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Review

The Progress, Hotspots, and Prospects of Restoration of Abandoned Mines: A Scientometric Analysis

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Abstract

With the increasing awareness of ecological and environmental protection and sustainable development, the restoration of abandoned mines has garnered more attention. However, there has been limited systematic analysis of the overall research status of the restoration of abandoned mines to date. A systematic approach employing CiteSpace was utilized to analyze and visualize knowledge maps of 393 research articles on the restoration of abandoned mines. The findings reveal exponential growth in publication numbers following an initial budding stage, reaching a peak in 2020. China emerges as a central player in collaboration efforts. The top three highly cited journals are Ecological Engineering, Science of the Total Environment, and Restoration Ecology. In the keyword co-occurrence analysis, "ecological restoration" emerges as the most frequently occurring keyword, highlighting its significance as a primary research focus. Keyword co-occurrence clustering analysis reveals eight clusters, including restoration methods, soil restoration, hydrology, land-use change, acid mine drainage, soil nutrients, vegetation succession, earthworms, and abandoned mine areas, representing primary research topics. This study provides a comprehensive analysis of the current research progress and development trends in abandoned mine restoration, facilitating an understanding of key focus areas in the field.

Keywords: abandoned mines, scientometric, restoration, CiteSpace, knowledge mapping

Introduction

The exploitation of mineral resources has driven rapid global economic growth and significantly contributed to the advancement of human society [1]. However, mining activities worldwide, particularly illegal and excessive mining, have led to extensive pollution and destruction, resulting in various ecological and environmental problems [2]. Abandoned mines represent a distinct category of land where ecological environments have been severely compromised following the cessation of mineral extraction. The removal of vegetation cover and the accumulation of abandoned minerals during mining have caused ecological imbalances, including

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soil compaction, groundwater contamination, soil acidification, reduced water retention capacity, loss of ecological diversity, and secondary geological hazards such as collapses, landslides, and debris flows [3-9]. These issues pose significant threats to the lives and property of local residents. It is evident that the environmental problems associated with abandoned mines have emerged as a major concern for sustainable development.

Currently, many developed countries, especially major mining nations, have conducted extensive research on the ecological restoration of abandoned mines [10-13]. The United States, as one of the first countries to undertake ecological mining restoration, enacted laws and regulations related to the ecological environment of mines in 26 states in the 1930s. Through legislative requirements, the country mandated measures to restore the ecological environment of abandoned mine areas damaged during mining operations [14]. The enactment of national laws and successful research on advanced ecological restoration techniques have led to significant outcomes in ecological restoration projects for most abandoned mines in the United States. Stehouwer et al. [15] focused on local mining ecological restoration areas, demonstrating that enhancing microbial community diversity in soil can rapidly regenerate ecological vegetation in mining areas. Jenisem et al. [16] implemented an integrated restoration model for abandoned mining sites, transforming them into various landscape green spaces, including leisure parks and cultural landscapes. Australia is recognized as a leader in advanced and successful ecological restoration techniques for abandoned mine areas, with research emphasizing the technical aspects of restoring the ecological environment [10]. Moreover, advanced instruments and equipment are employed for continuous long-term monitoring of ecological restoration efforts. For example, Bakr et al. [17] utilized GIS remote sensing monitoring technology to track changes in vegetation and survival rates during ecological restoration in mining areas. Interdisciplinary collaboration is a prominent feature of mine ecological restoration in Australia, as demonstrated by Marroquin-Castillo et al. [18], who improved soil substrates through human intervention while concurrently developing eco-industries such as rural tourism and organic agriculture. As a signatory to the 2016 Paris Agreement, China has implemented the double carbon strategy aiming to achieve carbon peak by 2030 and carbon neutrality by 2060. Concurrently, China has enacted its most stringent ecological policies to date, aligning with the "Lucid waters and lush mountains are invaluable assets" strategy. The restoration of abandoned mines has emerged as a vital component of China's ecological and environmental protection efforts [1, 19]. Many Chinese scholars have conducted extensive research on the restoration and utilization of abandoned mines. Li et al. [20] studied natural recovery of metal mines, assessed ecosystem multifunctionality, and examined the influence of soil microbial and fungal populations on ecosystem multifunctionality by utilizing advanced sequencing techniques. Wang et al. [21] employed oil-metagenome sequencing to analyze the evolving shifts in soil microbial metabolic potential functions during the transition from biological soil crusts to mixed broadleaf-conifer forests in a representative Pb-Zn mine. Their study provided genetic insights into biogeochemical cycling mechanisms and underscored critical factors.

It is apparent that scholarly attention to the restoration of abandoned mines has become widespread [22-26]. The employment of scientometric analysis emerges as a crucial approach for delineating the evolution of specific research themes [27], allowing a more nuanced understanding of trends and emerging interests. Through statistical methodologies, scientometric analysis affords a macroscopic examination of the published literature. To date, certain review articles have offered insights into the ecological restoration of abandoned mines, alongside the geotechnical engineering reinforcement of abandoned mines [1-3, 28-30]. However, these reviews are confined to a limited selection of articles within specific research niches and lack an evaluation of this field from a bibliometric point of view on the restoration of abandoned mines research. Employing the scientometric analysis holds the promise of delivering a thorough examination, unveiling core points, and guiding prospective research directions on the subject. Furthermore, the scientometric approach mitigates distortion and bias arising from subjective database retrieval by extensively surveying foundational literature in the research domain.

