THE SCIENTIFIC LANDSCAPE OF PHYTOREMEDIATION OF TAILINGS: A BIBLIOMETRIC AND SCIENTOMETRIC ANALYSIS

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KEYWORDS

Phytoremediation, mine tailings, CiteSpace, research trends, bibliometrics

ABSTRACT

This article seeks to evaluate the scientific landscape of the phytoremediation of mine tailings through a series of bibliometric and scientometric techniques. Phytoremediation has emerged as a sustainable approach to remediate metal-contaminated mine waste areas. This study presents a scientometric analysis of 913 relevant publications on phytoremediation of mine tailings indexed in Web of Science over 1999-2023. CiteSpace mapping elucidates an actively expanding literature landscape demonstrating rising interdisciplinarity. Environmental sciences represents the core underpinning category with contributions spanning soil science, ecology, microbiology, and green engineering fields. Keyword network analysis reveals predominant attention to plant-metal accumulation behaviors, microbial tolerance partnerships, bioavailability modulation tactics, and field testing validation efforts. Reference co-citation network analysis points to seminal works examining native species capacities, plant-microbe interactions enhancing uptake in tailings, and amendment effects on immobilization. Temporal mapping indicates progression from early risk and native plant inquiries towards integrated biological systems, economic feasibility and sustainability spotlights. Recent directions increasingly recognize multidimensional factors influencing adoption. The work portrays an evolving knowledge terrain demonstrating intensifying translation as multifaceted ecological solutions advance from scientific novelty towards engineering practice. The application of scientometric methods allowed a qualitative and quantitative understanding of research trends and hotspots in the field of phytoremediation of mine tailings. These findings can aid future researchers and practitioners in understanding the developments of this research field.

1. INTRODUCTION

Tailings can pose significant environmental risks if not managed properly, as they may contain toxic substances like heavy metals and chemicals used in mineral extraction (Karaca *et al*. 2018; *Lam et al.* 2018; Lam *et al.* 2023a). Catastrophic failures of tailings dams can lead to disastrous spills that contaminate water sources and surrounding areas (Kossoff *et al.* 2014). Tailings refer to the materials left over after the processing of mined ore to extract valuable minerals or metals. These byproducts are typically a slurry mixture of crushed rock, processing chemicals, and water that is stored in tailings ponds or tailings dams (Falagán *et al.* 2017).

In addition to containment, treatment, and monitoring measures, there is a growing recognition of the importance of stabilizing tailings to mitigate associated risks such as dust emissions, acid drainage, and structural failures (Lam *et al.* 2023a; Lam *et al.* 2023b). Phytostabilization, one such stabilization technique, involves the use of plants to immobilize contaminants within the tailings matrix, reducing their mobility and potential for environmental exposure (Lam *et al.* 2017; Lam *et al.* 2018). This method capitalizes on the natural abilities of certain plants to absorb and accumulate heavy metals and other pollutants from the surrounding soil, thereby reducing the risk of leaching and dispersion into the environment (Mendez and Maier 2008a; Lam *et al*. 2016).

Given the relevance and effectiveness of phytostabilization in tailings management, it becomes imperative to conduct a bibliometric analysis (Lin *et al.* 2024) to comprehensively understand the existing research landscape, identify key trends, and assess the progress in this field. Such an analysis would provide valuable insights into the state-of-the-art methodologies, emerging research directions, and areas requiring further investigation. By synthesizing and evaluating the existing literature on phytoremediation and tailings, researchers and practitioners can inform decision-making processes, optimize remediation strategies, and advance towards more sustainable mining practices. Integrating bibliometric analysis (Lin *et al.* 2024) into research endeavors on phytoremediation and tailings can enhance the efficiency and effectiveness of environmental remediation efforts while promoting scientific rigor and knowledge dissemination.

Mining, mineral processing, and smelting mobilize persistent and bioaccumulative heavy metals that disrupt ecosystems (García-Ordiales *et al.* 2016; Lam *et al.* 2018; Lam *et al.* 2023a; Ahamed and Lichtfouse 2021). Cost-effective, efficient remediation technologies for cleaning up this metal pollution have gained attention globally (Song *et al.* 2020; Guo *et al.* 2021; Lam *et al.* 2023b). Phytoremediation, which uses plants to remove contaminants, emerged in the late 1900s as a sustainable solution for remediating metal contamination (Tonelli *et al.* 2022; Kumar *et al.* 2022).

After decades of phytoremediation research development, publications continue rising steadily, evolving as a field. Much work examines phytoremediation of metal-contaminated soils (Peng *et al.* 2018). However, there is also increasing attention on applying phytoremediation to remediate metal-rich mine wastes (Peco *et al.* 2021; Muthusamy *et al.* 2022), though systematic examination of research hotspots and trends specifically for mine tailings phytoremediation is still lacking. While recent scientometric reviews (Li *et al*. 2019) have examined the broader phytoremediation domain, specific focus on mine tailings applications is missing. Our work provides an in-depth analysis targeting the applications of phytoremediation in this context, using techniques like keyword network mapping and co-citation cluster analysis.

With phytoremediation of mine tailings reaching a critical juncture for field-scale implementation and commercialization, summarizing the current status and emerging directions is imperative. Bibliometric analysis (Wang *et al.* 2023) applies mathematical and statistical techniques to quantitatively assess research themes' developmental patterns through published literature. This method helps researchers efficiently grasp a field's evolutionary trajectory, guiding subsequent efforts. Our study's purpose is a comprehensive, systematic review of the literature on phytoremediation of mine tailings using the CiteSpace scientometric tool (Chen 2016). We explore research hotspots and trends to provide an updated landscape for practitioners and researchers.

2. MATERIALS AND METHODS

2.1. Data Collection and Processing

The Web of Science (WoS) databases served as our core literature source given their comprehensive coverage, as demonstrated in prior studies evaluating scholarly databases for systematic reviews (Harzing and Alakangas 2016). Additionally, WoS databases rank as some of the most extensive and widely utilized in natural science research fields (Chadegani *et al.* 2013; Huang *et al.* 2022).

In particular, the following query string was used to retrieve the articles from the WoS collection:

("phytoextraction*" OR "phytostab*" OR "phytovolatili*" OR "accumulator plant*" OR "hyper*accumulator*" OR "phytomining" OR "metal* translocation" OR "bioconcentration factor*" OR "bioaccumulation factor*" OR "translocation factor") AND (("tailing*" OR "dump*") AND ("mine*" OR "mining*"))

The search retrieved 913 documents in total. Out of these, we only keep research articles (860), review articles (53), proceeding papers (24), and book chapters (1). Then, we remove 5 non-English research articles from the list. After applying these filters, we have 907 documents. These documents appeared in 219 different sources from 1999 to 2023. This set of documents had an h-index of 78 as indexed by Web of Science, indicating that 78 articles were cited at least 78 times each. The average citations per document was 32.52. The total number of citations was 26,716. These documents were authored by 1,059 institutions across 79 countries, with 3,055 total authors.

2.2. Scientometrics Analysis Methods and Tools

Scientometric techniques utilizing social network analysis can systematically study the relationships and interactions within scholarly communities by mapping connections among basic elements like publications and authors (Wasserman and Faust, 1994; Cross and Sasson, 2003). These techniques are capable of handling large datasets to identify critical knowledge gaps and emerging research themes within a field (Khan and Park 2012; Khan and Wood, 2015), providing guidance for new research. Specifically, citation analysis reveals the underlying knowledge structure and academic communities (Vidgen *et al.* 2007; Rauchfleisch and Schäfer, 2018).

Bibliometric analyses are often applied to elucidate research and innovation landscapes in developing domains (Janik *et al*. 2021). Trend identification through popularity-based or network-based approaches enhances understanding of a field over time (Choi and Lee 2011). Popularity-based approaches analyze changes in concepts (Ord *et al.* 2005), including mining keywords in patents to reveal technological opportunities (Yoon and Park, 2005). Network-based approaches examine citation or collaboration networks, highlighting emerging themes and structures (Galliers and Whitley 2007). For example, Khan and Wood (2015) utilized a social network approach to identify emerging information technology management themes. Our work takes a similar network-based approach to systematically review research hotspots and trends in the phytoremediation of mine tailings.

In this work, scientometric mapping of the knowledge domain was conducted using CiteSpace 6.2.R7 software to perform co-citation analysis and identify pivotal contributions, intellectual turning points, and research fronts (Chen 2016; Chen and Song 2019). Document co-citation network maps were generated using citation data from the Web of Science Core Collection to visualize the structure and evolution of research areas over time. Keywords co-occurrence network mapping was also carried out to elucidate conceptual subdomains and uncover disciplinary and temporal patterns. By tracking citation bursts, rising trends, and betweenness centrality metrics, CiteSpace enables revelation of impactful publications, seminal discoveries, and emerging innovations that have shaped and continue to advance the scientific landscape of phytoremediation for mine tailings (Chen 2016). The duality of retrospective understanding alongside prospective horizon scanning provided by these scientometric techniques offers both contextual and forward-looking intelligence to guide ongoing growth.

Finally, we note that throughout this work we rely on clustering analysis performed by CiteSpace, which automatically generates cluster labels using title terms extracted from highly cited documents within each group based on three statistical labeling approaches: Log-Likelihood Ratio (LLR), Latent Semantic Indexing (LSI), and Mutual Information (MI) tests (Chen and Song 2019). These methods identify salient phrases characteristic of each cluster by determining term frequency differences between the focal group and the overall background domain to capture the essence and themes portrayed in that segment of literature (Chen *et al*. 2010). Applying this multi-faceted labeling methodology provides descriptive, interpretable tags denoting the research focus central to each co-citation cluster community.

