STATE OF THE ART AND RESEARCH HOTSPOTS OF ECOLOGICAL REHABILITATION OF TAILINGS - A VISUAL ANALYSIS BASED ON KNOWLEDGE MAPPING

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(Received 23rd Feb 2025; accepted 22nd Apr 2025)

Abstract. Tailings ecological restoration constitutes a pivotal element within China's green development strategy, exerting profound significance in mitigating land occupation and ecological degradation precipitated by mining activities. Utilizing bibliometric analysis, this study integrates CiteSpace and VOSviewer tools to conduct a systematic dissection of the evolutionary trajectory, research hotspots, and developmental trends characterizing tailings ecological restoration. A comprehensive dataset comprising 342 Chinese and English articles, sourced from CNKI and Web of Science databases and spanning the period from 2014 to 2024, was employed. The study's findings are encapsulated as follows: (1) Policy impetus emerges as the central driving force propelling tailings restoration. Through strategic policies such as the *Action Plan for Carbon Dioxide Peaking Before 2030* and the *Master Plan for Major Projects of Protection and Restoration of Important Ecological Systems*, China has catalyzed a transformative shift in tailings restoration from pollution abatement to ecological reconstruction. (2) The technical framework exhibits a pronounced diversification. Phytoremediation, substrate amendment, and microbial synergistic technologies have ascended to the forefront. A dual-track technological paradigm has crystallized, juxtaposing heavy metal pollution management (e.g., Cd, Cu) with resource valorization (e.g., building materials, fertilizer production). (3) Research hotspots have traversed a tripartite evolutionary arc: an initial focus on the physical stability of tailings (2014–2017), succeeded by an exploration of substrate improvement and heavy metal migration mechanisms (2018–2020), and culminating in a recent pivot towards a carbon neutrality-oriented ecological-economic synergy model (2021–2024). (4) Interdisciplinary integration is markedly pronounced. The confluence of soil science, microbiology, and materials science has propelled cutting-edge advancements, epitomized by rhizosphere microenvironment regulation, biological soil crusts, and enzymatic antioxidant technologies. Future research endeavors must prioritize the fortification of long-term field validation, cross-scale technological integration, and mechanisms for social engagement to actualize the vision of tailings-free mines. This study furnishes a systematic visual foundation for the academic evolution and technological innovation of tailings restoration.
Keywords: *tailings, ecological restoration, bibliometrics, visualization and analysis, knowledge map*

Introduction

In contemporary China, the volume of metal tailings generated is considerable, constituting over half of the total industrial solid waste produced in the country. The environmental issues commonly associated with bulk industrial solid waste are primarily manifested in two aspects: firstly, the extensive extraction of raw ores leads to ecological degradation at the source; secondly, improper storage practices result in land contamination. Once land contamination occurs, its characteristics of

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2305_95699589

concealment, persistence, and complexity significantly increase the difficulty and cost of future remediation efforts (Shi et al., 2024). To enhance the remediation of tailings, the Ministry of Finance and the General Office of the Ministry of Natural Resources jointly issued the Notice on Supporting the Demonstration Project of Ecological Restoration of Abandoned Mines Left Over from History in 2021. This policy highlights the necessity of mine ecological restoration projects for the Action Plan of Carbon Peak by 2030 (Zhao et al., 2024). Additionally, in 2020, the National Development and Reform Commission and the Ministry of Natural Resources released the *General Plan for the Protection and Restoration of Major National Important Ecosystems (2021-2035)*, which offers more comprehensive policy support and planning guidance for mine ecological restoration. In recent years, against the backdrop of nationwide advocacy for green development, the Chinese government has promulgated numerous policies and regulations mandating the ecological restoration of abandoned mines. This requirement is not only a legal obligation but also a manifestation of social responsibility.

Over the past decade, the global annual production of base metals has reached several million tons, concomitantly generating a volume of tailings approximately 100 times greater. Metal tailings (BMTs) exhibit intrinsic toxicity, and even after decades of weathering, no vegetation growth is observed, rendering them a principal category of environmentally harmful industrial waste (Karaca et al., 2018). Globally, the ecological restoration of tailings continues to confront a multitude of challenges. Traditional restoration models have proven to be largely ineffective. The nature of the tailings themselves imposes significant constraints on the implementation of restoration measures. Moreover, biological remediation remains severely limited (Xue et al., 2016). Moreover, research on tailings restoration is predominantly confined to laboratory settings or short-term, small-scale trials, with a notable absence of long-term, large-scale field applications to validate the effectiveness of these methods (Li and Huang, 2015). In Guangdong, China, studies on the weathered tailings of the Dabaoshan Mine have identified cadmium (Cd) and copper (Cu) as the primary carcinogenic factors in tailings, highlighting the necessity for preventing the oxidation of tailings (Shu et al., 2018). In Brazil, the failure of the Fundão Dam in Mariana, Minas Gerais, released 55-62 million cubic meters of metal-rich tailings slurry into the Doce River (Fernandes et al., 2016), marking the largest tailings dam failure in modern history. Therefore, the significance of this study is substantial (Edraki et al., 2014).

Against these macro backdrops, an increasing number of domestic scholars have begun to focus on the ecological restoration of tailings. However, due to the nascent development, the immaturity of related technologies, and the broad range of knowledge involved, the ecological restoration of tailings currently faces several challenges. These include complex environmental conditions, relatively limited technologies and methods, and inadequate detection and evaluation systems. Therefore, this study begins with the developmental trajectory and current research status of tailings ecological restoration in China to understand the developmental pathways and restoration models of tailings ecological restoration in recent years (Liu, 2024). It focuses on the successful experiences of ecological restoration of different types of tailings and related types of tailings, so as to provide references for the development of tailings ecological restoration in China and for subsequent researchers.

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
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Research methods

Bibliometrics serves as a quantitative analytical tool designed to thoroughly investigate and precisely illustrate the evolving nature and advancements within a particular academic discipline or research domain. Leveraging modern computational capabilities, this approach enables the effective visualization and analysis of bibliographic data, allowing for the intuitive presentation of findings through structured knowledge maps. This method thereby supports the visual analysis of disciplinary or research field development trends (Merigo et al., 2015). Visualization techniques and methods have emerged as powerful tools in academic research, primarily due to their ability to construct detailed knowledge maps of various disciplines. These maps offer a comprehensive, dynamic, and intuitive visualization of key aspects within a discipline, including development trends, research progress, hotspots, frontiers, and the evolving relationships within the knowledge structure, both at the domestic and international levels. This capability not only enhances the understanding of the current state and future directions of a discipline but also provides valuable guidance for subsequent research endeavors (Hu et al., 2013). However, with the exponential growth in the number of publications, the development of knowledge has become increasingly fragmented. This fragmentation complicates the task of knowledge accumulation and integration, making it more challenging to identify coherent patterns and trends. In this context, the accurate determination of knowledge structures and the precise identification of research frontiers in scientific fields are of paramount importance. They are not only essential for advancing research but also play a crucial role in informing policy-making and guiding practical applications (Zheng, 2006).

Use Citespace and VOSviewer for knowledge mapping. By Complementing each other's advantages, CiteSpace uses data standardization based on set theory to measure the similarity of knowledge units, and generates Timezone view and Timeline view in time slices through similarity algorithm. Furthermore, the path of knowledge evolution and the historical span of documents in clustering are clearly displayed in the time dimension, which helps researchers to understand the development context and trend of specific fields (Chen, 2006). In contrast, VOSviewer adopts a data standardization method based on probability theory. It provides network view (Network Visualization), overlay view (Overlay Visualization) and density view (Density Visualization) in multiple dimensions such as keywords, co-institutions and co-authors. Its drawing process is simple and the generated image has good aesthetic characteristics (Van Eck and Waltman, 2010). Based on this, combined with the traditional literature review mode and the bibliometric method of visual analysis software, this paper makes a quantitative analysis of the ecological restoration of tailings in recent years, and shows the development status and framework of this field through the way of atlas, and then explores its frontier development status and development path (Aria and Cuccurullo, 2017).

Data sources

The research samples were sourced from the China National Knowledge Infrastructure (CNKI) database. The search strategy involved exact matching, focusing solely on academic journals. The subject terms were searched using advanced search options, with the terms “tailings” AND “ecological restoration.” Conducted on December 1, 2024, the search identified 398 articles published between 2003 and 2024.