This study employed scientometric analysis to conduct a statistical examination of the literature, generating knowledge maps and quantifying the global research advancements on the restoration of abandoned mines from 1996 to 2024. Diverse criteria were utilized for literature analysis, and a data-driven scientometric investigation, informed by a review of current literature, was executed to identify factors for future research in the domain. The schematic representation of literature data collection and scientometric analysis is illustrated in Fig. 1.

Materials and Methods

Data Acquiring and Processing

The initiation of scientometric work necessitates the use of suitable databases and established search criteria. The Web of Science database (WOS) serves as a pivotal resource extensively utilized in academic research [31]. Renowned for its comprehensiveness and multidisciplinary nature, it is highly valuable for literature reviews and scientometric analyses spanning diverse fields. Furthermore, the WOS offers notable strengths, such as reference tracing and citation documentation. This capability is particularly vital

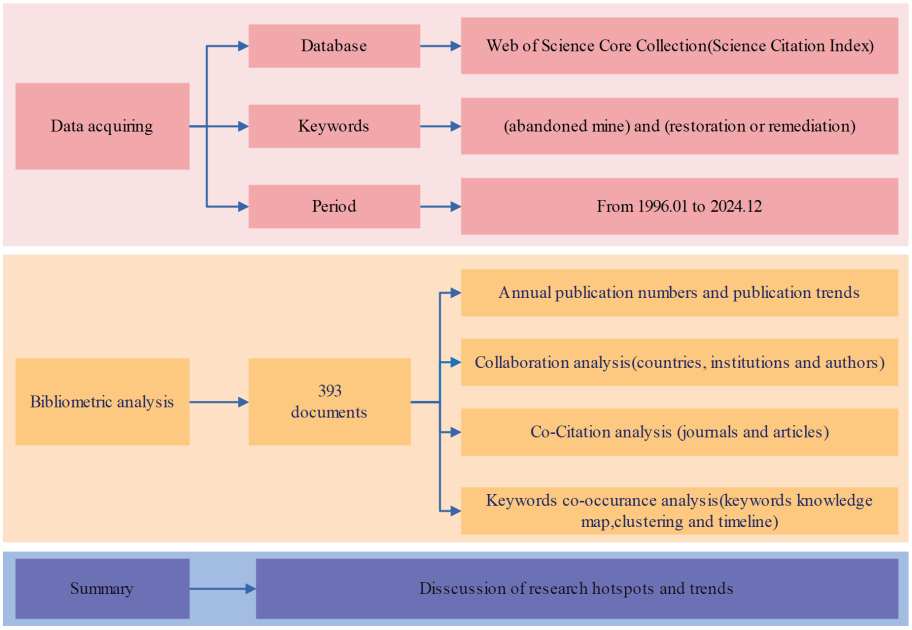

Fig. 1. The schematic representation of document collection and scientometric analysis.

for examining research outputs in specific fields or areas [32]. In this research, literature retrieval was executed through the utilization of the WOS database, with a specific focus on the Science Citation Index (SCI), a repository of substantial global impact within the domain of scientific and engineering research.

The WOS database provides a useful and inclusive search function, enabling the application of logical factors such as "AND," "OR", and "NOT" to achieve searches. In this study, the topic-based search was performed using the formula: TS = ("abandoned mine") AND TS = ("restoration" OR " remediation"). Only articles categorized as research articles were chosen and recorded as documents. Recognizing that the year 2025 is ongoing, the search period ranged from January 1st, 1996, to December 31st, 2024. After the retrieval process, the gathered articles were manually reviewed to eliminate irrelevant documents. Finally, a total of 393 pertinent articles were identified. To facilitate knowledge mapping analysis, information from both "All Records" and "References" for the 393 articles was exported from the database in plain-text format. This compiled dataset, comprising 393 articles, formed the database for knowledge mapping analysis.

Data Acquiring and Processing

The knowledge mapping method, a scientometric approach utilizing graphical analysis, focuses on information and knowledge in research. Its primary objective is to unveil the developmental trajectory and structural relationships inherent in scientific knowledge. By leveraging this method, researchers can rapidly grasp an academic field's overview and research progress from diverse perspectives, facilitating a thorough exploration of academic interactions and the evolution of knowledge units or clusters [27]. In this research, scientometric analysis based on the knowledge mapping method was executed using CiteSpace (version 6.2.R5), a software developed by Prof. Meichao Chen and built on the Java programming language [33-36]. CiteSpace employs co-citation analysis to visualize and examine the literature data under consideration, providing visualization features such as cooperative networks, literature linkage, and clustering of research focal points. It defines and depicts research focal points by evaluating the intensity of connections among nodes pertaining to particular scientific queries. The literature dataset, compiled from the reputable WOS database, was uploaded into the CiteSpace software. Visualization parameters were adjusted to achieve the study's scientific measurement goals through the generation of knowledge maps. The analysis covered four perspectives in this research: characteristics of publication output, collaboration analysis, co-occurrence analysis of keywords, and clustering analysis, resulting in a comprehensive knowledge map.

