11368-022-03303-y
 8. Cao Y, Cheng Q, Bao C, Zhang Z, Wu W, Yang H. Biochar mitigates Cr toxicity by improving soil properties, promoting plant growth, and reducing Cr accumulation in tropical bamboo *Dendrocalamus brandisii*. *Ind Crops Prod*. 2025;237:122315.
doi: 10.1016/j.indcrop.2025.122315
 9. Zhang X, Li Q, Zhong Z, Huang Z, Bian F. Characterization of the composition, structure, and functional potential of bamboo rhizosphere archaeal communities along a chromium gradient. *Front Microbiol*. 2024;15.
doi: 10.3389/fmicb.2024.1372403
 10. Zhang Y, Zhao S, Liu S, *et al.* Enhancing the Phytoremediation of Heavy Metals by Combining Hyperaccumulator and Heavy Metal-Resistant Plant Growth-Promoting Bacteria. *Front Plant Sci*. 2022;13:912350.
doi: 10.3389/fpls.2022.912350
 11. Zhu Z, Zhou S, Zhou X, *et al.* Effective Remediation of Arsenic-Contaminated Soils by EK-PRB of Fe/Mn/C-LDH: Performance, Characteristics, and Mechanism. *IJERPH*. 2022;19(7):4389.
doi: 10.3390/ijerph19074389
 12. Zhang F, Jin Q, Peng H, Zhu T. Soil acidification in moso bamboo (*Phyllostachys edulis*) forests and changes of soil metal ions (Cu, Pb) concentration. *Arch Agron Soil Sci*. 2021;67(13):1799-1808.
doi: 10.1080/03650340.2020.1811237
 13. Li S, Islam E, Peng D, *et al.* Accumulation and localization of cadmium in moso bamboo (*Phyllostachys pubescens*) grown hydroponically. *Acta Physiol Plant*. 2015;37(3).
doi: 10.1007/s11738-015-1801-3
 14. Khalid S, Shahid M, Niazi N, *et al.* A comparison of technologies for remediation of heavy metal contaminated soils. *J Geochem Explor*. 2017;182:247-268.
doi: 10.1016/j.gexplo.2016.11.021
 15. Dermont G, Bergeron M, Mercier G, Richer-Lafleche M. Soil washing for metal removal: a review of physical/chemical technologies and field applications. *J Hazard Mater*. 2008;152(2):1-31.
doi: 10.1016/j.jhazmat.2007.10.043
 16. Sarwar N, Imran M, Shaheem M, *et al.* Phytoremediation strategies for soils contaminated with heavy metals: Modifications and future perspectives. *Chemosphere*. 2017;171:710-721.
doi: 10.1016/j.chemosphere.2016.12.116
 17. Yang Y, Liu Y, Li Z, Wang Z, Li C, Wei H. Significance of soil microbe in microbial-assisted phytoremediation: an effective way to enhance phytoremediation of contaminated soil. *Int J Environ Sci Technol*. 2020;17(4):2477-2484.
doi: 10.1007/s13762-020-02668-2
 18. Chen C, Liu Y, Yang S, Chen M, Liao J. A bibliometric and visual analysis of research trends and hotspots of familial hypertrophic cardiomyopathy: A review. *Medicine*. 2024;103(18):e37969.
doi: 10.1097/md.00000000000037969
 19. Tao L, Liang A, Xie N, Liu S. Grey system theory in engineering: a bibliometrics and visualization analysis. *GS*. 2022;12(4):723-743.
doi: 10.1108/gs-06-2022-0059
 20. Wu Q, Su Y, Tan W, Zhan R, Liu J, Jiang L. UAV Path Planning Trends from 2000 to 2024: A Bibliometric Analysis and Visualization. *Drones*. 2025;9(2):128.
doi: 10.3390/drones9020128

21. Chen P, Yuan L, Zhou Z, *et al.* Moso bamboo alleviates Uranium/Cadmium stress through altering the rhizosphere micro-environment and regulating roots carbon and nitrogen metabolism. *Environ Res.* 2025;276:121452.