After excluding conference papers, notices, submission information, and other non-journal documents, and retaining only journal articles from the past 10 years, 208 documents were selected as the sample literature database and exported in RefWorks format. Using advanced search methods in the Web of Science database, the following search terms were employed: "TS = ((“metal tailings” OR “mine tailings” OR “mineral waste”) AND (“ecological protection” OR “environmental protection” OR “ecological restoration”))" and "TS = (metal tailings AND ecological protection)". The search was conducted on March 31, 2025. The search yielded 116 and 18 English-language articles, respectively. After filtering to retain only the articles published within the last 10 years, a total of 134 articles remained. The number of articles retrieved in both English and Chinese is moderate, and the content is accurate, making the data suitable for analysis and research on the ecological restoration of tailings.

Statistical analysis of the number of published articles

The number of published papers is a key indicator for assessing the scale of research in the field of ecological restoration of tailings reservoirs. Data from the China National Knowledge Infrastructure (CNKI) were analyzed to examine the quantity of research papers on tailings ecological restoration in China from 2014 to 2024 (see *Fig. 1*). The results demonstrate that the publications in this field over the past decade can be divided into three distinct phases. The first phase, from 2014 to 2016, saw the ecological restoration of tailings gradually enter the scholarly discourse. This period was marked by the promulgation of the *Regulations on the Prevention and Control of Environmental Pollution by Tailings (Draft for Opinions)* and the *Measures for the Supervision and Management of Tailings Safety*, which were based on the *Solid Waste Law* in 2015. These regulations established and refined the management system for tailings pollution prevention and control, clarifying the environmental management content and requirements for tailings reservoirs. The second phase, a brief period of stability, occurred from 2017 to 2018. The third phase, from 2019 to 2024, followed the issuance of the *Opinions of the Ministry of Natural Resources on Exploring the Use of Market-oriented Ways to Promote Mine Ecological Restoration* in December 2019. This policy aimed to address the significant issues of historical debts, contradictions, and insufficient investment in mine ecological restoration by establishing a government-led and enterprise-driven system. The accelerated ecological restoration of tailings, supported by a social organization and public participation-based environmental governance system, has attracted more scholars to this field.

In the development stage, China has introduced the environmental protection law, the soil and water conservation law, the mineral resources law, “land management law”, the law on the prevention and control of environmental pollution by solid waste, the land reclamation regulations and other laws and regulations, from different angles in different directions, the environmental protection of mineral resources development and utilization, to solve the tailings ecological restoration (Yang et al., 2012). At the national level, issued the revised draft mineral resources law (2024), the first batch of mine ecological restoration national standard (2024), the former explicitly mine ecological restoration scheme must contain special measures, put forward the principle of “mining, while repair”, to strengthen the government at or above the county level for the repair work as a whole and supervision, and the mining enterprises to strengthen tailings whole life cycle management, the latter encourages social capital to participate

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
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in tailings repair, support market operation and scientific management mode, such as tailings backfill, comprehensive utilization, etc. At the local level, Guangxi issued the Measures for the Management of Ecological Restoration of Waste Mines (2022), proposing the restoration idea of “natural restoration mainly, supplemented by engineering restoration”, to support market-oriented operation and diversified restoration methods (such as transformation to cultivated land or construction land). Domestic tailings ecological restoration policies and regulations are guided by “green development”, combined with technical specifications and responsibility mechanism, and aim to achieve the multiple goals of ecological restoration, efficient utilization of resources and safety risk prevention and control.

The global tailings governance presents a multi-dimensional and cross-regional synergistic trend, and countries respond the environmental and security challenges brought by tailings through policies and regulations, technological innovation and international cooperation. At the policy level, Chile proposes the 2025-26 tailings agenda, plans to upgrade domestic standards to international level, establish tailings database and promote resource engineering, focuses on the extraction of copper and rare earth elements, and strengthens the responsibility of tailings owners through legislation. The European Union Mine Waste Directive requires mining enterprises to formulate full cycle management plans, covering tailings storage, closure monitoring and public supervision, emphasizing environmental impact assessment and pollution prevention. Canada uses the Tailings Facilities Management Guide to promote best practices and promote the application of tailings recycling in building materials and other fields. In terms of international collaboration and standard setting, the Global Industrial Standard for Tailings Management (GISTM) aims at “zero harm”, integrates social, environmental and technical elements, and has been adopted by mining companies in many countries. However, governance still faces challenges, such as the US key mineral supply chain depends on China and the policy fragmentation problem is prominent; some tailings ponds in Chile have been idle for a long time and are in urgent need of systematic repair. In the future, deepening regional alliances (such as the United States and Mexico), strengthening technology research and development and standards coordination will be the key path to build the resilience of global tailings governance.

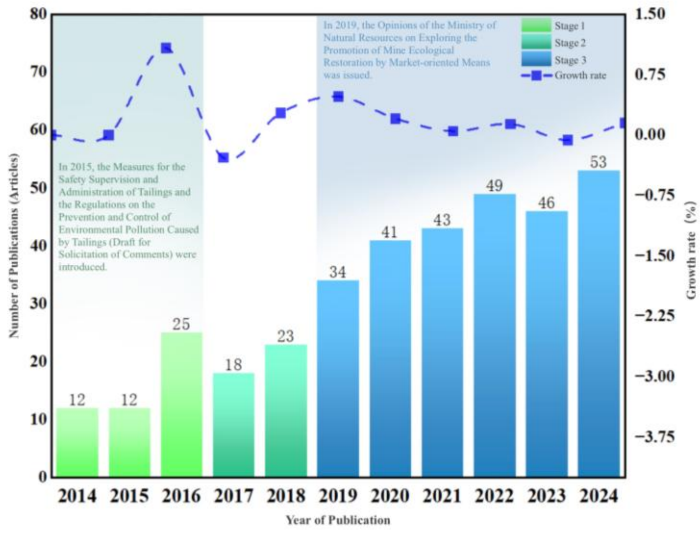

Figure 1. *Data volume of research papers on tailings ecological restoration in China from 2014 to 2024*

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Analysis of issuing organization

Table 1 displays the statistics of the top 10 publishing institutions. According to *Table 1* (which consolidates the various secondary colleges under the research institutions), universities are still the dominant research institutions for tailings ecosystem restoration in China. It is also clear that Yunnan Province, known for its significant non-ferrous metal resources and extensive mining activities, has made considerable contributions to the scientific research on tailings ecological restoration. Given China's vast territory and diverse types of mineral resources, research in the field of mine tailings is characterized by significant regional specificity. For instance, in Inner Mongolia, the primary focus is on the ecological restoration of tailings. In Yunnan, the abundance of nonferrous metals has led to a rich body of research on the treatment of tailings from nonferrous and rare metal mines. As a major province for nonferrous metals, Yunnan has made substantial scientific contributions to the ecological restoration of tailings. This province also offers advantageous scientific research conditions for scholars in related fields within the region.

Table 1. *Names of the top 10 institutions in terms of the number of published documents*

Serial number	Issuing agency	Number of articles published	Number of citations
1	School of Mining Engineering, North China University of Science and Technology	7	7
2	College of Environment, Liaoning University	5	2
3	China Nonferrous Metals Industry Kunming Survey and Design Institute Co., Ltd.	4	1
4	Sinosteel Maanshan Mining Research Institute Co., Ltd.	4	3
5	Chengdu Institute of Organic Chemistry, Chinese Academy of Sciences	3	3
6	College of Life Sciences, Sun Yat-sen University	3	4
7	Yunnan Deshang Mining and Metallurgy Environmental Protection Technology Co., Ltd.	3	0
8	Yunnan Key Laboratory of Geotechnical Engineering and Geological Hazards	3	1
9	Guangdong Jiangxi Taolin Ecological Environment Co., Ltd.	3	3
10	Hebei Key Laboratory of Mining Development and Safety Technology	3	2

Publishing journal analyses

Conducting statistical analyses of relevant journals can effectively identify key research directions within the field (Liang et al., 2017). As the volume of research literature on tailings ecological restoration continues to grow, the number of journals publishing such articles has correspondingly increased. A comprehensive survey of 208 articles themed around "tailings" and "ecological restoration" in the CNKI database reveals that these articles were disseminated across a diverse range of journals. The top

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
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8 journals in terms of publication volume are detailed in *Table 2*. Notably, Metal Mines stands out as the journal with the highest number of publications on this topic, with a total of 10 articles. It is closely followed by Mining Research and Development, which published 8 articles. These two journals, with their relatively higher publication volumes compared to others, have emerged as high-quality platforms for research on tailings ecological restoration in China.

Similarly, in the WOS database, a total of 151 articles on tailings ecological restoration were published across 65 different journals. The top 8 journals in terms of publication volume, as shown in *Tables 2* and *3*, include Science of the Total Environment, Environmental Science and Pollution Research, Journal of Hazardous Materials, and Journal of Environmental Management. Among these, Science of the Total Environment and Environmental Science and Pollution Research have demonstrated exceptional academic quality and influence, as evidenced by their leading publication volumes. Their prominence underscores the significance of these journals in advancing the field of tailings ecological restoration.