3. RESULTS

3.1. Characteristics of Publication Outputs

Our search retrieved 913 phytoremediation documents related to mine tailings, published from 1975-2023, with 1999 representing the earliest actual result. We show the number of publications and citations from 1999 to 2023 in Figure 1. The peak number of publications (84) and citations (3,580) occurred in 2021. Considering that publications from 2019 to 2023 account for roughly 40% of all documents regarding mine tailings phytoremediation, interest in this specific application has substantially intensified in the past five years. This highlights the field's emergent status, as nearly half of all relevant studies were published very recently, pointing to rapidly expanding scholarly attention.

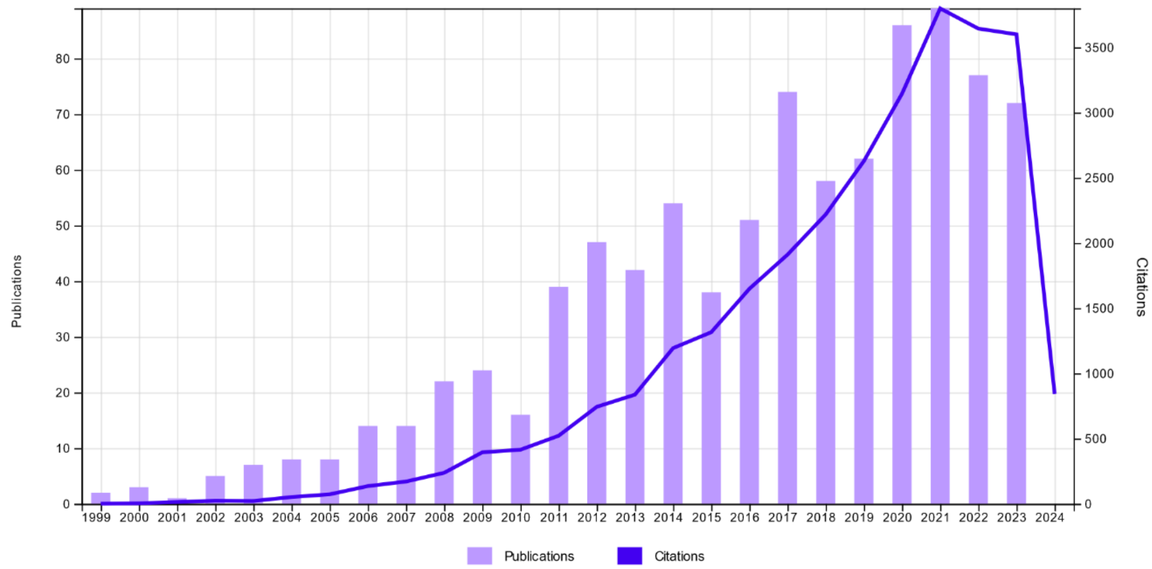

Figure 1. Publications and citations report generated using Web of Science (note that publications from 2024 are excluded).

3.2. Subject Categories Co-Occurrence Analysis

Web of Science assigns one or more subject categories to each indexed article. Analyzing article categorization reveals the topical breadth across a literature set. Among the retrieved mine tailings phytoremediation documents, Table 1 (provided in the supplementary materials) displays the 10 most frequently occurring Web of Science categories.

Conducting a co-occurrence examination of subject categories provides insights into the disciplinary breadth and interdisciplinarity underpinning a research domain (Xiang *et al.* 2017). Applying this technique to the mine tailings phytoremediation literature reveals 49 subject nodes interconnected by 63 links, as illustrated in Figure 2. This mapping portrays a multifaceted, wide-ranging knowledge structure, with contributions spanning soil sciences, environmental studies, ecology, plant sciences, microbiology, biotechnology, green engineering, and more. The subject category connectivity reflects the integration of principles and approaches across disciplines that enables the advancement of phytoremediation solutions for cleaning up metal-contaminated mine wastes.

In Figure 2 each circular node represents a unique Web of Science subject category assigned to the retrieved phytoremediation documents. Lines between nodes indicate publications with joint categorization, reflecting integration across disciplines. Node size corresponds to the frequency of the category. Line thickness shows the strength of co-categorization links between subject categories based on shared assignments. The tree-ring bands signify the number of co-occurrences arising in a given year.

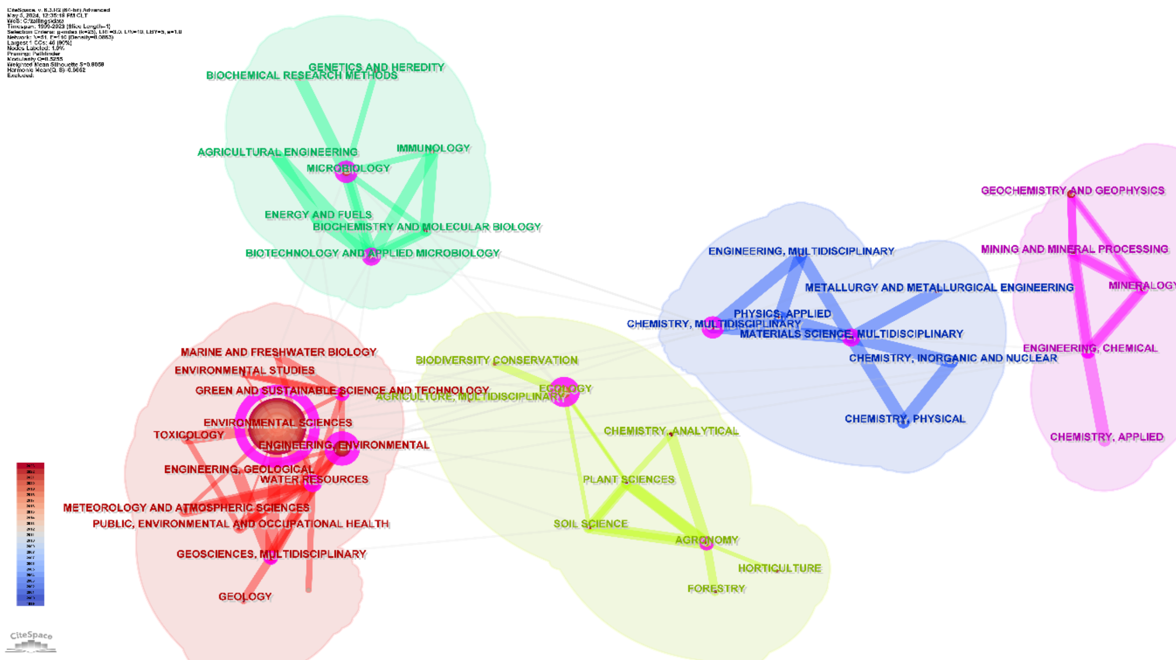

Figure 2. Co-occurrence network showing the connections between 51 subject category nodes with 110 links. A higher resolution version of this figure is included in the supplementary materials.

Based on the CiteSpace analysis of subject category co-occurrence in research on phytoremediation of mine tailings from 1999-2023, it is evident that environmental science is the most central and interconnected field (Wang *et al.* 2017). This aligns with the environmental focus of phytoremediation as a remediation strategy (Nedjimi 2021). Ecology also features prominently, highlighting the importance of understanding ecological dynamics in phytoremediation systems (Favas *et al*. 2014; Tosini *et al*. 2020; Li *et al*. 2014). The prominence of green and sustainable science/tech and geosciences shows the positioning of phytoremediation as a sustainable approach within the broader geoscience domain (Dong *et al.* 2021; Hunt *et al.* 2014). More specialized fields like microbiology, chemistry, soil science, and water resources reflect the multidisciplinary nature of phytoremediation research involving microbial processes (Wu *et al*. 2022), chemical interactions (Evangelou *et al*. 2007), soil matrices (Mench et al, 2010), and hydrological factors (Alvi *et al.* 2023). Overall, the landscape reveals the environmental, ecological, sustainability, and multidisciplinary dimensions that characterize the scientific foundations and ongoing research directions in phytoremediation of mine tailings (Paz-Ferreiro *et al.* 2018).

Overall, the scientific landscape captured by this co-occurrence graph highlights the multidisciplinary nature of phytoremediation research, with environmental sciences at the core along with contributions from engineering, soil, plant, aquatic, ecological, geochemical, toxicological, agronomic, and public health domains (Evangelou *et al.* 2007). This diversity of research fields has collectively advanced scientific knowledge on the environmental application and efficacy of phytoremediation for mine tailings remediation. The top 10 most important categories according to centrality criteria of the network are listed in Table 2 (provided in the supplementary materials).

Table 3 displays the top 15 subject categories demonstrating the most intense surges of activity over time based on our analysis of the phytoremediation literature. These categories exhibited spike increases in annual assignment numbers that qualify as strong bursts of rising attention within the field. The nodes listed showed pronounced expansions as research fronts receiving growing focus in the knowledge domain.

Table 3. The top 15 subject categories found through burst analysis from the co-occurrence network in the period from 1999 to 2023.

WoS Category	**First Appearance**	**Burst Strength**	**Burst Begin**	**Burst End**
Plant Sciences	1999	1.96	1999	2005
Agronomy	2000	1.68	2000	2006
Meteorology and Atmospheric Sciences	2005	2.66	2005	2013
Biotechnology and Applied Microbiology	2006	1.82	2006	2010
Agricultural Engineering	2006	1.79	2006	2010
Energy and Fuels	2006	1.69	2006	2010
Chemistry, Analytical	2007	2.99	2011	2013
Ecology	2008	4.77	2013	2017
Soil Science	2002	2.15	2017	2017
Geochemistry and Geophysics	2005	2.04	2017	2017
Toxicology	1999	2.69	2018	2019
Microbiology	2008	2.05	2019	2019
Chemistry, Multidisciplinary	2012	1.96	2020	2023
Green and Sustainable Science and Technology	2009	2.30	2022	2023
Public, Environmental and Occupational Health	2005	2.02	2022	2023

A category's co-occurrence frequency signifies output efficiency, indicating research activity within that specific domain. However, high betweenness centrality means publications in that category garner attention from the broader scientific community focused on the topic. Thus, categories with both high frequency and betweenness centrality represent pivotal areas driving knowledge growth. As shown in Tables 1 and 2, categories like environmental sciences, ecology, toxicology, soil science, and water resources constitute foundational pillars underlying mine tailings phytoremediation research based on their central positioning spanning otherwise disconnected scholarship. These categories' dual prominence for productivity and scientific influence qualify them as hotspots fueling advances in applying phytoremediation to remediate contaminated mine wastes.