doi: 10.1016/j.envres.2025.121452
22. Yang Y, Jiang M, Chen C, *et al.* The phytomanagement of Pb-contaminated soil by *Indocalamus decorus* through mowing and inoculation of *Acidithiobacillus thiooxidans*. *J Environ Chem Eng.* 2025;13(5):119218.
doi: 10.1016/j.jece.2025.119218
23. Sahoo R, Sow S, Ranjan S, *et al.* Unveiling the potential of plant growth promoting rhizobacteria (PGPR) in phytoremediation of heavy metal. *SN Appl Sci.* 2024;6(6):324.
doi: 10.1007/s42452-024-06024-8
24. Qiu X, Zheng J, Yan X, *et al.* Preparation of calcium-based phosphate adsorbent and mineral-rich humic acid fertilizer from biomass ash and bamboo by hydrothermal-pyrolysis: Performance and mechanism. *Environ Res.* 2025;264:120318.
doi: 10.1016/j.envres.2024.120318
25. Cao Q, Gou GQ, Dai ZX, Tan AJ, Yang GL. Research on the role of bamboo species in the restoration of heavy metal-contaminated soil. *J Environ Manag.* 2025;384:125565.
doi: 10.1016/j.jenvman.2025.125565
26. Chaturvedi RK. Restoration of Mine Spoil in a Dry Tropical Region: A Review. *Proc Indian Natl Sci Acad.* 2017;93(0).
doi: 10.16943/ptinsa/2017/49123
27. Karunaratne TN, Nayanathara RMO, Navarathna CM, *et al.* Pyrolytic synthesis of graphene-encapsulated zero-valent iron nanoparticles supported on biochar for heavy metal removal. *Biochar.* 2022;4(1).
doi: 10.1007/s42773-022-00196-5
28. Pham CD, Dang MDT, Ly TB, *et al.* A review of the extraction methods and advanced applications of lignin-silica hybrids derived from natural sources. *Int J Biol Macromol.* 2023;230:123175.
doi: 10.1016/j.ijbiomac.2023.123175
29. Wu F, Zhu D, Yang T, *et al.* Soil Heavy Metal Accumulation and Ecological Risk in Mount Wuyi: Impacts of Vegetation Types and Pollution Sources. *Land.* 2025;14(4):712.
doi: 10.3390/land14040712
30. Zhang L, Wu Y, Zhu Z, *et al.* Synergistically enhancing nitrate reduction into N₂ in water by N-doped Pd-Cu biochar bimetallic single-atom electrocatalysis. *Biochar.* 2024;6(1).
doi: 10.1007/s42773-023-00298-8
31. Liu D, Chen J, Mahmood Q, *et al.* Effect of Zn toxicity on root morphology, ultrastructure, and the ability to accumulate Zn in Moso bamboo (*Phyllostachys pubescens*). *Environ Sci Pollut Res.* 2014;21(23):13615-13624.
doi: 10.1007/s11356-014-3271-3.
32. Tan X, Liu Y, Gu Y, *et al.* Immobilization of Cd(II) in acid soil amended with different biochars with a long term of incubation. *Environ Sci Pollut Res.* 2015;22(16):12597-12604.
doi: 10.1007/s11356-015-4523-6
33. Li S, Sun X, Liu Y, *et al.* Remediation of Cd-contaminated soils by GWC application, evaluated in terms of Cd immobilization, enzyme activities, and pakchoi cabbage uptake. *Environ Sci Pollut Res.* 2020;27(9):9979-9986.
doi: 10.1007/s11356-019-07533-5
34. Wang R, Shafi M, Ma J, *et al.* Effect of amendments on contaminated soil of multiple heavy metals and accumulation of heavy metals in plants. *Environ Sci Pollut Res.* 2018;25(28):28695-28704.