Table 2. *Table of top 8 organizations in terms of number of publications on tailings research in CNKI databases*

Serial number	Name of journal	Number of articles issued
1	Metal mine	10
2	Mining Research and Development	8
3	China Mining Industry	4
4	Environmental Science and Technology	4
5	Journal of Agri-Environmental Science Learning	3
6	Journal of Ecology and Environment	3
7	Scientific Environment	3
8	Chinese Geology	2

Table 3. *Table of top 8 organizations in terms of number of publications on tailings research in WOS databases*

Serial number	Name of journal (in English)	Number of articles issued
1	Science of the Total Environment	12
2	Environmental Science and Pollution Research	9
3	Journal of Hazardous Materials	7
4	Journal of Environmental Management	6
5	Chemosphere	4
6	Applied Soil Ecology	3
7	Buildings	3
8	Ecological Engineering	3

Keyword analysis

Keywords serve as the core and essence of an article. By analyzing keyword contributions, we can pinpoint the hot spots in a specific scientific field. CiteSpace was employed to generate the keyword co-occurrence network view of 208 documents, with keywords appearing at least twice selected for visualization. Setting the threshold at 2,

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Figure 2 was produced. The network consists of 228 nodes and 246 links, with a network density of 0.0095. Each node corresponds to a keyword, with larger nodes indicating higher keyword frequency. Lines connecting nodes signify co-occurrence relationships, with thicker lines denoting stronger connections. The color of the links between keywords indicates when these connections were first established. By incorporating the time dimension with the VOSviewer view, the research development trend is intuitively displayed through the color gradient. Node size represents the number of posts, while node color indicates the time distribution, as depicted in *Figure 3*.

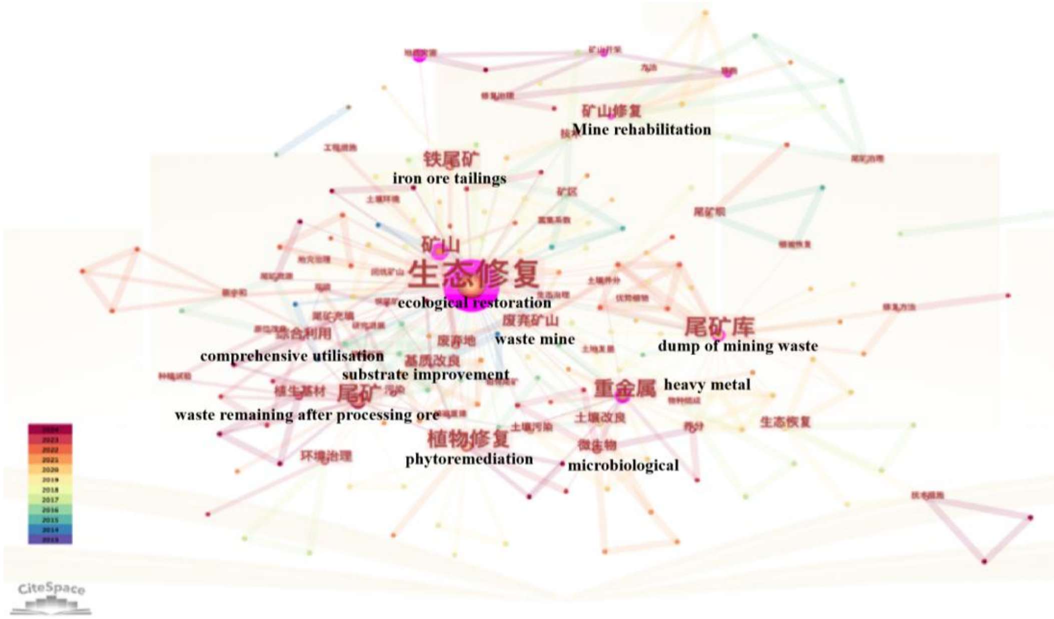

Figure 2. *Keyword co-occurrence map of CiteSpace 2014-2024(in China)*

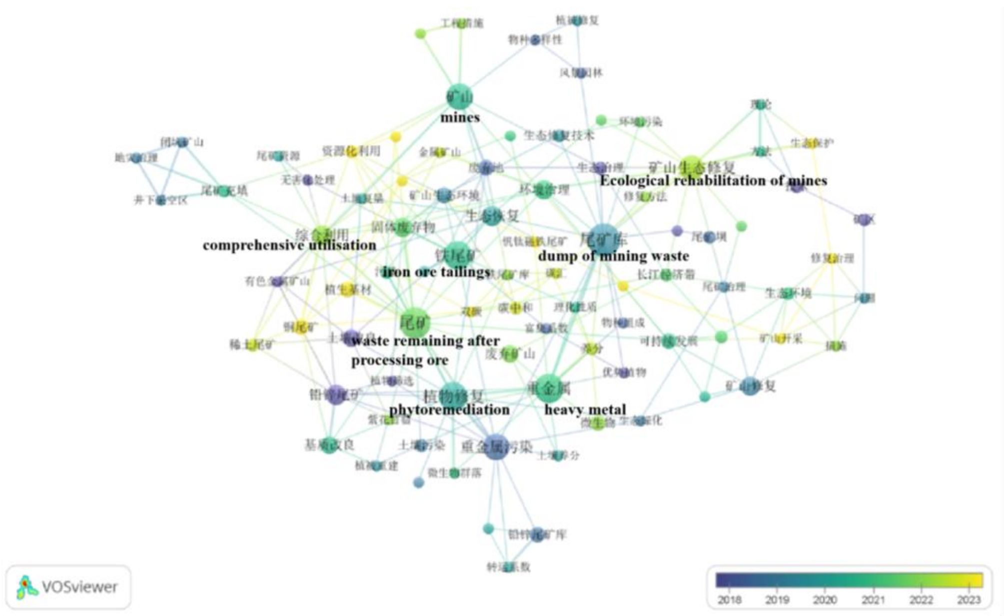

Figure 3. *Time evolution of VOSviewer keyword*

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As evidenced by the color of the keyword connections, over time, research on mine ecological restoration, tailings reservoirs, and phytoremediation has progressively shifted towards environmental policy issues such as “resource utilization,” “carbon neutralization,” and “carbon peak.” This transition is largely attributed to heightened environmental protection awareness. Scholars have increasingly recognized that the environmental damage caused by traditional mining and tailings disposal is long-term and irreversible. As a result, the research focus has broadened from simple ecological restoration to encompass broader environmental governance and sustainable resource use. Additionally, the escalating severity of global climate change has prompted governments and international organizations to introduce relevant policies. Among these, “carbon neutralization” and “carbon peak” have emerged as a global consensus, propelling the rapid development of research in related fields. The utilization of tailings not only mitigates environmental pollution but also promotes resource recycling, aligning with policy objectives. Moreover, advancements in research provide technical support for these goals. With the rapid development of mine restoration technology, comprehensive utilization and development, matrix improvement, and other fields, researchers are exploring more efficient and environmentally friendly tailings treatment methods and ways to transform them into valuable resources.

Additionally, the frequency and centrality of keywords were sorted, as shown in *Table 4,* which lists the top 12 high-frequency words in the field of tailings ecological restoration research. The frequency and centrality of keywords reflect their significance. As shown in the table, the topic of “ecological restoration” has been a focal point (Wang et al., 2024b), “phytoremediation” has been the predominant tailings remediation technology, and “microbial” research on tailings ecological restoration has garnered increasing scholarly attention.

Table 4. *Keyword frequency and center table*

Serial number	Keywords	Frequency	Centrality	Year of occurrence
1	Ecological restoration	81	1.02	2014
2	Tailings pond	18	0.30	2014
3	Tailings	16	0.16	2016
4	Heavy metals	14	0.28	2016
5	Phytoremediation	13	0.11	2016
6	Iron tailings	10	0.06	2015
7	Mine	10	0.29	2014
8	Mine rehabilitation	6	0.13	2016
9	Comprehensive utilization	5	0.04	2016
10	Matrix modification	5	0.01	2016
11	Abandoned mine	5	0.06	2021
12	Microorganism	4	0.04	2020

Through a global co-occurrence analysis of keywords in the field of tailings ecological restoration (*Fig. 4*; *Table 4*), CiteSpace revealed the core research theme in this field, “heavy metals”, which focuses on the behavior of heavy metals in the environment, ecological risks and restoration strategies. The core keyword “heavy

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metals" is at the center of the network and directly connected to "availability", "contaminated soils" and "bio accessibility", which reflects the research focus on the occurrence of heavy metals and their environmental migration. The secondary keywords "steps" and "mineral" further point to the adsorption and fixation mechanism of heavy metals at the soil-mineral interface, while "amendments" and "carbon" imply the technical path of regulating heavy metal activity through the addition of exogenous substances. In terms of ecological restoration direction, "Phyto stabilization", "ecological restoration" and "revegetation" formed a close cluster, which indicates that phytoremediation and ecological engineering has become a research trend. Moreover, the association between "bacterial community" and "growth" reveals the response mechanism of microbial-plant interactions under heavy metal stress and its potential for application in bioremediation. CiteSpace Generated co-occurrence network through node density and connection strength, intuitively presents the heavy metal research from the basic mechanism to technology transformation of knowledge framework, and highlights the multidisciplinary cross (such as environmental science, microbiology and ecological engineering) research characteristics, for the future innovation of heavy metal pollution control strategy provides a theoretical basis and visual reference.