Citation burst analysis provides insights into the evolving research priorities and growth areas in phytoremediation of mine tailings over the past two decades. In the early 2000s, there was a focus on soil interactions and amendments, as evidenced by the strong burst in plant science research from 2002-2006 (Shahandeh and Hossner 2002; Yun-Guo *et al.* 2006). This was followed by bursts in meteorology/atmospheric sciences in 2005-2013 (Romero *et al.* 2005; Meeinkuirt *et al.* 2013) and biotechnology/engineering/energy applications in 2006-2010 (Chiu *et al.* 2006; Juárez-Santillán *et* *al.* 2010), reflecting growing interests in climate factors and practical applications. In the early 2010s, attention shifted to analytical advances detected through the burst in analytical chemistry in 2011-2013 (Gupta *et al.* 2011; Yang *et al.* 2013) and ecological dynamics seen in the ecology burst of 2013-2017 (Marchiol *et al.* 2013; Honeker *et al.* 2017).

The mid-2010s brought greater multidisciplinary integration with the rise of multidisciplinary sciences in 2013-2016 (Ashraf *et al.* 2019; Li *et al.* 2016) along with emphases on geochemical processes evidenced by soil science, geoscience and geochemistry/geophysics bursts in 2016-2017 (Bech *et al.* 2016; Tapia *et al.* 2017). More recently in 2018-2019, research priorities centered on toxicity assessments and microbial mechanisms, indicated by bursts in toxicology and microbiology (Bacchetta *et al.,* 2018; Li *et al.* 2019).

In the last few years, the focus has been on sustainability and innovations, shown by chemistry and green/sustainable science bursts in 2020-2023 (Li *et al*. 2020; Sengupta *et al*. 2020; Toishimanov *et al*. 2023; Xie and Zyl 2023), while also considering human health aspects as seen in the public/environmental/occupational health burst in 2022-2023 (Martínez-Carlos *et al*. 2022; He *et al.* 2023). Altogether, these evolving research bursts have collectively advanced scientific knowledge and applications of phytoremediation for remediation of mine tailings over the past twenty years.

3.3. Keywords Co-Occurring Analysis

Keywords concisely encapsulate publications' core content and concepts (Zhang *et al.* 2016), making co-occurrence examination useful for identifying hot topics and trends. Our analysis extracted a network of 561 keyword nodes with 2,825 connections from the 913 phytoremediation articles.

Table 4 (provided in the supplementary materials) shows the 10 most frequent keywords in the co-occurrence network. "Heavy metals" ranked first at 420 assignments, followed by "mine tailings" (314) and "phytoremediation" (272) - logical given the research focus. The prominence of these terms reflects the literature emphasis on applying phytoremediation approaches to mitigate ecological risks from heavy metal pollution residing in mine waste deposits.

Table 5 (provided in the supplementary materials) displays the 10 keywords with top betweenness centrality scores, indicating terms bridging otherwise disconnected scholarship. Descriptors like "contaminated soils," "accumulation," and "copper" showed high betweenness centrality up to 0.13, meaning publications featuring these keywords link disparate research areas. Furthermore, terms including "growth," "zinc," and "phytoremediation" earned both high frequency and betweenness centrality, signifying distinct influence in connecting and guiding inquiries on applying phytoremediation in mine tailings. The dual prominence of these keywords qualifies them as research hotspots for enabling progress in this domain.

We identified 25 important keywords through burst analysis. We show the extracted keywords in Table 6. The burst analysis and the resulting keywords provide insight into the changing research foci over time in the literature on phytoremediation of mine tailings. In the early 2000s, there were bursts around specific plant species like *Pteris vittata* (2002-2007) (Visoottiviseth *et al.* 2002; Lou *et al.* 2007) and emerging interest in broader ecology like revegetation (2006-2009) (Li 2006; Carmona *et al*. 2009) and populations (2008-2012) (Xiaohai *et al.* 2008; Mohtadi *et al.* 2012). By the mid-

2000s, keywords like soils (2005-2011), reclamation (2006-2013), and zinc (2007-2011) burst onto the scene, indicating growing emphases on soil remediation (Yun-Guo *et al.* 2006), major contaminant metals (Conesa *et al.* 2007a, 2007b), and land reclamation (Fellet *et al.* 2011). In the early 2010s, there was increasing attention to specific species, such as Indian mustard and (2006-2013) *Thlaspi caerulescens* (2008-2015) (McGrath *et al.* 2006) and general issues such as metal accumulation (2009-2016) (Fellet *et al.* 2014). By the mid-2010s, tailings (2015-2016), plant growth (2016-2019) and native plants (2016-2019) burst, showing relevant application interests (Burges *et al.* 2016; Martínez-Martínez *et al.* 2019). In the late 2010s, integrative concepts like microbial community (2018-2020) and organic matter (2018-2020) rose rapidly, reflecting ecological and organic emphases (Valentín-Vargas *et al.* 2018; Yang *et al.* 2019; Robertson *et al.* 2020). More recently in the late 2010s-early 2020s, rising bursts included oxidative stress (2019-2023), drainage (2019-2023), phytomanagement (2020-2023), and organic amendments (2020-2023).

Table 6. List of the 25 keywords that had occurrence bursts from 1999–2023. The keywords are listed by the starting date of the citation burst. (*) The "L" keyword is related to botanical name conventions and appears on its own due to the limitations of the CiteSpace software.

Keywords	**First Appearance**	**Burst Strength**	**Burst Begin**	**Burst End**
Populations	2002	6.78	2002	2012
Pteris vittata	2002	3.74	2002	2007
Reclamation	2002	3.34	2002	2008
Copper	2005	4.66	2005	2010
Soils	2002	4.28	2005	2011
Degraded soils	2006	5.74	2006	2012
Indian mustard	2006	4.6	2006	2013
Revegetation	2000	4.26	2006	2009
Zinc	2000	7.01	2007	2011
Thlaspi caerulescens	2000	3.84	2008	2015
Metal accumulation	2009	5.27	2009	2016
Sp nov	2014	3.46	2014	2019
Cu	2009	3.41	2014	2015
Tailings	2009	4	2015	2016
Native plants	2011	3.53	2016	2019
Plant growth	2010	3.31	2016	2019
Microbial community	2014	4.41	2018	2020
Organic matter	2012	3.33	2018	2020
Oxidative stress	2016	3.82	2019	2023
Drainage	2019	3.63	2019	2023
L	2012	4.2	2020	2021
Mechanisms	2012	3.68	2020	2023
Phytomanagement	2016	3.34	2020	2023
Organic amendments	2017	3.3	2020	2023
Potentially toxic elements	2017	4.5	2021	2023

Conducting cluster analysis on the keyword co-occurrence network provides insights into the topical distribution and evolutionary trajectories of phytoremediation research of mine tailings. As visualized in Figures 3 and 4, this network segmented into 15 clusters automatically labeled by CiteSpace in the format “# + number + label” based on prominent keywords. Examining cluster emergence over time enables analysis of research focuses and themes gaining attention across the knowledge domain’s history. The labeled cluster network and timeline reveal how inquiries have expanded from initial plant-microbe-metal interactions and risk assessments to integrated ecological engineering systems and field testing.

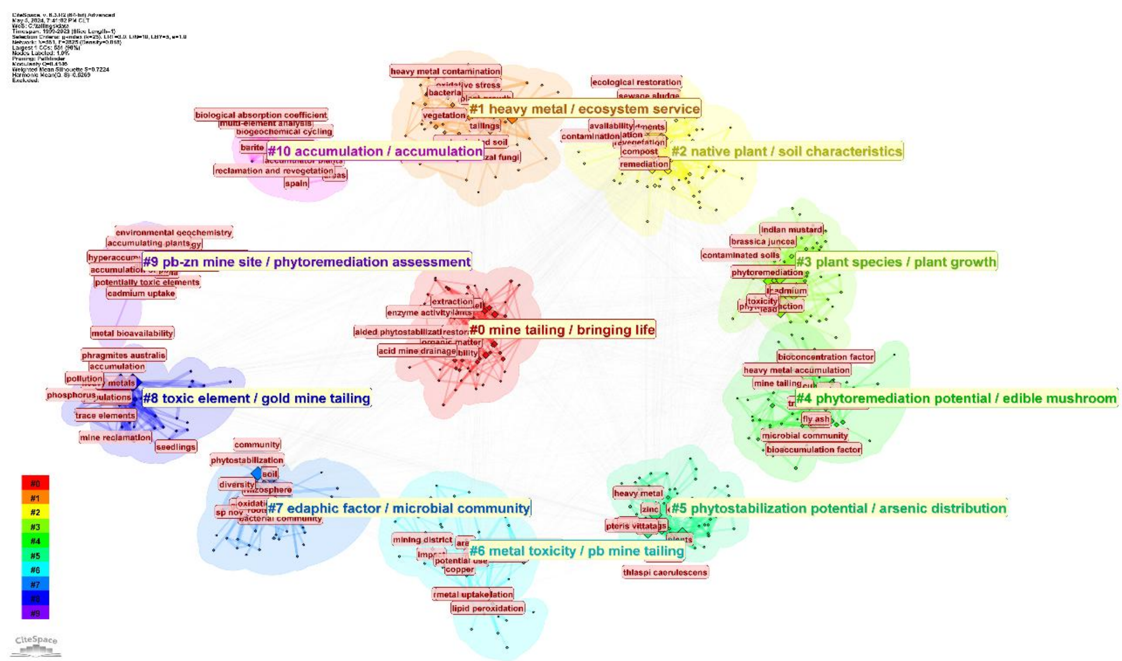

Figure 3. Circular network visualization of the 11 topical clusters identified in the keyword co-occurrence analysis, delineating the major research areas that have developed over time regarding phytoremediation approaches for mine tailings. A higher resolution version of this figure is included in the supplementary materials.