During the analysis process conducted by CiteSpace to generate specific knowledge maps, betweenness centrality is a commonly used and valuable metric for quantitatively assessing the significance of nodes within these knowledge maps. Betweenness centrality measures how often a node serves as a core among other nodes in the network, indicating its importance. Nodes exhibiting high betweenness centrality values (exceeding 0.1) indicate their pivotal role in the network, denoting them as crucial points [37]. Introduced by Freeman et al. [38, 39], the betweenness centrality (Ci) is computed using the Equation (1):

$$C_i = \sum \frac{n_{jk}^i}{g_{jk}} \quad (1)$$

Where g_{jk} is the number of shortest paths from node j to node k, and n_{jk}^i is the number of shortest paths traversing through node i. Betweenness centrality stands out as a pivotal factor in network analysis, with nodes having centrality values exceeding 0.1 being considered significant and holding crucial roles in the network. Greater centrality values signify the increased influence of the nodes within the research domain.

Results

Scientometric Analysis of Publication Trends

The fluctuation in the volume of publications within the domain of the restoration of abandoned mines serves as a crucial gauge of advancements in this field of study. Analyzing the allocation of publication quantities across the years provides researchers with a holistic comprehension of the developmental phases in this domain, allowing for predictions about future trends [40]. Fig. 2 depicts the annual and cumulative numbers of articles analyzed by the dataset.

As delineated in Fig. 2, the inaugural research article on the restoration of abandoned mines was published in 1996. The annual publication count has consistently increased, signifying a growing research emphasis in this domain. Analyzing the publication trend in the realm of the restoration of abandoned mines reveals three discernible stages based on growth pattern (gradual linear growth, rapid linear growth, and exponential growth), which were subsequently fitted and presented in Fig. 2.

Sprouting Stage (1996-2014): This phase witnessed the publication of 107 articles, constituting a mere 27.33% of the overall publications. This indicates that research on the restoration of abandoned mines was in its infancy, receiving limited scholarly attention. However, there was a modest rise in publications from 2 in 1996 to 14 in 2014, suggesting a gradual growth in interest over time.

Stable Development Stage (2015-2019): Characterized by a notable increase in the number of articles relative to the previous stage, this period maintained an average annual publication count of approximately 20. It reflects a sustained scholarly emphasis on restoration issues during the construction and operation phases of abandoned mines.

Rapid Development Stage (2020-2024): In 2020, the number of articles published (34) increased by 1.7 times compared with 2019 (20), illustrating a robust growth trajectory and reaching its zenith in 2023 (41). During this stage, 186 articles were published, encompassing 47.33% of the total. This surge indicates that the restoration of abandoned mines has attracted considerable interest among scholars, entering a phase of rapid expansion. It is noteworthy that at the 75th United Nations General Assembly in 2020, Chinese President Xi Jinping solemnly pledged that China aims to peak its carbon dioxide emissions before 2030 and strive for carbon neutrality by 2060 [19]. In line with his strategic directive, China has embarked on numerous restoration and management projects in mining environments, especially in abandoned mines. This has presented substantial opportunities and challenges for the in-depth exploration of issues

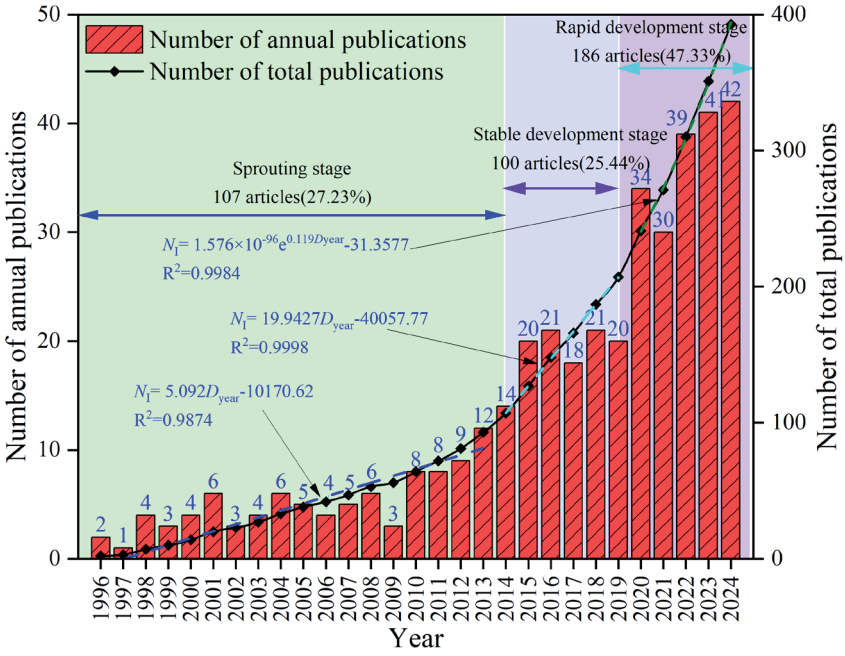

Fig. 2. The number of publications on the restoration of abandoned mines per year from 1996 to 2024.

related to the restoration of abandoned mines [41-44]. Examining the publication counts of scholars from various countries in the literature from 2020 to 2024 (rapid development stage) revealed that Chinese scholars contributed 67.47% of the research in the field of restoration of abandoned mines, contributing significantly to the substantial increase in publications since 2020.