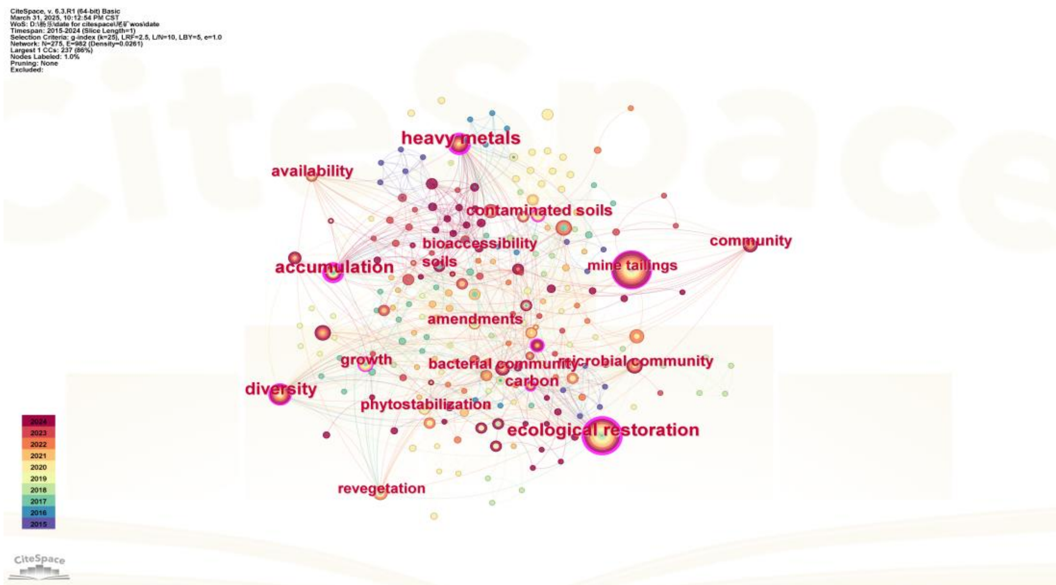

Figure 4. *2014-2024 CiteSpace keyword co-occurrence map*

As the mining industry continues to expand, the ecological environment of a large number of metal mines and their tailings has been increasingly compromised. Heavy metal pollution in tailings, soil degradation, and sparse vegetation are among the most pressing issues, posing substantial threats to the ecosystem. Research on the ecological restoration of tailings covers multiple areas, such as the ecological restoration of various types of mining areas, phytoremediation (Yuan et al., 2021), improvement technologies for tailings matrices, and the development and utilization of tailings resources.

Tailings is a potential secondary resource, comprehensive utilization includes re-selection, production of building materials and fertilizer, etc., but the current recovery is far less than the required treatment. The treatment methods vary from mine to mine, such as underground mine using goaf area, open pit tailings dam as dump, surface

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stacking without dam and synchronous reclamation of tailings paste (Cai et al., 2000). The development direction is to establish without tailings mine (Dong et al., 2009).

In the case of iron tailings, the ratio of sewage to iron tailings can be reconstructed through soil improvement (Shi et al., 2023). Alternatively, mixing iron tailings with sludge at a ratio of 9:1 can enhance the fertility of tailings soil (Tan et al., 2023). This method effectively promotes vegetation restoration and establishes an evaluation system for the effectiveness of vegetation restoration (Xu et al., 2022). To achieve the goal of tailings remediation, tailings can be modified using cement, bagasse, polyacrylamide, water-absorbing resin, and acid fertilizer (Tian et al., 2020). These amendments improve the shear strength and stability of the tailings matrix and provide suitable conditions for plant growth (Wang et al., 2024a). Mixing tailings with fine-grained soil to create a planting substrate can enhance soil nutrients and physical and chemical properties, thereby promoting plant growth (Wang et al., 2020). Additionally, treating tailings soil with chemical and biological amendments to produce “artificial soil” for soil improvement can be widely applied in ecological restoration (Wang et al., 2023).

For the phytoremediation of other heavy metal contaminated tailings (Zhao et al., 2016), hyperaccumulators such as alfalfa and Bermudagrass can be planted (Cheng et al., 2023). Combined with microbial technology, a plant-microbial combined remediation system is formed (Chi et al., 2024; Cheng et al., 2024). There is also Plembizincicola endophyte metal-resistant bacteria, which constructed a new plant extraction system composed of superaccumulating plant Southeast View Sky and its endophytic bacteria for the repair of polymetal-contaminated soil (Ma et al., 2015). Plant slope protection is also a common tailings dam slope stabilization and ecological technology restoration technology, mainly through the way of plant lakes, using roots to fix the slope soil to reduce the risk of landslides, but also to reduce heavy metal pollution in the tailings dam area, can also play a role in beauty (Cheng et al., 2024). The phytoremediation of heavy metals also includes plant stability, plant volatilization, and plant degradation. Such research provides a theoretical basis for the treatment of heavy metal pollution in soil and water, helps to select appropriate remediation technologies and plants, and promotes the application of in phytoremediation technologies (Muthusaravanan et al., 2018).

Phosphate tailings can be used as building materials (concrete aggregate, ceramsite), agricultural applications (fertilizer, soil improvement) and environmental protection materials (adsorbent) for the development and utilization of tailings resources (Gong et al., 2022). Recovering valuable components such as rare earth, iron and niobium from the tailings through processes such as beneficiation and flotation (Wu et al., 2024). Realize the reuse of resources and promote the sustainable development of mine ecological environment.

Cluster analysis

The cluster analysis of keywords can reflect the important topics in the research field. The correlation analysis of keyword co-occurrence was carried out using CiteSpace software. Nodes were selected as keywords, and the threshold was set to 2, resulting in the keyword cluster view of tailings ecological restoration. The residential labels are categorized into eight aspects: iron tailings, matrix improvement, tailings reservoir, heavy metals, ecological restoration, comprehensive utilization, mine

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restoration, and damaged abandoned land. The keywords under each cluster are summarized as shown in *Table 5*. According to the cluster diagram (*Fig. 5*), there is a certain intersection between clusters. For example, “tailings reservoir” (#2) is closely related to “substrate improvement” (#1) and “phytoremediation” (#4), indicating a certain synergy between different technological directions. “Heavy metal” (#3) has strong cluster independence but has weak connections with “ecological restoration” (#4) and “mine restoration” (#6), suggesting that heavy metal pollution control remains a significant challenge in tailings ecological restoration.