doi: 10.1007/s11356-018-2918-x
35. Gao Y, Jiang M, Tian Y, *et al.* Risk-spreading strategies of two dwarf bamboos in heterogeneous Pb (lead) environments. *Glob Ecol Conserv.* 2023;48:e02714.
doi: 10.1016/j.gecco.2023.e02714
36. Emamverdian A, Ding Y, Mokherdoran F, *et al.* Different Physiological and Biochemical Responses of Bamboo to the Addition of TiO₂ NPs under Heavy Metal Toxicity. *Forests.* 2021;12(6):759.
doi: 10.3390/f12060759
37. Bhanse P, Singh L, Qureshi A, Functional and Genomic Potential of Burkholderia contaminans PB_AQ24 Isolate for Boosting the Growth of Bamboo Seedlings in Heavy Metal Contaminated Soils. *Appl Biochem Biotechnol.* 2025;197(4):2437-2456.
doi: 10.1007/s12010-024-05156-2
38. Zhang H, Shao J, Zhang S, Zhang X, Chen H. Effect of phosphorus-modified biochars on immobilization of Cu (II), Cd (II), and As (V) in paddy soil. *J Hazard Mater.* 2020;390:121349.
doi: 10.1016/j.jhazmat.2019.121349
39. Singh S, Chakraborty S. Performance of organic substrate amended constructed wetland treating acid mine drainage (AMD) of North-Eastern India. *J Hazard Mater.* 2020;397:122719.
doi: 10.1016/j.jhazmat.2020.122719
40. Katangale P, Agashe A, Sawarkar R, *et al.* Unlocking the hidden power of bamboo rhizomes: A comprehensive review of their role in nutrient storage, water retention, and plant growth. *Adv Bamboo Sci.* 2025;10:100122.
doi: 10.1016/j.bamboo.2025.100122
41. Arumugam V, Kalaivani R. Bamboo Plantations for

- Phytoremediation of Cadmium in Tannery Effluent: Plant Response and Nutrient Uptake. *Int J Life Sci Pharma Res.* 2023;13(5):249-259.
doi: 10.22376/ijlpr.2023.13.5.1249-1259
42. Emamverdian A, Ding Y, Barker J, *et al.* Nitric Oxide Ameliorates Plant Metal Toxicity by Increasing Antioxidant Capacity and Reducing Pb and Cd Translocation. *Antioxidants.* 2021;10(12):1981.
doi: 10.3390/antiox10121981
43. Timko M, Woodard T, Garham A, *et al.* Thinking globally, acting locally in the 21st century: Bamboo to bioproducts and cleaned mine sites. *iScience.* 2024;27(10):110763.
doi: 10.1016/j.isci.2024.110763
44. Cristaldi A, Conti G, Jho E, *et al.* Phytoremediation of contaminated soils by heavy metals and PAHs. A brief review. *Environ Technol Innov.* 2017;8:309-326.
doi: 10.1016/j.eti.2017.08.002
45. Yan W, Mahmood Q, Peng D, *et al.* The spatial distribution pattern of heavy metals and risk assessment of moso bamboo forest soil around lead–zinc mine in Southeastern China. *Soil Tillage Res.* 2015;153:120-130.
doi: 10.1016/j.still.2015.05.013
46. Zhang J, Chen C, Li J. Visualizing the Intellectual Structure with Paper-Reference Matrices. *IEEE Trans Vis Comput Graph.* 2009;15(6):1153-1160.
doi: 10.1109/tvcg.2009.202
47. Chen C, Dubin R, Kim MC. Emerging trends and new developments in regenerative medicine: a scientometric update (2000 – 2014). *Expert Opin Biol Ther.* 2014;14(9):1295-1317.
doi: 10.1517/14712598.2014.920813
48. Chen C, Ibekwe-SanJuan F, Hou J. The structure and dynamics of cocitation clusters: A multiple-perspective cocitation analysis. *J Am Soc Inf Sci.* 2010;61(7):1386-1409.