Scientometric Analysis of Collaborative Networks

As globalization advances, academic exchanges and collaborations have become increasingly common. Understanding collaborative relationships is crucial for comprehending the current research landscape. Collaborative networks at national, institutional, and author levels offer insights into collaborative relationships on the macro, meso, and micro scales, respectively.

Collaboration Networks Among Countries

Utilizing the software, the knowledge map of the co-occurrence network illustrating international collaboration in the restoration of abandoned mines (Fig. 3) was analyzed and depicted. In the knowledge maps, each node symbolizes a country, with its size proportional to the country's publication count. The colored rings signify different years, and the thickness of the rings indicates the publication volume for each year. Connections between nodes depict co-authorship relationships among countries, with line thickness and darkness reflecting collaboration strength [45, 46]. Table 1 showcases the top ten

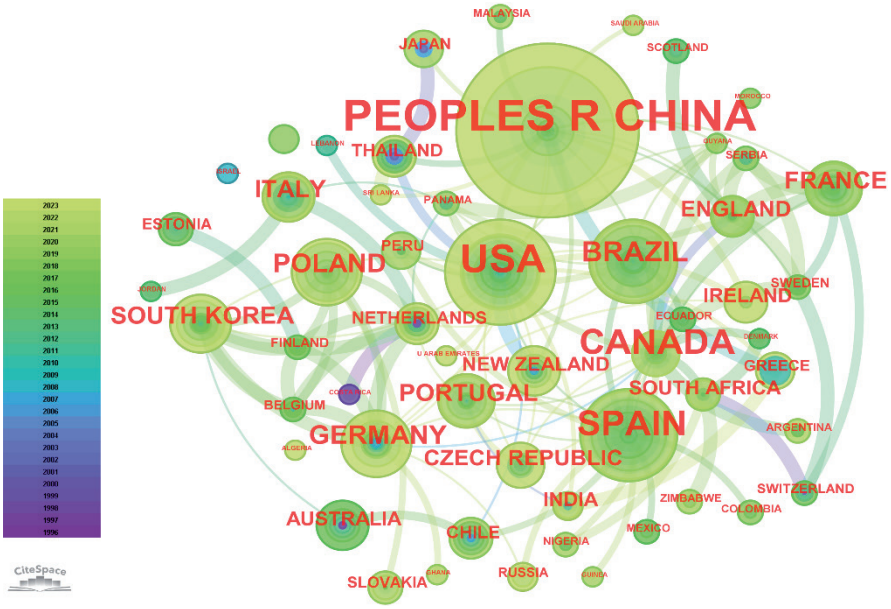

Fig. 3. Knowledge map of collaboration networks among countries on the restoration of abandoned mines from 1996 to 2024.

Table 1. Top ten countries on the restoration of abandoned mines from 1996 to 2024 by number of publications.

No.	Country	Publication Number	Centrality	First Publication Year
1	China	104	0.33	1998
2	The United States	60	0.39	1997
3	Spain	35	0.30	2010
4	Canada	34	0.38	1996
5	Brazil	20	0.04	2004
6	Germany	14	0.31	2001
7	Poland	14	0.06	2014
8	Italy	12	0.06	2004
9	Portugal	11	0.03	2004
10	South Korea	11	0.05	2008

influential countries in this research domain, along with their inaugural publication year and betweenness centrality.

Research on the restoration of abandoned mines has involved a total of 59 countries/regions. The top ten contributors in terms of overall publications include China, the United States, Spain, Canada, Brazil, Germany, Poland, Italy, Portugal, and South Korea. Among these, five countries exhibit significant betweenness centrality (>0.1): China, the United States, Spain, Canada, and Germany, ranked from high to low. China, leading in publications, has contributed 104 articles spanning from 1996 to 2024, constituting 29.63% of the global total. This exceeds the second-ranked United States by 1.73 times and the third-ranked Spain by 2.97 times. With a betweenness centrality of 0.33, China occupies an unequivocal core position in the global restoration of abandoned mines domain. However, an examination of the network knowledge map reveals that despite China's central status, its links with other countries are relatively sparse, suggesting a lower international collaboration level.

Analyzing global collaboration networks provides insights into the distribution of research output and collaborative ties among countries in the domain. This understanding serves as a basis for exploring international collaboration dynamics further and for identifying opportunities for future research cooperation in this field.

Collaboration Networks Among Institutions

Fig. 4 illustrates the institutional collaboration network knowledge map in the domain of the restoration of abandoned mines. Table 2 provides a summary of the top ten research institutions, including their publication contributions, inaugural publication year, and betweenness centrality.