We first analyze the quality of the co-occurrence network's clustering. To measure this, we evaluated the evaluation metrics reported by CiteSpace, the mean Q value of 0.4146 and the mean S value of 0. 7224. These metrics indicate that the network is not easily separated into clusters due to its connections, but that the clusters found within them are consistent (Wu *et al*. 2020). Thus, we consider the clusters sufficiently robust for analyzing the keyword co-ocurrence network based on the 11 major topical clusters associated with phytoremediation of mine tailings.

The largest cluster (#0) in this bibliometric analysis focuses on the remediation of heavy metal contaminated soils, particularly in areas affected by mining activities (Mourinha *et al*. 2022; Zhang 2021). The cluster emphasizes the use of various soil amendments, such as organic matter and organic amendments, to reduce the mobility and bioavailability of heavy metals in the soil (Manyiwa and Ultra 2022; Luo *et al*. 2019). Additionally, the cluster explores the potential of native plants and aided phytostabilization techniques to revegetate and stabilize contaminated sites (Luo *et al.* 2019). The studies within this cluster aim to develop effective strategies for the restoration of polluted areas, with the ultimate goal of transforming these sites into recreational spaces (Parra *et al*. 2022).

The second largest cluster (#1) in this bibliometric analysis concentrates on the phytoremediation of metalliferous soils and mine tailings, with a focus on the use of grasses, legumes, and other plant species to facilitate the process (Kumar *et al*. 2017; Novo *et al.* 2013). The cluster investigates the distribution of heavy metals, such as arsenic, antimony, zinc (Zn), and cadmium (Cd), within plants growing in contaminated areas (Jana *et al.* 2012; Kumar *et al*. 2017). Additionally, the cluster explores the role of rhizosphere microbial communities and their survival strategies in oligotrophic and metal(loid) contaminated iron tailings areas (Geng *et al.* 2022). The studies within this cluster also highlight the potential of specific microbial species, such as Penicillium aculeatum and Trichoderma sp., to promote phytoremediation and bioenergy production in mine tailing soils (Babu *et al*. 2014).

The third largest cluster (#2) in this bibliometric analysis focuses on the soil characteristics and the use of various soil amendments, such as biochar, to stabilize heavy metals in multi-metal mine tailings (Huang *et al.* 2018; Ramirez-Zamora *et al*. 2022). The cluster investigates the potential of native plant species, such as *Cassia alata L.* and *Prosopis laevigata* (*Fabaceae*), coupled with biochar for assisted phytostabilization of mine tailings (Huang *et al.* 2018; Ramirez-Zamora *et al.* 2022). The studies within this cluster also quantify the heavy metal content in mining-affected soils and assess the bioaccumulation of these metals in native plant species (Nawab *et al.* 2015). Additionally, the cluster explores the influence of diverse fertilizer regimes on the phytoremediation potential of specific plant species, such as *Pteris vittata*, in abandoned nonferrous metallic mining sites (Wan *et al.* 2023). Initial studies for the phytostabilization of mine tailings from specific mining districts, such as the Cartagena-La Union mining district in Spain, are also included in this cluster (Conesa *et al.* 2007b).

The bibliometric analysis of the clusters beyond the top three reveals a wide range of research focused on phytoremediation and the interactions between plants, microbes, and contaminated soils in mining areas. The clusters investigate the potential of various plant species, including edible mushrooms, to accumulate heavy metals and stabilize contaminated soils (Rani *et al.* 2017; Narayanan *et al*. 2021; Rana and Maiti 2018). They also explore the distribution of arsenic and other heavy metals in soils and plants (Visoottiviseth *et al.* 2002; Xiaohai *et al.* 2008), as well as the use of organic amendments to promote plant growth and microbial community dynamics in mine tailings (Pardo *et al.* 2014; Valentin-Vargas *et al*. 2018; Liu *et al.* 2020). The bioaccumulation and toxicity of silver compounds (Ratte 1999) and the phytoremediation potential of transgenic plants (Bennett *et al.* 2003) are also investigated. Additionally, the clusters assess the contamination of soils by potentially toxic elements in mining areas (Timofeev *et al.* 2018) and the accumulation of elements in plants and soils around barite mining sites (Raghu 2001).

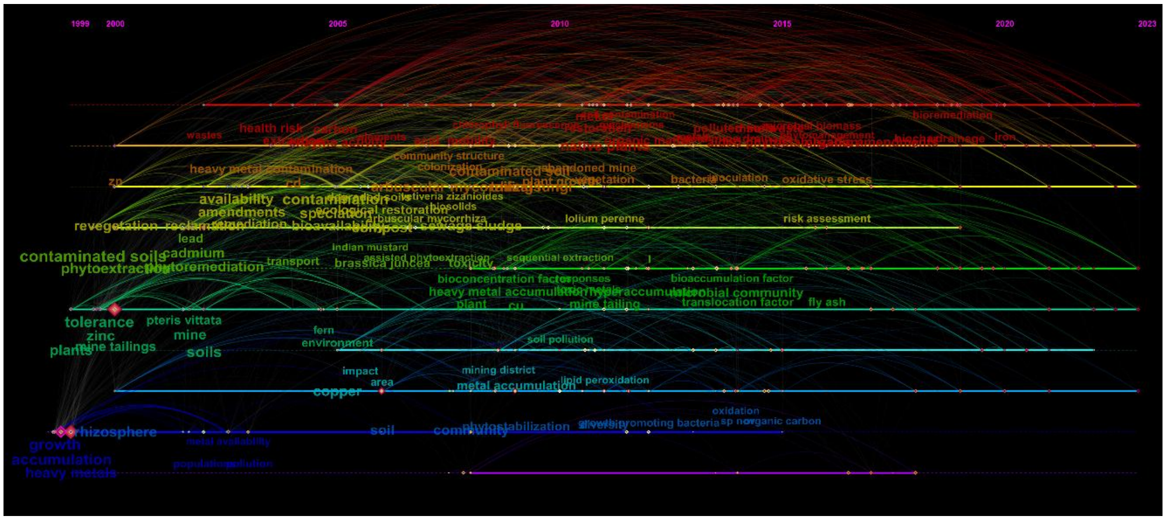

Figure 4. Timeline portrayal of the 18 keyword co-occurrence clusters' emergence chronologically over the last two decades. This temporal landscape reflects the evolution of research attention rising and falling across various thematic focuses related to applying phytoremediation solutions to metal-contaminated mining waste. A higher resolution version of this figure is included in the supplementary materials.

Analyzing the mean publication year and the clustering timeline, shown in Figure 4, provides perspective into the research progression across the clusters in the field of phytoremediation and mine tailings remediation. The earlier clusters (Cluster #8 and #10) from the early 2000s focus on the bioaccumulation and toxicity of heavy metals in plants and soils (Ratte 1999; Raghu 2001), while the mid-range clusters (Cluster #5 and #6) from 2008 to 2014 investigate the distribution of specific heavy metals and the use of organic amendments (Xiaohai *et al.* 2008; Pardo *et al.* 2014). The more recent clusters (Cluster #3, #4, and #7) from 2017 to 2020 explore the potential of various plant species, including edible mushrooms, and the role of microbial communities in the remediation process (Rani *et al.* 2017; Rana and Maiti 2018; Liu *et al.* 2020). This progression reflects a shift from basic understanding of metal accumulation in plants to more applied research on specific contaminants, amendments, and diverse plant species and microbial communities for enhanced phytoremediation.

3.4. Reference Co-Citation Overview

Scientific progress builds upon accumulating knowledge, with publications typically citing relevant prior work to contextualize contributions. Papers referenced concurrently signal intrinsic connections across studies, underlying scholarly structure. Co-citation analysis elucidates relationships and dynamics by examining citation overlaps revealing linkages between works.

Figure 9 shows the co-citation network associated with the mine tailings phytoremediation literature. This web of scholarly influences highlights seminal publications, research groups, and concepts catalyzing development of phytoremediation solutions for cleaning up toxic mining waste deposits. Examining citations traversing the genesis and evolution of this research area provides insights uncovering progress drivers across the knowledge domain.