Table 5. *Keyword information under cluster analysis*

Cluster number	Cluster name	Main keywords included in the category
1	Iron tailings	Mining area, abandoned land, vegetation ecological concrete, heavy metal pollution, ecological restoration, vegetation coverage, sediment reduction effect, plant growth promotion
2	Matrix modification	Tailings filling, abandoned land, land disaster control, harmless disposal, comprehensive utilization and ecological materials
3	Tailings pond	Effect, rural revitalization, industrial wasteland, community structure, heavy metal enrichment plants, natural restoration
4	Heavy metals	Microorganisms, ecological restoration, non-ferrous metals, tolerant plants, ecological risk, regional characteristics
5	Ecological restoration	Mine restoration, tailings treatment, hybrid paper mulberry, ecological greening, geological disasters, sustainable development
6	Comprehensive utilization	Phytoremediation, waste land, heavy metal pollution, substrate improvement, heavy metal pollution, lead-zinc tailings
7	Mine rehabilitation	Technical measures, environmental pollution, landform destruction, soil erosion, soil improvement and biodiversity
8	Damaged disposal site	Heavy metal pollution, soil nutrient, comprehensive evaluation of fuzzy mathematics, soil environmental quality

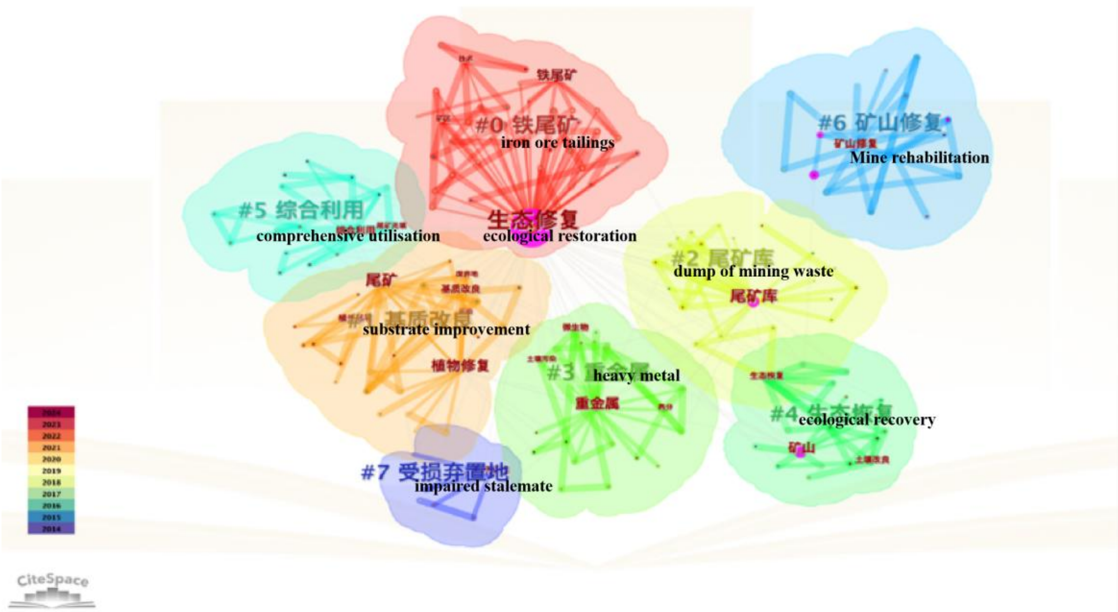

Figure 5. *CiteSpace cluster map 2014-2024 (in China)*

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By analyzing the keywords under the cluster analysis, it can be observed that the research topics are relatively concentrated, focusing on core keywords such as “tailings reservoir,” “heavy metals,” and “ecological restoration.” The research hotspots are gradually evolving from basic management to ecological reconstruction and technological upgrading. The study of tailings ecological restoration involves the intersection of multiple disciplines, including “soil science,” “botany,” “microbiology,” and “urban and rural planning”.

The cluster analysis of the keywords presented in *Table 6* and *Figure 6* reveals that several unique theme groups have been formed within the current research field of heavy metal pollution. Cluster #0 (heavy metals), as the core node, is closely connected with Cluster #4 (ecological risk assessment) and Cluster #2 (geochemical indices). This association clearly delineates the core direction of heavy metal pollution research, which is to accurately quantify the degree of pollution using geochemical methods and to conduct a comprehensive and in-depth assessment of its ecological risks. Clusters #5 (rhizosphere soil cover) and #7 (biological soil crusts) focus on the soil-microbe-plant interface, highlighting the significant potential of rhizosphere microenvironment regulation and biotechnology in heavy metal immobilization.

Table 6. *Keyword information under cluster analysis*

Cluster number	Cluster name	Main keywords included in the category
1	Heavy metals	Phytostabilization, biodiversity, bacterial community, arbuscular mycorrhizal fungi, rhizosphere
2	Mine tailings	Hardpan, leaching column, soil respiration, organic carbon, edaphic filters, calcicole
3	Geochemical indices	Mine tailings, adsorption, behavior
4	Arsenic contamination	Heavy metals, accumulation, soils, ecological risk
5	Ecological risk assessment	Arsenic contamination, contaminated soils, risk assessment
6	Rhizosphere soil cover	Carbon, ecological engineering, bacterial communities
7	Terraformation	Growth, environment, biological properties, earthworms
8	Biological soil crusts	Community, biomonitors, biological soil coagulant
9	Enzymatic antioxidants	Trace elements, organic conditioner, contaminated soil
10	Citizens awareness	Copper production, quality

Of particular interest is the technological innovation trend in the field of heavy metal pollution research, as reflected by Clusters #8 (enzymatic antioxidants) and #6 (terraformation). Cluster #8 focuses on the physiological response mechanisms of plants under heavy metal stress conditions, while Cluster #6 points to the frontier exploration of reconstructing soil function through artificial intervention. Additionally, the independent existence of Cluster #9 (citizens’ awareness) underscores the importance of social participation in heavy metal pollution control, indicating that the research perspective is expanding from the traditional single-technology repair model to a “technology-society” collaborative governance model. This analytical framework provides a valuable visual support for systematically delineating the disciplinary boundaries and innovation pathways of heavy metal pollution research.

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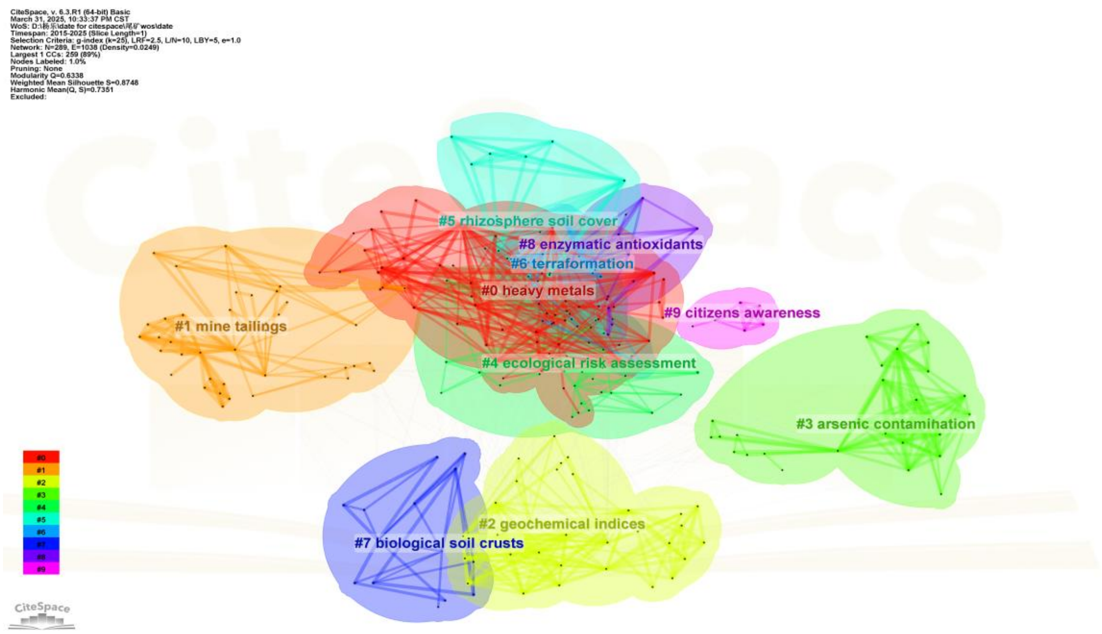

Figure 6. *2014-2024 CiteSpace clustering map*

Hot spot evolution trend analysis

The temporal and spatial clustering analysis functions and the keyword emergence function of CiteSpace can be used to intuitively reflect the change law of the research hotspots in the field of tailings ecological restoration on the time scale. It can be seen that the research hotspots of tailings ecological restoration in the past decade have evolved in the following processes: from 2014 to 2017, the main research objects were "tailings treatment" and "iron tailings," which were biased towards the early stage of treatment technology research. The research mainly focused on the analysis of the physical stability and pollution characteristics of tailings (Wang et al., 2015), such as "tailings reservoir treatment" and "iron tailings utilization," while the technical level was biased towards resource utilization and pollution source analysis, and the method of ecological restoration was not yet mature.

From 2018 to 2020, research hotspots such as "heavy metals" and "matrix improvement" emerged, and scholars began to pay attention to specific remediation technologies and pollutant treatment. The relevant keywords reflect that the research began to focus on improving the characteristics of tailings reservoir substrate to utilize the development of phytoremediation technology, and the related research has entered a certain stage of exploration. For example, hyperaccumulators such as alfalfa (*Medicago sativa*) and Bermudagrass (*Cynodon dactylon*) can be planted for the phytoremediation of heavy metal-contaminated tailings. Combined with microbial technology, a plant-microbial combined remediation system is formed. This integrated approach not only enhances the uptake of heavy metals but also improves soil fertility and microbial activity. Start to deeply understand the possibility, demand and bottleneck of tailings recycling in the mining industry. The potential of tailings recycling in solving the shortage of mineral resources, reducing environmental pollution and realizing economic profit is clarified, which provides a theoretical basis for the transformation of mining industry to circular economy (Kinnunen and Kaksonen, 2019).