doi: 10.1002/asi.21309
49. Chang Y, Yang F, Yang C, *et al.* Silicon reduces cadmium accumulation in Moso bamboo (*Phyllostachys edulis*) cell sap of root by sequestering cadmium in hemicellulose. *Pedosphere.* 2024;43(6):1002-1013.
doi: 10.1016/j.pedsph.2023.07.015
50. Yang F, Xie X, Zhao Y, *et al.* Silicon reduces lead accumulation in Moso bamboo via immobilization and suppression of metal cation transporter genes in roots. *Tree Physiol.* 2025;45(1):002.
doi: 10.1093/treephys/tpaf002
51. Chen Z, Xu X, Wu Z, *et al.* Native Bamboo (*Indosasa shibataeoides* McClure) Invasion of Broadleaved Forests Promotes Soil Organic Carbon Sequestration in South China Karst. *Forests.* 2023;14(11):2135.
doi: 10.3390/f14112135
52. Zhang C, Shan B, Zhu Y, Tang W. Remediation effectiveness of *Phyllostachys pubescens* biochar in reducing the bioavailability and bioaccumulation of metals in sediments. *Environ Pollut.* 2018;242:1768-1776.
doi: 10.1016/j.envpol.2018.07.091
53. Hou J, Yang X, Chen C. Measuring researchers' potential scholarly impact with structural variations: Four types of researchers in information science (1979-2018). *PLoS ONE.* 2020;15(6):e0234347.
doi: 10.1371/journal.pone.0234347
54. Hu Z, Chen C, Liu Z. How are collaboration and productivity correlated at various career stages of scientists? *Scientometrics.* 2014;101(2):1553-1564.
doi: 10.1007/s11192-014-1323-6
55. Stach E, Maruyama, Chen C, Using Operando Characterization, Data Analytics, and Artificial Intelligence to Understand Mechanistic Links between Processing and Structure. *Microsc Microanal.* 2018;24(S1):258-259.
doi: 10.1017/s1431927618001782
56. Ma J, Rukh G, Ye Z, Xie X, Ruan Z, Liu D. Effect of Hypoxic Stress and Levels of Mn on the Physiology and Biochemistry of *Phyllostachys praecox*. *Toxics.* 2022;10(6):290.
doi: 10.3390/toxics10060290
57. Liao J, Jiang M, Lu Y, *et al.* Lead Tolerance and Remediation Potential of Four *Indocalamus* Species in Lead-Contaminated Soil. *Plants.* 2024;13(13):1823.
doi: 10.3390/plants13131823
58. Zhang X, Huang Z, Zhong Z, Li Q, Bian F. Forest management impacts on soil phosphorus cycling: Insights from metagenomics in Moso bamboo plantations. *J Environ Manag.* 2025;373:123735.
doi: 10.1016/j.jenvman.2024.123735
59. Ranieri E, Gikas P, Ranieri F, D'Onghia G, Ranieri AC. Phytoextraction by Moso Bamboo under high level chromium stress in mediterranean conditions. *J Environ Manag.* 2022;317:115479.
doi: 10.1016/j.jenvman.2022.115479
60. Wang Y, Zhong B, Shafi M, *et al.* Effects of biochar on growth, and heavy metals accumulation of moso bamboo (*Phyllostachys pubescens*), soil physical properties, and heavy metals solubility in soil. *Chemosphere.* 2019;219:510-516.
doi: 10.1016/j.chemosphere.2018.11.159
61. Liu S, Chen C. The proximity of co-citation. *Scientometrics.* 2012;91(2):495-511.
doi: 10.1007/s11192-011-0575-7

62. Liu S, Chen C. The Effects of Co-citation Proximity on Co-citation Analysis. In: Proceedings of the 13th Conference of the International Society for Scientometrics and Informetrics (ISSI). Durban, South Africa. 2011.
doi: 10.1016/j.ecoenv.2015.12.023
63. Mahar A, Wang P, Ali A, *et al.* Challenges and opportunities in the phytoremediation of heavy metals contaminated soils: A review. *Ecotoxicol Environ Saf.* 2016;126:111-121.
doi: 10.3389/fmicb.2023.1120679
64. Guo W, Zhang J, Li M, Qi L. Soil fungal community characteristics vary with bamboo varieties and soil compartments. *Front Microbiol.* 2023;14:1120679.
doi: 10.1016/j.neubiorev.2022.104979.