It's evident that more than 100 research institutions are actively involved in this field, with a significant concentration in China. Notably, the Chinese Academy of Sciences (18 articles), China University of Mining and Technology (10 articles), Nanjing Forestry University (8 articles), Yunnan University (7 articles), China University of Geosciences (6 articles), and China Agricultural University (6 articles) are all based in China. The Chinese Academy of Sciences stands out with the highest publication output and betweenness centrality, contributing 1.20 times more articles and 1.64 times more centrality than the second-ranked institution, Laval University, accounting for 5.13% of the total publications. Its significant betweenness centrality of 0.18 underscores its pivotal role in research on the restoration of abandoned mines. As China's foremost academic institution in natural sciences and its top advisory body for science and technology, it comprises 11 branch academies, over 100 research institutes, and more than 130 national-level key laboratories and engineering centers, making substantial contributions to the restoration of abandoned mines. Additionally, institutions such as Laval University (with a centrality of 0.11), the Czech Academy of Sciences (with a centrality of 0.10), and Centre National de la Recherche Scientifique (with a centrality of 0.11) also exhibit noteworthy betweenness centrality values (>0.1), indicative of their integral roles in advancing research on the restoration and utilization of abandoned mines.

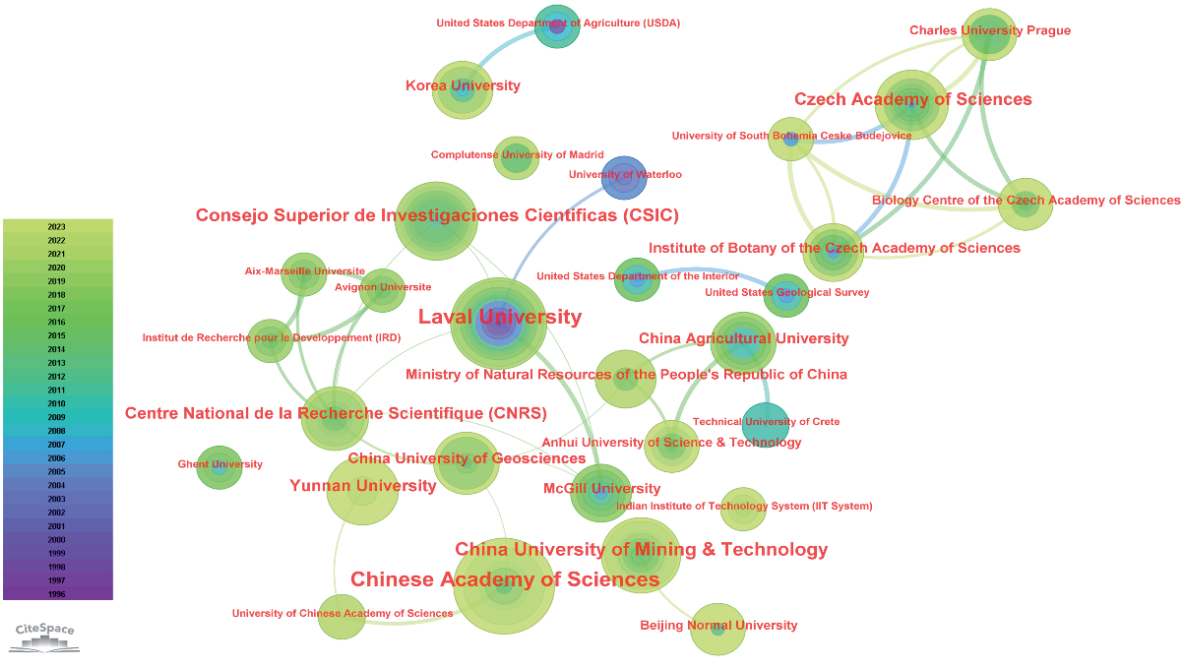

Fig. 4. Knowledge map of collaboration networks among institutions on the restoration of abandoned mines from 1996 to 2024.

Table 2. Top ten research institutions on the restoration of abandoned mines from 1996 to 2024 by number of publications.

No.	Research Institutions	Publication	Centrality	First Publication Year
1	Chinese Academy of Sciences	18	0.18	1998
2	Laval University	15	0.11	1996
3	China University of Mining and Technology	10	0.08	2015
4	Consejo Superior de Investigaciones Cientificas (CSIC)	9	0.09	2011
5	Czech Academy of Sciences	8	0.10	2006
6	Nanjing Forestry University	8	0.03	2017
7	Yunnan University	7	0.01	2022
8	Centre National de la Recherche Scientifique (CNRS)	7	0.12	2016
9	China University of Geosciences	6	0.09	2014
10	China Agricultural University	6	0.02	2010

Collaboration Networks Among Authors

The authors' collaboration network knowledge map in the field of the restoration of abandoned mines is depicted in Fig. 5.

The knowledge map elucidates the network's efficacy in delineating author collaboration relationships and identifying influential authors. Among the leading contributors, Claude Lavoie holds the highest position with 8 articles, followed by Jinchi Zhang with 6 articles, Zhaohui Jia with 6, Chong Li with 6, and Xin Liu with 6 articles. These authors occupy central roles within the collaborative network, underscoring extensive collaboration. However, the overall authorship pattern exhibits a dispersed structure and several small clusters. None of the authors have a betweenness centrality value exceeding 0.1, indicating limited collaboration among different research teams. Therefore, enhancing collaborative exchanges between teams is imperative to mitigate this dispersion.