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From 2021 to now, with the further strengthening of policy, the maturity of technology, and the integration of multi-disciplines, “phytoremediation” and “ecological restoration” have become the main research trends. Researchers pay more attention to the actual effect of ecological restoration and the sustainability of the environment. The ecological restoration of tailings has been gradually integrated into regional development, forming a trend of coordinated promotion of policy, technology, and economy. For example, phosphate tailings can be used as building materials (concrete aggregate, ceramsite), agricultural applications (fertilizer, soil improvement), and environmental protection materials (adsorbent) for the development and utilization of tailings resources. Recovering valuable components such as rare earth, iron, and niobium from the tailings through processes such as beneficiation and flotation realizes the reuse of resources and promotes the sustainable development of mine ecological environments.

By analyzing the keywords under the cluster analysis, it can be found that the research topics are relatively concentrated, focusing on core keywords such as “tailings reservoir,” “heavy metals,” and “ecological restoration.” The research hotspots are gradually evolving from basic management to ecological reconstruction and technological upgrading. The study of tailings ecological restoration involves the intersection of multiple disciplines, including “soil science,” “botany,” “microbiology,” and “urban and rural planning” (*Figs. 7* and *8*).

From the perspective of emergence intensity and time span (*Figs. 9* and *10*), research themes on a global scale exhibit distinct characteristics of phased focus and continuous in-depth exploration. Specifically:

Early technological exploration phase (2017–2020): The term “phytoremediation” first emerged in 2017 (intensity 1.94), signifying the initial application of phytoremediation techniques in the remediation of heavy metal pollution. By 2020, the concurrent emergence of “heavy-metals” (intensity 2.78), “vegetation” (intensity 2.31), and “ecological risk” (intensity 1.76) indicated a shift in research focus from single-technology validation to a systemic study of heavy metal migration mechanisms and ecological risk assessment. This transition is closely related to the frequent occurrence of tailings pollution incidents worldwide (such as the Fundão Dam failure in Brazil) and the strengthening of environmental policies under the Paris Agreement framework.

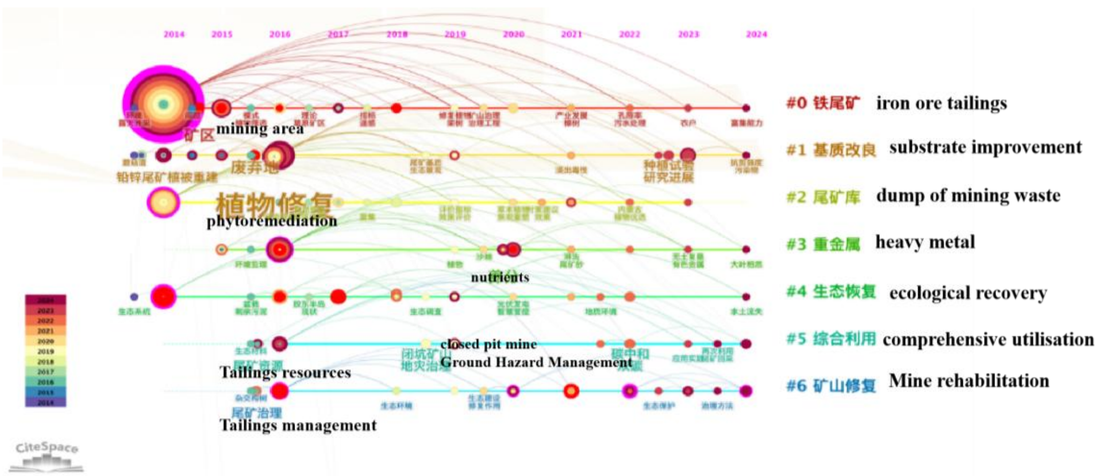

Figure 7. *CiteSpace research hotspot timeline 2014-2024 (in China)*

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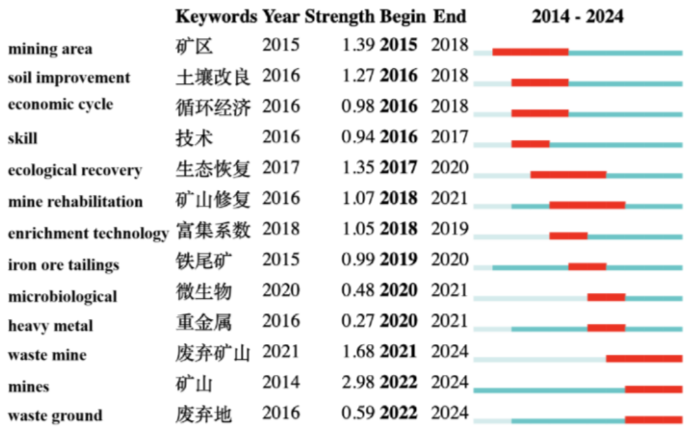

Figure 8. *2014-2024 CiteSpace keyword burst chart (in China)*

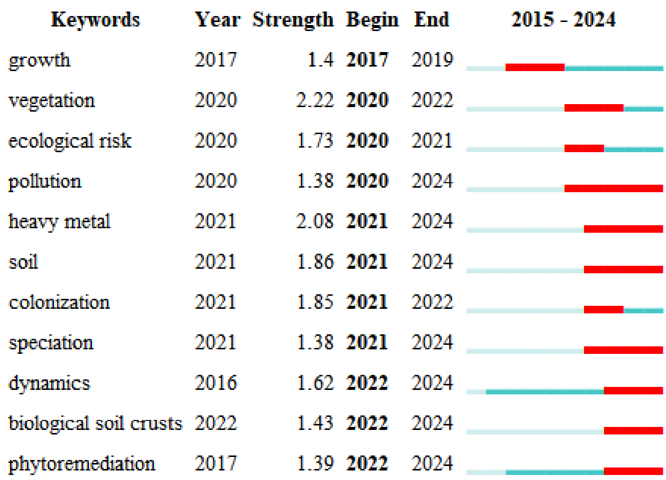

Figure 9. *CiteSpace Keyword Emergence Map 2014-2024*

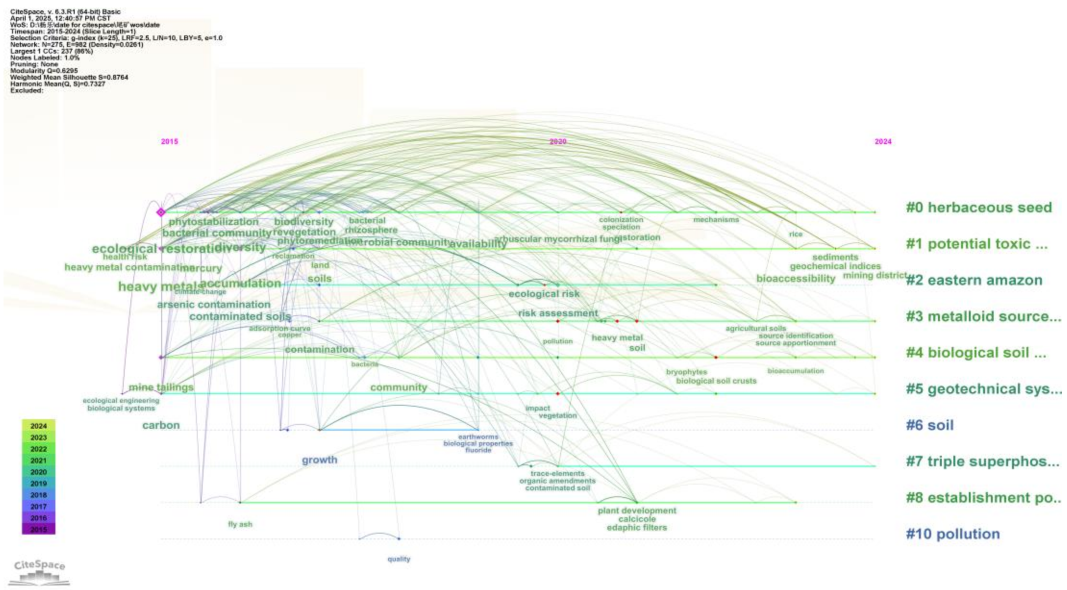

Figure 10. *CiteSpace Research Hotspot Timeline 2014-2024*

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Mid-term interdisciplinary integration phase (2021–2023): The continuous emergence of "heavy metal" (intensity 2.14), "soil" (intensity 2.05), and "colonization" (intensity 1.88) demonstrated that research delved into the soil-microbe-plant interface, focusing on the regulation of rhizosphere microenvironments and microbial colonization mechanisms. Meanwhile, the short-term emergence of "plants" (intensity 1.75) revealed a phased breakthrough in the selection and adaptability studies of hyperaccumulator plants.