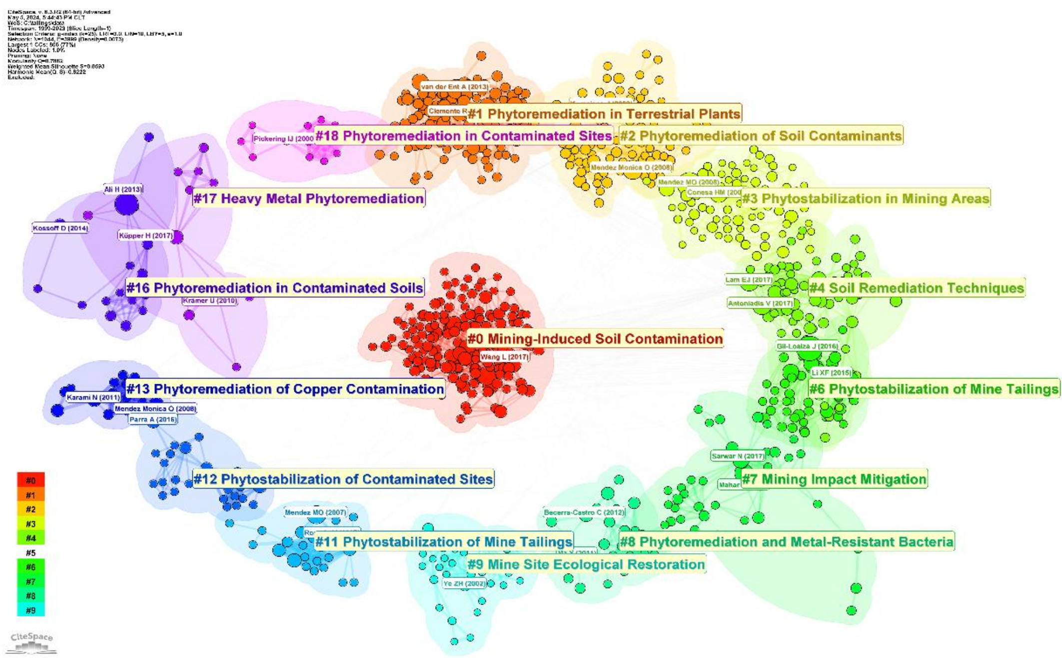

Figure 5. Network visualization of 1,032 reference nodes connected by 2,944 co-citation links across the phytoremediation literature, denoting connections and seminal influences. Node size reflects citation counts. Labels and tree rings indicate the identified clusters and their burstiness levels in driving emerging research fronts over time. This co-citation mapping reveals the intellectual base and impactful scholarship propelling phytoremediation approaches to remediate contaminants in mining-associated wastes.

This co-citation analysis reveals several highly cited works that have strongly influenced the research landscape around phytoremediation of mine tailings. We show the top cited papers in Table 7 (provided in the supplementary materials).

The most cited paper by Gil-Loaiza *et al.* (2016) focuses on assessing the plant growth promotion and metal tolerance mechanisms conferred by bacteria partnerships. In particular, this work highlights how optimizing plant-microbe interactions aids the effectiveness and feasibility of phytoremediation approaches. The second most cited paper by Wang *et al.* (2017) examines accumulation and phytostabilization of metals like cadmium using amendments and soil conditioners. This contributes useful evidence on managing contamination risks. Additional seminal works analyze the tolerance strategies, bioaccumulation behaviors, and toxicity impacts of heavy metals on different plant species and varieties. Screening and selection of native plants is critical for suitable match to local soil conditions and climate, as shown by prominent works from Mendez and Maier (2008a, 2008b), Ali *et al.* (2013), Li and Huang (2015), and van der Ent *et al.* (2015).

Beyond lab research, increasing attention towards field testing and demonstrations reflects a translation of phytoremediation science into practice, as evidenced by the cited paper from Yan *et al.* (2020). Bridging knowledge gaps between controlled trials and in situ contexts can accelerate adoption. The prominence of these works highlights active research foci on plant-bacteria partnerships, native species selection, metal bioavailability, and field application that shape the scientific discourse and knowledge base around effective, ecologically integrated approaches to remediate mine waste contamination.

3.5. Temporal Co-Citation Clusters Analysis

We show the evolution of the co-citation clusters in Figure 6. The earliest major cluster, #3, emerged in 2004 and focuses on phytoremediation of soil contaminants, particularly heavy metals like arsenic. Key themes in this foundational cluster include assessing phytoremediation techniques at various scales, their ecological impacts on native flora, and the limitations of these technologies in different environmental conditions (Mendez and Maier 2008a; Wong 2003). Cluster #9, which appeared in 2001, builds upon this by emphasizing mine site ecological restoration through vegetation growth, soil improvement, and heavy metal management. Organic amendments like manure compost are highlighted for their role in promoting plant growth on toxic substrates (Conesa *et al.* 2007c; Ye *et al.* 2000).

As the field progressed, new clusters emerged that expanded the scope and depth of phytoremediation research. Cluster #1, surfacing in 2012, delves into evaluating terrestrial plants for phytoremediation, comparing the effectiveness of grasses, shrubs, and trees (Parraga-Aguado *et al.* 2014; Pardo *et al.* 2014). Cluster #6, arising in 2016, explores the biological and ecological aspects of mine tailing rehabilitation, focusing on the impact of treatments on microbial community dynamics and the role of specific plants in soil recovery (Gil-Loaiza *et al.* 2016; Valentín-Vargas *et al.* 2018). Cluster #0, the most recent and largest cluster from 2018, addresses the contamination of soils due to mining activities, reviewing various remediation strategies and the associated environmental impacts and health risks (Burges *et al.* 2017; Wang *et al.* 2017). Throughout the timeline, there is a progression from fundamental research on plant-based remediation towards more holistic, ecosystem-oriented approaches that consider microbial communities, soil health, and long-term sustainability. The temporal analysis highlights the field's evolution towards increasingly interdisciplinary and applied research aimed at developing effective, site-specific phytoremediation solutions for mine tailings.

3.6. Reference Co-Citation Clusters Analysis

The analysis identified 19 potential clusters indexed from 0 to 18. However, we note that the CiteSpace analysis did not report multiple co-citation network clusters, specifically clusters #5, #10, and then #14 and #15, which were excluded from network diagrams and output data. The exclusions were caused by lack of connections with the main co-citation network. Thus, we end up with a total of 15 clusters. We now show a detailed analysis of each extracted cluster. Nevertheless, the co-citation network clustering achieved high reliability based on the evaluation metrics reported by CiteSpace: a mean Q value of 0.7882 and a mean S value of 0.8593. These metrics signify distinct, coherent clusters.

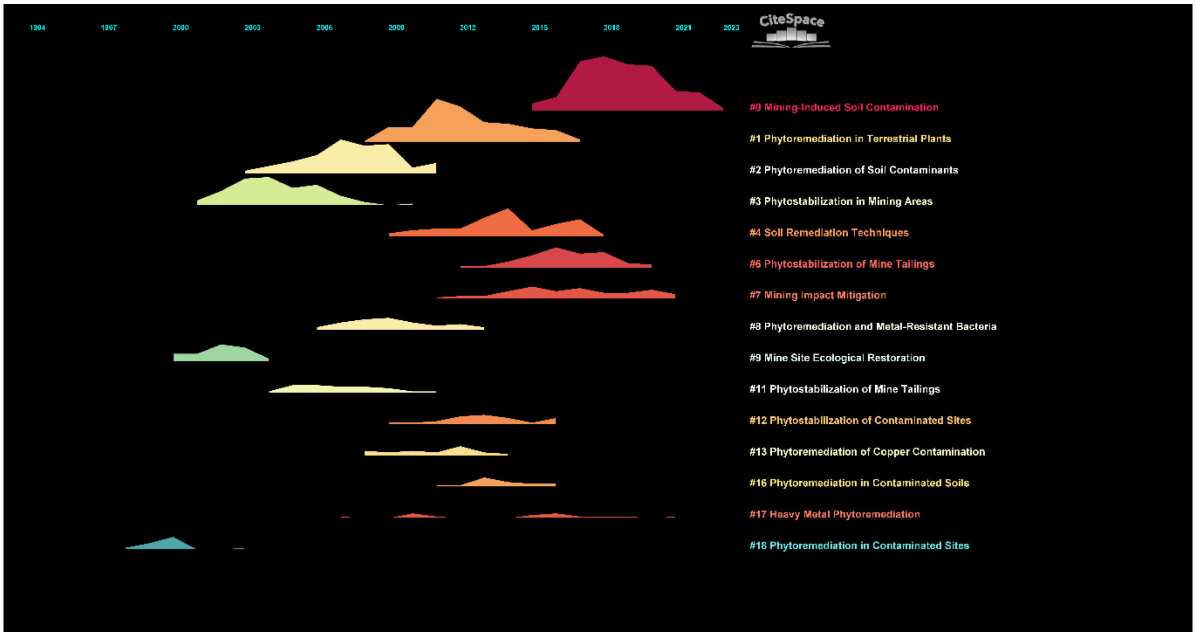

Figure 6. Timeline view visualizing the emergence sequence of the central 15 co-citation clusters over the past two decades, denoting evolutionary research fronts driving scholarly progress in applying phytoremediation solutions for metal-contaminated mine wastes.

The co-citation analysis reveals 15 major clusters focusing on various aspects of phytoremediation in mine tailings. Cluster #0, the largest and most recent, centers on mining-induced soil contamination, reviewing remediation strategies, environmental impacts, and health risks (Mourinha *et al*. 2022; Xie and Zil 2020). Cluster #1 evaluates the phytoremediation potential of terrestrial plants, comparing the effectiveness of grasses, shrubs, and trees (Buscaroli 2017; Parraga-Aguado *et al.* 2014). Cluster #2 investigates the fate of contaminants in soil-plant systems and the successes and limitations of phytoremediation technologies (Dickinson *et al.* 2009).

Cluster #3 focuses on phytostabilization techniques in mining areas, using plants and amendments to stabilize heavy metals (Alvarenga *et al.* 2008; Conesa *et al.* 2007a). Cluster #4 explores innovative soil remediation methods, such as organic and mineral amendments, to enhance plant growth and metal stabilization (Antoniadis *et al.* 2017; Lam *et al.* 2017). Cluster #6 delves into the biological and ecological aspects of mine tailing rehabilitation, examining microbial community dynamics and plant-microbe interactions (Honeker *et al.* 2019; Valentín-Vargas *et al.* 2018).

Cluster #7 addresses ecological strategies for mitigating mining impacts, focusing on phytoremediation and microbial rehabilitation in sub-Saharan Africa (Bruneel *et al.* 2019; Festin *et al.* 2019). Cluster #8 investigates the role of metal-resistant bacteria in enhancing phytoremediation efficiency and plant growth (Becerra-Castro *et al.* 2012; Ma *et al.* 2011). Cluster #9 emphasizes mine site ecological restoration through vegetation growth, soil improvement, and heavy metal management (Li 2006; Remon *et al.* 2005).