Scientometric Analysis of Co-Citation Literature

When a third paper cites two other papers, a co-citation relationship is established [47]. This concept extends to co-citation analysis of journals. The analysis involves two aspects: literature and journal co-citation analysis. In the visual representation, lines signify a connection between 2 articles when they are cited by another article, thereby establishing a co-citation relationship between them. In the figure of the co-citation network knowledge map, nodes reflect the citation time, with node size directly proportional to the frequency of citations [48, 49].

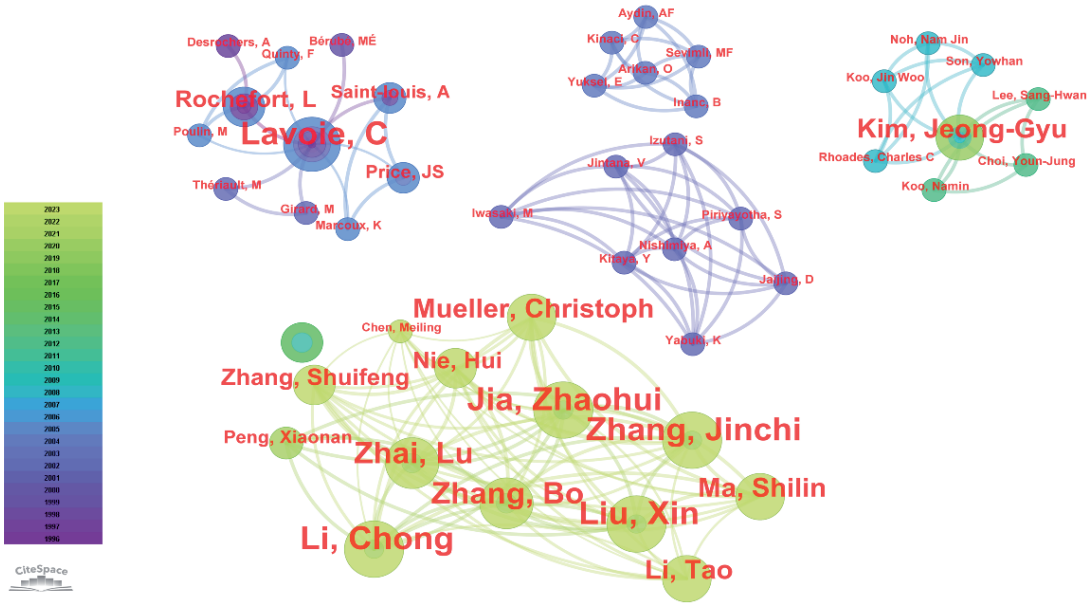

Fig. 5. Knowledge map of collaboration networks among authors on the restoration of abandoned mines from 1996 to 2024.

Co-Citation Journals

Fig. 6 depicts the co-cited journal network knowledge map in the domain of the restoration of abandoned mines. Table 3 provides the top ten journals in terms of host country, citation frequency in the field of abandoned mines, and impact factors for 2023.

The size of each node in the graph corresponds to the citation frequency in the domain for a given journal, as evident in both the figure and the table [50, 51]. It's widely recognized that journals with higher citation frequencies possess greater authority and influence within the domain. Notably, Ecological Engineering, Science of the Total Environment, Restoration Ecology, and Chemosphere are positioned centrally within the knowledge map, indicative of their cohesive connections with other journals. These four journals boast high impact factors in 2023, standing at 3.8, 9.8, 3.2, and 8.8, respectively. They are considered leading journals in the realm of environmental restoration and have been referenced 167, 165, 134, and 120 times in abandoned mine restoration research.

In addition to the aforementioned journals, the top ten cited journals include Environmental Pollution, Environmental Science and Pollution Research, Journal of Environmental Management, Plant and Soil, Soil Biology and Biochemistry, and Journal of Applied Ecology. These journals have all garnered more than 80 citations in the database, underscoring their significant roles in the field of abandoned mine restoration. Notably, the top four journals have published no fewer than 20 articles each, indicating their esteemed importance among scholars in the domain. Remarkably, the three most frequently cited journals also rank among the top four in terms of publication count, signifying their substantial contributions to the restoration of abandoned mines research.

Co-Citation Articles on Restoration of Abandoned Mines

Scrutinizing literature citations allows for the identification of notable articles within the domain of abandoned mine restoration, with citation count serving as a crucial metric of a paper's research significance [27, 46]. The co-cited article network knowledge map in the realm of the restoration of abandoned mines is depicted in Fig. 7. Here, each node refers to a publication, identified by the primary author's name and the year of publication, while the node's size is proportional to the number of citations. Larger nodes signify articles that have garnered multiple citations, indicative of their widespread recognition among scholars and their pivotal role in the field. It's pertinent to acknowledge that the citation counts shown were derived from the retrieval database of the 393 relevant articles, thus differing from the total citation counts in the Web of Science.