Recent comprehensive governance phase (2024–2025): The emergence of "patterns" (intensity 1.98) and "heavy metal contamination" (intensity 1.94) marked a shift in research from micro-mechanisms to the construction of macro-ecological restoration models, with particular attention to the synergistic pathways of tailings resource utilization and pollution control under the goal of carbon neutrality.

It is worth noting that "soil" emerged across phases (2021–2025), highlighting the core role of soil function reconstruction in long-term ecological recovery. The re-emergence of "contamination" in 2023 is directly related to the frequent occurrence of global tailings disasters and the policy-driven upgrade of pollution control under the "dual carbon" targets. Overall, the evolution of these emerging terms reveals a transformation trend in tailings restoration research from single-point technological breakthroughs to full-chain innovation encompassing "mechanisms-technology-models."

Research trends and prospects

Based on the above analysis, tailings remediation is facing comprehensive innovation and upgrading under the background of green sustainable development strategy, and the following predictions are made for the future research trends: 1. Tailings soil usually presents problems such as poor physical and chemical properties, lack of nutrients, and high heavy metal content (Huang et al., 2023). such as organic fertilizers, microorganisms (Guo et al., 2022). Fertilizers improve the mine substrate while using plants and microbes (Yang et al., 2024; Lu et al., 2023). Tailings can also be used to make microcrystalline glass, glass brick, wall and floor tiles to improve the comprehensive utilization of tailings (Zhang et al., 2005; Chen et al., 2012). Synergistic repair effect through engineering means (Huang et al., 2023). Plant stabilization of copper in tailings using the native plant Carpobrotus aequilaterus and addition of potassium humic (Tapia et al., 2017). To form a multi-technology integrated system ecological restoration of tailings, which will also be the core development direction of tailings ecological restoration in the future. 2. Plant mine restoration realizes soil improvement, biodiversity enhancement and pollution reduction of tailings through plant ecological restoration function. Phytoremediation can introduce new biological communities into the tailings area, such as the formation of moss, which can not only promote soil improvement, but also provide support for higher-level plant communities (Wei et al., 2024). The combination of native plants suitable for growth (such as seabuckthorn) and economic crops (such as traditional Chinese medicine) can also achieve the win-win benefits of ecological restoration and economic value of tailings (Hao et al., 2020; Xiao et al., 2024). Tailings remediation is not only limited to the vegetation coverage of tailings, but also committed to building a long-term stable and sustainable ecosystem (Hou et al., 2024; Wang et al., 2019; Lei et al., 2024).

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Conclusion

Tailings ecological restoration is an essential component of mine environmental governance in China. Currently, driven by both policy and technological innovation, it is rapidly evolving towards diversification and sustainability. This study employs bibliometric analysis to construct a visualized knowledge graph, summarizing the research hotspots and development trends of tailings ecological restoration in China. The following major conclusions are drawn:

1. Policy and Technology Synergy: The national “dual carbon” goals, in conjunction with local regulations such as the Management Measures for the Ecological Restoration of Abandoned Mines, have collectively established a policy framework for tailings restoration. This framework has propelled the research from single-dimensional governance to a multi-dimensional paradigm integrating “ecology-resource-economy”.

2. Dual-Track Technological Innovation: On one hand, plant-microbe joint remediation (e.g., the synergistic action of hyperaccumulator plants like alfalfa and endophytes) and substrate improvement (e.g., mixtures of iron tailings and sludge, biochar addition) have significantly enhanced the immobilization efficiency of heavy metals. On the other hand, the resource utilization of tailings (e.g., rare earth recovery, ceramic pellet production) has achieved a balance between environmental and economic benefits.

3. Interdisciplinary Integration and Frontier Breakthroughs: Research on soil-microbe interaction mechanisms, rhizosphere antioxidant responses, and geochemical risk assessment has bridged the gap between micro-scale mechanisms and macro-scale applications. Meanwhile, technologies such as biological soil crusts and artificial soil reconstruction have provided new ideas for the long-term stability of ecosystems.

4. Challenges and Future Directions: Current research is still constrained by insufficient laboratory-scale validation, high technology costs, and low levels of social participation. Future efforts should focus on four main directions: developing low-cost, high-efficiency amendments; establishing multi-scale monitoring and evaluation systems; exploring “restoration-industry” linkage models; and strengthening international cooperation to address global tailings disasters. Through multidisciplinary collaborative innovation and the optimization of policy tools, tailings ecological restoration is expected to become a vital paradigm for global sustainable mining development.

REFERENCES

[1] Aria, M., Cuccurullo, C. (2017): Bibliometrix: an R-tool for comprehensive science mapping analysis. – Journal of Informetrics 11(4): 959-975.

[2] Cai, S., Yang, P. (2000): Metal mine tailings problems and their comprehensive utilization and governance. – Chinese Journal of Engineering Science 4: 89-92.

[3] Chen, C. (2006): Citespace II: detecting and visualizing emerging trends and transient patterns in scientific literature. – Journal of the American Society for Information Science and Technology 3: 359-377. DOI: https://doi.org/10.1002/asi.20317

[4] Chen, H., Shen, W., Shan, L., Xiong, C., Su, Y., Liu, B., Yao, J. (2012): Discussion on the discharge and comprehensive utilization of iron tailings at home and abroad. – Concrete 2: 88-92.

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2305_95699589

[5] Cheng, C., Liu, W., Zhao, H., Zheng, T., Feng, Z., Jin, W. (2023): Formulation and planting test of cement-BPSF modified tailings-type planting substrate. – Nonferrous Metal Engineering 13(3): 146-154.
[6] Cheng, C., Liu, W., An, J., Dai, S., Ning, F. (2024): Strength and microscopic mechanism of cement-BPSF modified tailings-type planting substrate. – Mining Research and Development 44(6): 248-257.
[7] Chi, C., Liu, Y., Wang, C., Zhang, D., Wang, C. (2024): Research progress in soil-based ecological restoration technology for non-ferrous metal mine tailings. – Gold 2024,45(12):8-12+138
[8] Dong, L., Tong, X., Li, X., Li, X., Zhou, J., Wang, S., Liu, B. (2019): Some developments and new insights of environmental problems and deep mining strategy for cleaner production in mines. – Journal of Cleaner Production, 210: 1562-1578.
[9] Edraki, M., Baumgartl, T., Manlapig, E., Bradshaw, D., Franks, D.mM., Moran C.mJ. (2014): Designing mine tailings for better environmental, social and economic outcomes: a review of alternative approaches. – Journal of Cleaner Production 84: 411-420. https://doi.org/10.1016/j.jclepro.2014.04.079
[10] Fernandes, G. W., Goulart, F. F., Ranieri, B. D. Coelhoa, M.S., Dales, K., Boesche, N., Bustamante,M., Carvalho, F.A., Carvalho, D.C., Dirzo, R., Fernandes, S., Galetti P.M. Jr., Millan,V.E.G., Mielke, Ch, Ramirez. J.L., Neves, A., Rogass, Ch., Ribeiro, S.P., Scariot, A., Soares-Filho, B. (2016): Deep into the mud: ecological and socio-economic impacts of the dam breach in Mariana, Brazil. – Natureza & Conservação 14(2): 35-45. DOI: 10.1016/j.ncon.2016.10.003
[11] Gong, F., Jiang, X., Yang, H., Zhang, X., Zhao, S., Liu, K., Liu, Y. (2022): Quantitative evaluation and selection of slope vegetation on gold mine tailings dam. – Journal of Hunan City University (Natural Science Edition) 31(4): 31-35.
[12] Guo, L., Yang, R., Sun, W. (2022): Isolation and screening of nitrogen-fixing bacteria in tailings and their plant growth-promoting effects. – Journal of Environmental and Ecological Science 31(11): 2180-2188.
[13] Hao, Z., Chen, N., Zhang, Y., Zhang, L., Xiao, S. (2020): Correlation analysis between the comprehensive properties of tailings dam soil and the growth status of Hippophae rhamnoides. – Journal of Liaoning University (Natural Science Edition) 47(1): 42-49.
[14] Hou, L. H., Zhu, J., Liao, K. J., Fu, Y. J., She, S. J., Li, Y., Ye, W. xY., Chen, L. Z. (2024). Promoting effect of in-situ inoculation on colonization of moss crusts and phytoremediation in lead-zinc tailings. – Safety and Environmental Engineering, 1-13. DOI:10.13578/j.cnki.issn.1671-1556.20231306.
[15] Hu, Z., Sun, J., Wu, Y. (2013): A review of the application of knowledge graphs in China. – Library and Information Work 57(3): 131-137 + 84.
[16] Huang, W. (2023): Application analysis of tailings solid waste-type planting substrate in mine ecological restoration. – China Metal Bulletin 10: 207-209.
[17] Karaca, O., Cameselle, C., Reddy, K. R. (2018): Mine tailing disposal sites: contamination problems, remedial options and phytocaps for sustainable remediation. – Reviews in Environmental Science and Bio/Technology 17: 205-228.
[18] Kinnunen, P. H. M., Kaksonen, A. H. (2019): Towards circular economy in mining: opportunities and bottlenecks for tailings valorization. – Journal of Cleaner Production 228: 153-160.
[19] Lei, M., Kang, X. (2024): Current status and market analysis of China's molybdenum industry in 2023. – China Molybdenum Industry 48(4): 60-64.
[20] Li, X., Huang, L. (2015): Toward a new paradigm for tailings phytostabilization—nature of the substrates, amendment options, and anthropogenic pedogenesis. – Critical Reviews in Environmental Science and Technology 45(8): 813-839.
[21] Liang, Y. D., Li, Y., Zhao, J. Wang X-Y., Zhu H-Z., Chen X-H. (2017): Study of acupuncture for low back pain in recent 20 years: a bibliometric analysis via CiteSpace. – Journal of Pain Research10: 951-964. doi: 10.2147/JPR.S132808