Clusters #11-18 focus on specific aspects of phytoremediation, such as the use of metallophytes and hyperaccumulators (Cluster #17), the effectiveness of transgenic plants (Cluster #18), and the application of phytoremediation techniques in various contaminated sites, including copper mines (Cluster #13) and semiarid environments (Cluster #11) (Barajas-Aceves *et al.* 2015; Bennett *et al.* 2003; Novo *et al.* 2013).

Overall, the clusters highlight the multidisciplinary nature of phytoremediation research in mine tailings, encompassing aspects of plant science, microbiology, ecology, and environmental engineering. The temporal evolution of the clusters reveals a progression from fundamental research on plant-based remediation to more holistic, ecosystem-oriented approaches that consider long-term sustainability and site-specific solutions.

3.7. Centrality Co-Citation Analysis

The centrality metric highlights publications serving integral bridging roles between research domains by virtue of their interstitial co-citation connections. Analyzing influential works with cross-cutting ties reveals key knowledge brokers spurring wider integration. Table 8 (provided in the supplementary materials) shows the top 10 references based on centrality. Here, Bech *et al.* (2012) demonstrates the highest betweenness, binding aspects of native plant screening with contamination characterization fundamentals. Vangronsveld *et al.* (2009) captures general lessons from field studies on phytoremediation of contaminated soils.

The top 10 references with the highest betweenness centrality play a crucial role in connecting various research clusters within the phytoremediation of mine tailings knowledge domain. Bech *et al.* (2012) bridges fundamental aspects of contamination characterization with the evaluation of plant species for phytoremediation. Mendez and Maier (2008a, 2008b) link foundational research on phytoremediation of soil contaminants with the specific application of phytostabilization techniques in mining areas. Clemente *et al.* (2008) and Vangronsveld *et al.* (2009) connect laboratory research with practical applications, promoting the integration of knowledge from different domains to develop effective and sustainable phytoremediation strategies. Ali *et al.* (2013) and Rascio and Navari-Izzo 2011 facilitate the exchange of knowledge on plant-based remediation strategies for heavy metal contamination, a primary concern in mine tailings. Lee *et al.* (2014) and Nedunuri *et al.* (2010) investigate the use of amendments and microorganisms to enhance phytoremediation efficiency, promoting the integration of knowledge on innovative approaches to optimize phytoremediation performance. These publications serve as bridge nodes, facilitating the flow of information and ideas between different subfields and research themes, ultimately contributing to the development of comprehensive, interdisciplinary strategies for the remediation of mine tailings.

3.8. Co-Citation Burst Analysis

To identify highly influential references and emerging trends, we conducted a reference burst detection analysis on the 2944-link reference co-citation network. Burst detection highlights articles that exhibited a sharp increase in citations over a period of time, indicating a rising popularity and impact in the field (Yu *et al.* 2023). Tables 9 and 10 present the top bursting references and research fronts over time based on spike surges in citation activity levels, signifying rapidly rising prominence within the literature of phytoremediation of mine tailings.

Table 9. Top 10 references with strong bursts listed by burst duration.

Reference	Year	Burst Strength	Burst Begin	Burst End
Mendez MO, 2008, ENVIRON HEALTH PERSP, V116, P278, DOI 10.1289/ehp.10608, DOI	2008	16.55	2008	2013
Wang L, 2017, CHEMOSPHERE, V184, P594, DOI 10.1016/j.chemosphere.2017.06.025, DOI	2017	14.22	2018	2023
van der Ent A, 2013, PLANT SOIL, V362, P319, DOI 10.1007/s11104-012-1287-3, DOI	2013	7.92	2013	2018
Lam EJ, 2017, J GEOCHEM EXPLOR, V182, P210, DOI 10.1016/j.gexplo.2017.06.015, DOI	2017	7.23	2018	2023
Antoniadis V, 2017, EARTH-SCI REV, V171, P621, DOI 10.1016/j.earscirev.2017.06.005, DOI	2017	6.87	2018	2023
Conesa HM, 2007, CHEMOSPHERE, V66, P38, DOI 10.1016/j.chemosphere.2006.05.041, DOI	2007	5.16	2007	2012
Pardo T, 2017, CHEMOSPHERE, V178, P556, DOI 10.1016/j.chemosphere.2017.03.079, DOI	2017	5.05	2018	2023
Fellet G, 2014, SCI TOTAL ENVIRON, V468, P598, DOI 10.1016/j.scitotenv.2013.08.072, DOI	2014	3.39	2014	2019
Gil-Loaiza J, 2016, SCI TOTAL ENVIRON, V565, P451, DOI 10.1016/j.scitotenv.2016.04.168, DOI	2016	14.44	2017	2021
Ali H, 2013, CHEMOSPHERE, V91, P869, DOI 10.1016/j.chemosphere.2013.01.075, DOI	2013	14.37	2014	2018

We start by performing a burst analysis based on the duration of the bursts. The results are shown in Table 9, the analysis identified highly influential seminal papers, reviews, and articles introducing new techniques in phytoremediation of mine tailings. The burst analysis of the reference co-citation network identified highly influential papers that significantly contributed to the advancement of phytoremediation research and its application in mine tailings management.

The article by Conesa *et al*. (2007b) focused on initial experiments of phytostabilization of tailings from the Cartagena-La Union mining district in Spain, while the 2008 review by Mendez and Maier (2008b) examined the emerging potential of phytoremediation in arid environments. A flurry of more recent review articles and papers have exhibited bursts, building upon these early works and extending the field's scope, including Antoniadis *et al.* (2017) review of trace element uptake mechanisms, Ali *et al.* (2013) coverage of major concepts and applications of heavy metal phytoremediation, van der Ent *et al.* (2013) analysis of hyperaccumulator plants, and Wang *et al.* (2017) comprehensive review of tailings phytoremediation techniques. Recent work also typified by Lam *et al.* (2017) focuses on evaluation of native plants for phytoremediation of copper mine tailings in Chile, illustrating a rising interest in regional field studies. Finally, highly cited recent articles such as Pardo *et al.* (2017), Gil-Loaiza *et al.* (2016), and Fellet *et al.* (2014) demonstrate the field's growing emphasis on novel approaches using halophytes, organic/inorganic amendments, and translating greenhouse results into field trials for real-world impact.

We continue the burst analysis focusing on burst strength rather than duration. The results are shown in Table 10. This burst analysis confirms the continued influence of early seminal works that established the potential of phytoremediation for mine tailings, such as Mendez and Maier (2008b) and Wong (2003) which focus on arid environments and metal-contaminated soils. Building upon these foundations, recent review articles exhibit strong citation bursts as researchers synthesize advancements, including the concepts and applications of heavy metal phytoremediation by Ali *et al.* (2013) and the examination of revegetation approaches by Yan et al (2020). Highly cited articles also demonstrate rising interest in translation of phytoremediation to field settings, typified by Gil-Loaiza *et al*. (2016) testing greenhouse methods in situ and Li *et al.* (2015) calling for a new paradigm shift incorporating real-world soil conditions. Both duration and frequency metrics point to sustained impact of Mendez and Maier works applying phytoremediation in semi-arid settings. Finally, the uptick in papers such as Mahar *et al.* (2016) reviewing challenges reflects wider recognition of knowledge gaps, helping direct research toward key issues of contamination severity, plant selectivity, and implementation obstacles needing resolution through interdisciplinary collaborations**.**

Table 10. Top 10 references with strong bursts listed by burst strength.

Reference	**Year**	**Burst Strength**	**Burst Begin**	**Burst End**
Mendez MO, 2008, ENVIRON HEALTH PERSP, V116, P278, DOI 10.1289/ehp.10608, DOI	2008	16.55	2008	2013
Gil-Loaiza J, 2016, SCI TOTAL ENVIRON, V565, P451, DOI 10.1016/j.scitotenv.2016.04.168, DOI	2016	14.44	2017	2021
Ali H, 2013, CHEMOSPHERE, V91, P869, DOI 10.1016/j.chemosphere.2013.01.075, DOI	2013	14.37	2014	2018
Wang L, 2017, CHEMOSPHERE, V184, P594, DOI 10.1016/j.chemosphere.2017.06.025, DOI	2017	14.22	2018	2023
Wong MH, 2003, CHEMOSPHERE, V50, P775, DOI 10.1016/S0045-6535(02)00232-1, DOI	2003	11.76	2005	2008
Mendez MO, 2008, REVIEWS ...... CE AND BIO/TECHNOLOGY, V7, P47, DOI	2008	10.87	2009	2013
Mendez MO, 2007, J ENVIRON QUAL, V36, P245, DOI 10.2134/jeq2006.0197, DOI	2007	10.34	2008	2012
Yan A, 2020, FRONT PLANT SCI, V11, P0, DOI 10.3389/fpls.2020.00359, DOI	2020	9.91	2021	2023
Mahar A, 2016, ECOTOX ENVIRON SAFE, V126, P111, DOI 10.1016/j.ecoenv.2015.12.023, DOI	2016	9.45	2018	2020
Li XF, 2015, CRIT REV ENV SCI TEC, V45, P813, DOI 10.1080/10643389.2014.921977, DOI	2015	8.9	2016	2020

3.9. Country, Institution and Author Productivity Analysis

To assess the global distribution of research on phytoremediation of mine tailings, we analyzed the productivity of countries based on the number of articles and their centrality in the collaboration network. Table 11 (provided in the supplementary materials) presents the top 10 most important countries ranked by betweenness centrality, which measures their role in connecting different research communities. China, Spain, and the United States emerged as the most central countries, with high betweenness centrality values and a large number of articles. These countries play a crucial role in bridging research collaborations and facilitating knowledge exchange across different regions. This can be attributed to their strong research funding, policy support, and international collaboration initiatives in the field of phytoremediation. These countries also have significant mining industries and face challenges related to mine tailings management, which may have contributed to their work on this topic.