The examination of the top ten articles and a thorough literature review indicate that current studies on abandoned mine restoration primarily focus on two key aspects. Firstly, there is a notable emphasis on the ecological restoration of abandoned mines through chemical, microbial, phytoremediation, and landscape remediation methods [52-59].

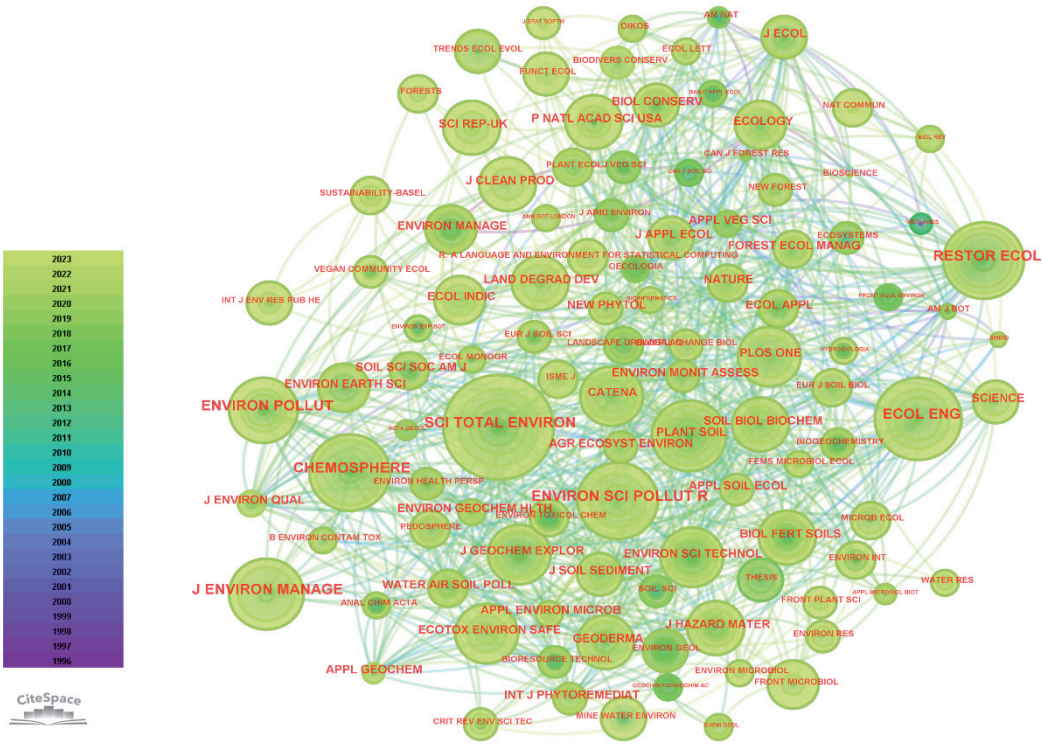

Fig. 6. Knowledge map of co-citation journals on the restoration of abandoned mines from 1996 to 2024.

Table 3. Top ten journals on the restoration of abandoned mines from 1996 to 2024 by number of citations.

No.	Journal	Host Country	Cited Times	Impact Factor (2023)
1	Ecological Engineering	Netherlands	167	3.8
2	Science of The Total Environment	Netherlands	165	9.8
3	Restoration Ecology	The United States	134	3.2
4	Chemosphere	England	120	8.8
5	Environment pollution	England	96	8.9
6	Environmental Science and Pollution Research	Germany	95	5.8
7	Journal of Environmental Management	England	92	8.7
8	Plant and Soil	Netherlands	86	4.9
9	Soil Biology and Biochemistry	England	84	9.7
10	Journal of Applied Ecology	England	80	5.7

For instance, Chong Li et al. [60] enhanced the substrate with a mineral-solubilizing microbial strain in *Robinia pseudoacacia* and Lespedeza bicolor pots to simulate external-soil spray seeding for restoration. Monitoring from December 2018 to November 2019, they observed improved root growth in *Robinia pseudoacacia* and strengthened soil shear strength and root tensile properties with the added strain. Although *Robinia pseudoacacia* grew faster, its root-reinforced soil had lower shear strength than that of Lespedeza bicolor. These findings suggest that adding a microbial strain to the substrate enhances soil strength and plant effects, enriching data on the effects of mineral-solubilizing microbial strains on plant roots and guiding future research on external-soil spray seeding. MacDonald et al. [61] recommended enhancing the Forestry Reclamation Approach by: (1) mimicking natural landforms and creating diverse topographies; (2) using overburden and organic materials to aid soil development and tree growth; (3) aligning landform, soil, and tree species for diverse ecosystems; (4) optimizing tree planting methods and species diversity; (5) promoting natural regeneration; (6) rapidly restoring native understory vegetation; and (7) managing succession selectively. Effective ecosystem restoration requires flexible regulations accommodating diverse goals and outcomes. Secondly, there is a growing emphasis on the utilization of underground spaces in abandoned mines for geotechnical engineering restoration [19, 41, 43, 44, 62]. In comparison to the former, this endeavor entails