[22] Liu, X. (2024): Guarding greenness and promoting a new image for mining. – China Mining News 12-30(001).
[23] Lu, S., Gu, H., Ai, Y., Zhang, Y., Li, F. (2023): Restoration effect of glomalin-related soil protein on the ecological environment of vanadium-titanium magnetite tailings. – Metal Mines 3: 250-258.
[24] Ma, Y., Oliveira, R. S., Nai, F., Rajkumar, M., Luo, Y.-M., Rocha, I., Freitas, H. (2015): The hyperaccumulator Sedum plumbizincicola harbors metal-resistant endophytic bacteria that improve its phytoextraction capacity in multi-metal contaminated soil. – Journal of Environmental Management 156: 62-69. DOI: 10.1016/j.jenvman.2015.03.024
[25] Merigó, J. M., Gil-Lafuente, A. M., Yager, R. R. (2015): An overview of fuzzy research with bibliometric indicators. – Applied Soft Computing 27: 420-433.
[26] Muthusaravanan, S., Sivarajasekar, N., Vivek, J. S., Paramasivan, T., Naushad, M., Prakashmaran, J., Gayathri, V., Al-Duaij, O.K. (2018): Phytoremediation of heavy metals: mechanisms, methods and enhancements. – Environmental Chemistry Letters 16: 1339-1359.
[27] Shi, C., Liu, M., Cheng, L., Lan, R. (2024): Research progress and engineering practice of comprehensive utilization of tailings. – China Mining Magazine 33(2): 107-114.
[28] Shi, Y., Yang, Z., Zhou, C., Dou, H. (2023): A study on the environmental governance and restoration technology of closed open-pit metal mines. – China Metal Bulletin 2: 222-224.
[29] Shu, X. H., Zhang, Q., Lu, G. N., Yi, X-Y., Dang,Z. (2018): Pollution characteristics and assessment of sulfide tailings from the Dabaoshan Mine, China. – International Biodeterioration & Biodegradation 128: 122-128.
[30] Tan, H., Xu, Q., Chen, H. (2023): a study on the effects of three types of iron tailings on ecological restoration in arid areas. – Modern Mining 39(5): 193-196.
[31] Tapia, Y., Bustos, P., Salazar, O., Casanova M., Castillo B., Acuña E., Masaguer A. (2017): Phytostabilization of Cu in mine tailings using native plant Carpobrotus aequilaterus and the addition of potassium humates. – Journal of Geochemical Exploration 183: 102-113.
[32] Tian, J., Ma, W., Qi, X., Xu, S., Xu, Y., Li, H. (2020): Vegetation restoration effects in the ecological restoration area of an iron mine tailings dam in Inner Mongolia. – Journal of Agricultural Resources and Environment 37(04): 601-608
[33] Van Eck, N. J., Waltman, L. (2010): Software survey: Vosviewer, a computer program for bibliometric mapping. – Scientometrics 2: 523-538.
[34] Wang, C., Guo, Y., Liu, L., Wang, Y., Luo, A., Liu, H., Xiao, Y., Zhou, J. (2023): A review and prospect of the comprehensive utilization of phosphorus tailings. – Yunnan Chemical Industry 50(4): 1-6.
[35] Wang, C., Bian, M., Yao, S. (2024): Characteristics of soil-plant heavy metal migration under different ecological restoration patterns of lead-zinc mine tailings dam. – Metal Mines12:204-291.
[36] Wang, J., Bai, Y., Liu, Y. (2015): Analysis of high-resolution remote sensing spectral characteristics and information extraction of iron tailings. – Land and Resources Science and Technology Management 32(1): 79-85.
[37] Wang, L., Xu, Y., Li, F., Feng, R. (2019): Effect and evaluation of planting Chinese medicinal plants for the restoration of iron tailings mining area. – Mining Research and Development 39(11): 105-108.
[38] Wang, X., Jiang, Y. (2020): Characteristics of heavy metal accumulation in iron tailings used for road construction and ecological restoration measures. – Environmental Science and Management 45(8): 149-153.
[39] Wang, Z., Li, R., Wang, H., Zhan, J. (2024b): A review and prospect of the risk of homestead use. – Chinese Journal of Agricultural Resources and Regional Planning 45(8): 162-172.

[40] Wei, G., Yan, S., Zhao, T., Yang, J., Jia, Z., Li, R. (2025): Effects and Evaluation of Different Vegetation Types on the Physical Properties of Iron Tailings Soil in the Zhang xuan Mining Area, Hebei Province [J]. Chinese Journal of Soil and Water Conservation (Chinese and English) 23(01):159-167.

[41] Wu, T., Gao, Y., Song, Z., Peng, Y., Xu, H., Dong, J. (2024): Current status and prospects of comprehensive utilization of rare earth tailings. – Chinese Journal of Rare Earths 42(4): 635-665.

[42] Xiao, X., Huang, J., Wang, H., Deng, Y. (2024): Impact of inoculation of AM fungi on alfalfa on the improvement of ion-adsorption type rare earth tailings soil. – Rare Earths 2024: 1-10.

[43] Xu, Q., Tan, H. (2022): A study on the ecological restoration of desertified grassland mining waste land with iron tailings. – Modern Mining 38(9): 24-27.

[44] Xue, S., Zhu, F., Kong, X., Wu,C., Huang,L., Huang,N., Hartley,W. (2016): A review of the characterization and revegetation of bauxite residues (red mud). – Environmental Science and Pollution Research 23: 1120-1132.

[45] Yang, J., Yang, K., Tian, L., Huang, R. (2012): The current situation and control measures of mine ecological environment in China. – Environmental Science and Technology 35(S2): 182-188.

[46] Yang, Z., Zou, Q., Wei, X., Zhou, K., Chen, Z. (2024): Research progress in the adaptation and regulation mechanisms of microorganisms in metal tailings. – Journal of Environmental and Ecological Science 33(1):155-166.

[47] Yuan, H., Xin, Z., Hou, J., Li, Z., Yang, L. (2021): Control pattern of soil and water loss in a typical small watershed in the hilly and gully region of the Loess Plateau. – Acta Ecologica Sinica 41(16): 6398-6416.

[48] Zhang, S., Xue, X., Liu, R., Jin, Z. (2005): Current status and prospects of comprehensive utilization of tailings. – Mining and Metallurgical Engineering 3: 44-47.

[49] Zhao, W., Shi, H. F., Zhou, Y., Li, D., Xu, H. (2016): Methods for the preparation of mixed soil for planting with mine solid waste and the effectiveness of ecological restoration. – Metal Mines 11: 147-151.

[50] Zhao, Y., Xia, X., Li, B. (2024): Research on the current situation of resource development and utilization of closed mines in China under the “Dual Carbon” strategy and policy regulations. – Coal Engineering 56(10): 130-138.

[51] Zheng, W. A. (2006): Comparative study of bibliometrics and content analysis. – Intelligence Magazine 5: 31-33.

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DOI: http://dx.doi.org/10.15666/aeer/2305_95699589