Table 12 (provided in the supplementary materials) shows the top 10 most productive institutions based on the number of articles. Spanish institutions, particularly the Consejo Superior de Investigaciones Científicas (CSIC) and the Universidad Politécnica de Cartagena, lead the list, followed by the Chinese Academy of Sciences and French institutions such as INRAE and CNRS. The University of Arizona in the United States also ranks among the top institutions, along with the University of Queensland in Australia and the Pontificia Universidad Católica de Chile. The productivity of the top institutions and authors can be explained by their specialized research focus, access to funding, and extensive collaboration networks. For example, the CSIC in Spain has a dedicated research group focusing on phytoremediation of mine tailings, while the University of Arizona in the United States has a strong program in environmental science and engineering with a focus on mine reclamation.

The analysis of author productivity in Table 13 (provided in the supplementary materials) reveals that Raina M. Maier from the University of Arizona is the most prolific author in the field, with 27 articles, followed by Hector M. Conesa from the Universidad Politécnica de Cartagena and Jon Chorover from the University of Arizona. Other prominent authors include Rosanna Ginocchio from the Pontificia Universidad Católica de Chile, Angel Faz from the Universidad Politécnica de Cartagena, and Longbin Huang from the University of Queensland. Table 14 (provided in the supplementary materials) presents the top 10 authors ranked by their degree of collaboration, which measures the extent of their co-authorship network. Raina M. Maier, Rosanna Ginocchio, and Christopher W. N. Anderson emerge as the most collaborative authors, with extensive networks of co-authors. Other highly collaborative authors include Bin Liao, Longbin Huang, Michel Mench, and Jaco Vangronsveld.

These findings highlight the global nature of research on phytoremediation of mine tailings, with significant contributions from institutions and authors in China, Spain, the United States, France, Australia, and Chile. The high degree of collaboration among authors from different countries underscores the importance of international partnerships in advancing this field. The productivity and centrality of these countries and institutions reflect their expertise and leadership in developing and applying phytoremediation technologies for the sustainable management of mine tailings.

4. DISCUSSION

The scientometric analysis reveals a robust and rapidly expanding literature landscape focused on phytoremediation of mine tailings over the past two decades. Environmental sciences represent the core category underpinning this interdisciplinary research domain alongside contributing fields spanning ecology (Favas *et al.* 2014), engineering (Evangelou *et al.* 2007), soil science (Mench *et al.* 2010), and geosciences (Dong *et al.* 2021). The prominence of integrative themes like green technologies and emphasis on ecological aspects reflect the positioning of phytoremediation as an emerging eco-friendly pollution control strategy (Paz-Ferreiro *et al.* 2018).

Examination of research foci progression over decades traces an arc from early risk and contamination characterization to translational optimizations targeting field implementation and commercial adoption. Following baseline delineation of pollution issues, efforts shifted towards selection criteria and amendment approaches to improve plant growth and metal immobilization outcomes (Novo *et al.* 2013; Pardo *et al*. 2014). Rising leverage of plant-microbe partnerships provides bio-assisted, low impact solutions through ecological synergies (Wu *et al.* 2006; Honeker *et al.* 2017; Liu *et al*. 2020; He *et al.* 2023). Increased in situ testing also signals translation beyond controlled studies towards tangible land revitalization progress (Yan *et al.* 2020; Gil-Loaiza *et al.* 2016). Contemporary directions transcend isolated factors to recognize multidimensional plant-soil-microbe interactions influencing the feasibility and sustainability of phytotechnologies for mine waste reclamation (Evangelou *et al.* 2007; Wu *et al*. 2020).

Keyword network analysis further reveals dominant attention to central concepts like heavy metals, accumulation patterns, plant growth responses, and phytoremediation mechanisms (Ali *et al.* 2013; Antoniadis *et al.* 2017). Examining associated clusters spotlights efforts to expand ecological knowledge around accumulator species (van der Ent *et al.* 2013), explore emerging organic and microbial partnerships (Liu *et al*. 2020; He *et al.* 2023), characterize site variability (Mourinha *et al*. 2022), and assess field performance (Wang *et al.* 2020). Recent surges in toxicity (Mahar *et al.* 2016), bioconcentration (Lam *et al.* 2017), vegetation dynamics (Conesa *et al.* 2007a, 2007b, 2007c), and sustainability considerations (Karaca *et al.* 2018) denote progressive refinement of risk evaluations, species selection, and solution optimizations. Tracing research priorities chronologically illustrates the domain's evolution from early emphasis on native plants and field contexts (Mendez and Maier, 2008a, 2008b; Conesa *et al.* 2007a, 2007b, 2007c) towards integrated biological systems and practical implementation challenges needing resolution through collaborative innovation alliances to progress the state of the art (Mahar *et al.* 2016).

Highly cited works strongly shaping the knowledge base highlight seminal reviews analyzing hyperaccumulator mechanisms (van der Ent *et al.* 2013) and amendments modulating bioavailability in mine soils (Vangronsveld *et al.* 2009). Sustained citation bursts around arid environment phytoremediation (Mendez and Maier, 2008a, 2008b) and examinations of accumulation concepts (Wong 2003) confirm these works' enduring impacts. Reviews synthesizing technological advancements and examining constraints affecting adoption (Mahar *et al.* 2016) signal wider recognition of prevailing limitations requiring interdisciplinary perspectives.

Bridging publications with cross-disciplinary connections accelerate integrated progress by linking plant selection fundamentals (Bech *et al.* 2012) with bioavailability assessments (Adriano *et al.* 2004) and practical amendment approaches (Lee *et al*. 2014). These works facilitate translational knowledge exchanges to connect biological mechanisms, soil variables, and field management strategies (Vangronsveld *et al.* 2009; Mendez and Maier, 2008a, 2007b). Additional central publications foster transfers between conceptual groundings and implementation contexts to align controlled trials with real-world conditions (Acosta *et al.* 2018; Chaney *et al.* 2007). Such boundary-spanning articles enable wider unification of phenomena characterization, process optimizations, and translational confirmations to collectively advance the phytoremediation domain (Pardo *et al.* 2017).

The cluster landscape highlights prevalent pursuits evaluating plant-metal-microbe interactions in tailings environments (Deng and Cao 2017; Ma *et al.* 2011) alongside increasing in situ demonstrations and sustainability spotlights (Conesa *et al.* 2007a, 2007b, 2007c; Karaca *et al.* 2018). Improving comprehension of interkingdom relationships and field performance factors guides prescriptive matching of versatile native species and bioaugmentation inoculations to address multifaceted pollution legacies. Meanwhile practical confirmations focus attention on implementation variables affecting adoption (Wang *et al.* 2020). Ultimately a fusion of mechanistic insights and systems evaluations can potentiate responsible scaling of ecological engineering solutions balancing economic growth, environmental integrity and societal wellbeing (Wu *et al.* 2022; Gil-Loaiza *et al.* 2016).

Timeline mapping of cluster maturation denotes relatively early concentrations examining native species capacities and field trial contexts to establish domain foundations (Mendez and Maier, 2008a, 2008b; Conesa *et al*. 2007a, 2007b, 2007c). Subsequent diversification elevated analyses of variable conditions (Wang *et al.* 2020), incremental solutions (Novo *et al*. 2013), and chloride evaluations to refine real-world guidance (Acosta *et al.* 2018). Meanwhile the emergence of collaborative biological systems (Wu *et al*. 2022) and integrated technology assessments (Li *et al.* 2015) signifies rising sophistication and adoption readiness. Recent directions centered on regional demonstrations (Lam *et al.* 2017) and interdisciplinary perspectives (Paz-Ferreiro *et al.* 2018) and sustainability considerations (Karaca *et al.* 2018) reinforce a sharpening implementation focus during this growth stage as the field transitions from a purely scientific enterprise toward translational engineering applications (Gil-Loaiza *et al.* 2016).

In summary, scientometric mapping portrays an actively evolving knowledge landscape demonstrating rising sophistication and expanding interdisciplinarity of the phytoremediation of mine tailings. Contemporary research pursuits transcend isolated phenomena to increasingly recognize systemic interactions between plants, microbes and soils that shape phytotechnology outcomes in heterogenous field environments (Evangelou *et al.* 2007; Wang *et al.* 2017). Meanwhile high-level patterns reveal progressive transition from conceptual proofs to translational testing signifying a growth trajectory toward integrated, sustainable mine remediation solutions ready for responsible scaling through ecological engineering partnerships (Gil-Loaiza *et al.* 2016). Continued analysis of knowledge structures and temporal developments (Choi and Lee 2011) can further strengthen dynamic insights to guide ongoing research as phytoremediation of mine tailings evolves from a fundamental science toward an established engineering practice.

4.1. Limitations

While this scientometric analysis provides a broad overview of research progress in phytoremediation of mine tailings, certain limitations persist. The single database literature search risks excluding relevant work disseminated through non-indexed channels (Falagas *et al.* 2008). Moreover, regional, linguistic and access biases may persist despite efforts to maximize diversity. Additionally, manual screening and snowballing approaches were not feasible given resource constraints, so further content filtering based on abstract reviews was not conducted.

The level of insight enabled by network mapping is balanced against visualization complexity challenges that can obscure specialized sub-domains containing key nuances (Shiffrin & Börner, 2004). Algorithmic clustering aiming for topic coherence also carries limitations, as some heterogeneity and less representative peripheral themes inevitably emerge from any data-driven automation (Velmurugan & Radhakrishnan, 2015). Chronological smoothing further relies on publication dates which fail to convey outlier timeline deviations potentially signifying pivotal milestones.