65. Sabe M, Chen C, Perez N, *et al.* Thirty years of research on negative symptoms of schizophrenia: A scientometric analysis of hotspots, bursts, and research trends. *Neurosci Amp Biobehav Rev.* 2023;144:104979.
doi: 10.1007/s11270-020-04759-9
66. Ranieri E, Tursi A, Giuliano S, *et al.* Phytoextraction from Chromium-Contaminated Soil Using Moso Bamboo in Mediterranean Conditions. *Water Air Soil Pollution.* 2020;231(8):408.
doi: 10.1117/12.2036768
67. Kolman S, Galkina E, Dufilie AS, Luo YF, Gupta V, Grinstein G. Linked visual analysis of structured datasets and document collections. *Proc SPIE.* 2013:901707.
doi: 10.1002/ldr.4571
68. Bian F, Zhang X, Zhong Z, *et al.* Introducing sedum affects root-soil interface phytoremediation of heavy metals in lei bamboo forest and potential risks from edible bamboo shoots. *Land Degrad Dev.* 2023;34(6):1820-1829.
doi: 10.1007/978-981-99-0015-2_6
69. Wan X, Lei M, Jun Yang, Chen T, Three-year field experiment on the risk reduction, environmental merit, and cost assessment of four in situ remediation technologies for metal(loid)-contaminated agricultural soil. *Environ Pollut.* 2020;266:115193.
doi: 10.1016/j.envpol.2020.115193
70. Piotto. A meta-analysis comparing tree growth in monocultures and mixed plantations. *For Ecol Manag.* 2008;255(3-4):781-786.
doi: 10.1016/j.foreco.2007.09.065
71. Qiu Z, Tang J, Chen J, Zhang Q. Remediation of cadmium-contaminated soil with biochar simultaneously improves biochar's recalcitrance. *Environ Pollut.* 2020;256:113436.
doi: 10.1016/j.jece.2023.109895
72. Chen Z, Liu J, Jia D *et al.* Migration and transformation pathways of chlorine and sulfur in producing pyrolytic biochar of a Zn/Cd-remediating plant amended with modified kaolin. *Fuel.* 2025;383:133856.
doi: 10.3390/toxics12120872
73. Zhang J, Qian Y, Wang S. *et al.* Effect and mechanism of biochar as a support on immobilization of different heavy metals by iron oxides in a multi-contaminated soil. *J Environ Chem Eng.* 2023;11(3):109895.
doi: 10.1007/978-981-99-0015-2_6
74. Nie X, Huang X, Li M, Lu Z, Ling X. Advances in Soil Amendments for Remediation of Heavy Metal-Contaminated Soils: Mechanisms, Impact, and Future Prospects. *Toxics.* 2024;12(12):872.
doi: 10.1007/s11368-021-03027-5
75. Rani M, Lathwal M, Singh AN, Chongtham N. Bamboo Act as a Phytoremediation Candidate for Heavy Metal Contaminated Soil: A Synthesis. In: *Environmental Footprints and Eco-Design of Products and Processes.* Singapore: Springer Nature; 2023:125-161.
doi: 10.1007/s11368-021-03027-5
76. Kondratova AV, Bryanin SV. Dynamics of heavy metals during litter decomposition in fire-affected boreal forests. *J Soils Sediments.* 2021;21(11):3682-3691.
doi: 10.1007/s11368-021-03027-5