5. CONCLUSIONS

Using scientometric analysis techniques through CiteSpace this work summarized key publication characteristics, interdisciplinarity traits, research hotspots, and knowledge progressions within the evolving domain of phytoremediation of mine tailings over the past two decades. Systematic literature mapping enables convenient examination of the landscape for new entrants while identifying salient patterns in how sub-areas grow. Tracking metrics over time including production volume, citations, keywords, and reference co-citations elucidates the rapid expansion and sustained development of this emerging field.

Phytoremediation research at the nexus of environmental and ecological sciences now integrates collaborations with soil science, plant biology, microbiology, and sustainability fields as progress shifts from conceptual proofs toward field applications. Our scientometric analysis elucidates an actively expanding phytoremediation research domain demonstrating heightened collaboration across environmental, ecological and biological disciplines over the past two decades. Category co-occurrence and burst analyses denote rising connections with engineering disciplines and green technology as biotechnology solutions mature from scientific novelty toward societal norms.

Finally, several promising directions for future research emerge from the current findings on phytoremediation of mine tailings. Further examination of plant genotype traits conferring metal resistance through bioinformatics approaches, such as genome-wide association studies. Additionally, meta-transcriptomic characterization of functional microbiome dynamics within plant rhizospheres and endospheres can elucidate key microbial mediators of plant tolerance and biogeochemical cycling amendments modulating bioavailability. On the applied side, future work should evaluate integrated ecological engineering systems incorporating vegetative caps, amendments, and microbial augmentation through expanded field demonstrations across soil and climatic contexts. Over the long term, geospatial scenario modeling and impact forecasting of scaled implementation would support strategic translation and policy planning for mine land revitalization programs. Overall, these complementary pursuits across bioinformatic, microbiological, technological and planning spheres could accelerate sustainable solutions to complex mining pollution legacies.

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Author contributions

Brian F. Keith: Conception/Research design/Data acquisition/Data analysis and interpretation/Manuscript draft. Elizabeth J. Lam: Conception/Research design/Data acquisition/ Data analysis and interpretation/Manuscript draft. Ítalo L. Montofré: Data analysis and interpretation/Manuscript draft. Vicente Zetola: Research design/Acquisition of data/Drafting the manuscript. Jaume Bech: Conception/Data analysis and interpretation/Manuscript draft. All the authors approved the final version to be submitted.

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Conflicts of interest

The authors have no conflicts of interest relevant to the content of this article.

Animal research

This study did not include animal research. Therefore, no consent was needed for the participation or publication of animal data, and ethical considerations for consent forms do not apply.

Consent to Participate

This study did not include human research. Therefore, no consent was needed for the participation or publication of human data, and ethical considerations for consent forms do not apply.

Consent to Publish

All authors agreed on publishing the manuscript, respecting the current sequence of authors listed. Likewise, all authors agreed on designating Elizabeth J. Lam as the corresponding author.

Supporting Information

Table 1. Top 10 most frequent WoS categories in the retrieved documents.

Rank	Frequency	WoS Category
1	610	ENVIRONMENTAL SCIENCES
2	99	ENGINEERING, ENVIRONMENTAL
3	86	SOIL SCIENCE
4	75	WATER RESOURCES
5	65	PLANT SCIENCES
6	49	ECOLOGY
7	44	GEOCHEMISTRY AND GEOPHYSICS
8	42	TOXICOLOGY
9	39	AGRONOMY
10	31	PUBLIC, ENVIRONMENTAL AND OCCUPATIONAL HEALTH

Table 2. The top 10 subject categories extracted from the co-occurrence network based on betweenness centrality, a measure reflecting connections bridging across the broader network.

Rank	Centrality	Node Name
1	0.83	ENVIRONMENTAL SCIENCES
2	0.43	CHEMISTRY, MULTIDISCIPLINARY
3	0.21	MATERIALS SCIENCE, MULTIDISCIPLINARY
4	0.21	BIOLOGY
5	0.16	BIOTECHNOLOGY AND APPLIED MICROBIOLOGY
6	0.15	MICROBIOLOGY
7	0.14	AGRONOMY
8	0.12	ENGINEERING, CHEMICAL
9	0.11	ENGINEERING, ENVIRONMENTAL
10	0.11	SOIL SCIENCE

Table 4. The 10 most common keywords assigned across the set of 913 phytoremediation publications, ranked by frequency of articles featuring the term.

Rank	Frequency	Keyword
1	420	Heavy metals
2	314	Mine tailings
3	272	Phytoremediation
4	244	Accumulation
5	155	Plants
6	149	Soil
7	142	Cadmium
8	141	Phytostabilization
9	121	Phytoextraction
10	118	Growth

Table 5. The top 10 keywords in the co-occurrence network by centrality across the set of 913 phytoremediation publications.

Rank	**Centrality**	**Keyword**
1	0.13	Contaminated soils
2	0.12	Accumulation
3	0.11	Copper
4	0.10	Growth
5	0.09	Zinc
6	0.08	Phytoremediation
7	0.07	Soils
8	0.07	Soil
9	0.07	Heavy metal
10	0.07	Trace elements

Table 7. The top 10 references from the co-citation network ranked by total citations. The frequent appearance of these works highlights the foundational ideas, methods, and discoveries.

Citation Counts	**Reference**	**DOI**
40	Gil-Loaiza J, 2016, SCI TOTAL ENVIRON, V565, P451	10.1016/j.scitotenv.2016.04.168
39	Wang L, 2017, CHEMOSPHERE, V184, P594	10.1016/j.chemosphere.2017.06.025
37	Mendez MO, 2008, ENVIRON HEALTH PERSP, V116, P278	10.1289/ehp.10608
35	Ali H, 2013, CHEMOSPHERE, V91, P869	10.1016/j.chemosphere.2013.01.075
24	Li XF, 2015, CRIT REV ENV SCI TEC, V45, P813	10.1080/10643389.2014.921977
23	Mendez MO, 2008, REVIEWS IN ENVIRONMENTAL SCIENCE AND BIO/TECHNOLOGY, V7, P47	10.1007/s11157-007-9125-4
22	van der Ent A, 2013, PLANT SOIL, V362, P319	10.1007/s11104-012-1287-3
21	Mendez MO, 2007, J ENVIRON QUAL, V36, P245	10.2134/jeq2006.0197
20	Lam EJ, 2017, J GEOCHEM EXPLOR, V182, P210	10.1016/j.gexplo.2017.06.015
20	Yan A, 2020, FRONT PLANT SCI, V11, P0	10.3389/fpls.2020.00359

Table 8. The top 10 most important references found in the co-citation network, ranked by betweenness centrality.

Centrality	Reference	DOI
0.17	Bech J, 2012, J GEOCHEM EXPLOR, V113, P106	10.1016/j.gexplo.2011.04.007
0.16	Mendez Monica O, 2008, REVIEWS IN ENVIRONMENTAL SCIENCE AND BIO/TECHNOLOGY, V7, P47	10.1007/s11157-007-9125-4
0.15	Mendez MO, 2008, ENVIRON HEALTH PERSP, V116, P278	10.1289/ehp.10608
0.12	Clemente R, 2008, ENVIRON POLLUT, V155, P254	10.1016/j.envpol.2007.11.024
0.11	Vangronsveld J, 2009, ENVIRON SCI POLLUT R, V16, P765	10.1007/s11356-009-0213-6
0.11	Ali H, 2013, CHEMOSPHERE, V91, P869	10.1016/j.chemosphere.2013.01.075
0.11	Lee SH, 2014, J ENVIRON MANAGE, V139, P15	10.1016/j.jenvman.2014.02.019
0.10	Mertens J, 2004, SCI TOTAL ENVIRON, V326, P209	10.1016/j.scitotenv.2003.12.010
0.10	Rascio N, 2011, PLANT SCI, V180, P169	10.1016/j.plantsci.2010.08.016
0.10	Nedunuri KV, 2010, INT J PHYTOREMEDIAT, V12, P200	10.1080/15226510903213928

Table 11. The top 10 most important countries found in the extracted articles, ranked by betweenness centrality.

Articles	Centrality	Year	Countries
201	0.32	2003	Peoples Republic of China
145	0.26	2003	Spain
88	0.32	2000	United States
59	0.03	2001	India
54	0.22	2000	France
51	0.05	2006	Mexico
47	0.19	2007	Australia
41	0.03	2008	Chile
40	0.04	2008	Italy
36	0.07	2004	Poland

Table 12. The top 10 most important countries found in the extracted articles, ranked by number of articles.

Articles	Institutions
52	Consejo Superior de Investigaciones Cientificas (CSIC)
46	Universidad Politecnica de Cartagena
43	Chinese Academy of Sciences
27	INRAE
26	Centre National de la Recherche Scientifique (CNRS)
26	University of Arizona
23	Sun Yat Sen University
22	University of Queensland
21	CSIC - Centro de Edafologia y Biologia Aplicada del Segura (CEBAS)
17	Pontificia Universidad Catolica de Chile

Table 13. The top 10 authors found in the extracted article, ranked by number of articles.

Articles	Author Name
27	Maier, Raina M
23	Conesa, Hector M
18	Chorover, Jon
14	Ginocchio, Rosanna
14	Faz, Angel
13	Huang, Longbin
13	Root, Robert A
12	Parraga-Aguado, Isabel
10	Zornoza, Raul
9	Yu, Haiying

Table 14. The top 10 authors found in the extracted article, ranked by degree of collaboration.

Degree of Collaboration	Author Name
53	Maier, Raina M
43	Ginocchio, Rosanna
38	Anderson, Christopher W N
34	Liao, Bin
33	Huang, Longbin
31	Mench, Michel
30	Vangronsveld, Jaco
29	Carrillo-gonzalez, Rogelio
29	Li, Jin-tian
29	Cleyet-marel, Jean-Claude