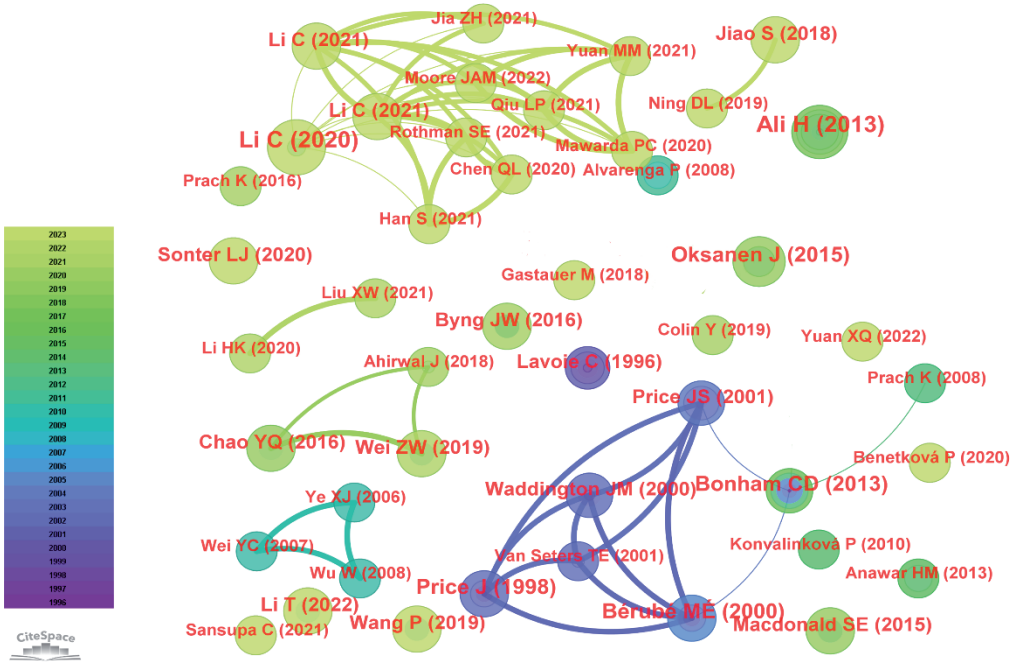

Fig. 7. Knowledge map of co-citation articles on the restoration of abandoned mines from 1996 to 2024.

smaller-scale interventions. However, with the advent of the dual-carbon strategy, researchers are increasingly recognizing the importance of leveraging underground spaces within abandoned mines.

Scientometric Analysis of Co-Occurrence Keywords

Keyword co-occurrence analysis delves into the central themes of a field, shedding light on prevalent research topics [63]. This method employs four approaches: keyword co-occurrence networks, keyword citation burst detection, keyword clustering, and keyword timelines of clusters. Besides the keyword citation burst in the form of a table, keywords are depicted as nodes, their size indicative of frequency, with larger nodes denoting higher occurrence. The node color denotes the publication year. Connecting lines between keywords signify co-occurrence, their thickness and color denoting strength and time, respectively.

Keyword Co-Occurrence and Citation Bursts

Fig. 8 presents the knowledge map of the keyword co-occurrence network on the restoration of abandoned mines.

In the network analysis, the size of keywords correlates with their frequency of occurrence. Notable keywords with frequencies exceeding 20 include "ecological restoration" (frequency = 53), "heavy metals" (frequency = 40), "vegetation" (frequency = 38), "soil" (frequency = 35), "mine tailings" (frequency = 32), "revegetation" (frequency = 26), "acid mine drainage" (frequency = 25), "biodiversity" (frequency = 23), "microbial community" (frequency = 21), and "phytoremediation" (frequency = 20). It's noteworthy that "restoration" and "abandoned mine" have been omitted, as they don't align with current research trends. Additionally, "tailings" and "mine tailings" were merged as they represent the same concept. Combining knowledge maps reveals interconnected relationships among keywords, with some having higher research frequencies, though the overall trend appears diverse. Notably, "ecological restoration" has dominated research in the past two decades, proving crucial for environmental and ecological health by enabling proactive measures. Keywords like "heavy metals", "microbial community", and "phytoremediation" are prominent, highlighting the study of ecological restoration of abandoned mines. These methods are mainly divided into the following four parts: chemical means, microbial means, phytoremediation means, and landscape remediation means. Understanding these ecological methods is foundational for abandoned mine restoration [64-69].

Keyword co-occurrence analysis offers insight into hot topics, but lacks the ability to analyze development trends, unlike keyword citation bursts, which indicate sudden increases in keyword usage, reflecting dynamic research issues [33, 49, 70]. Table 4 outlines the top ten keyword citation bursts over the past two decades.

Table 4 illustrates that these bursting keywords encapsulate the core aspects of abandoned mine research, covering subjects, topics, objectives, methodologies, and research scopes. Scholars predominantly focus on these keywords for discourse and exploration within the realm of abandoned mine restoration. These frequently occurring keywords first emerged in 1996, experiencing a concentrated burst period from 2001 to the present. Sequentially, the bursting keyword years are: natural revegetation, drainage, reclamation, contaminated soils, mine tailings, spontaneous succession, remediation, ecological restoration, water, and ecosystem services.

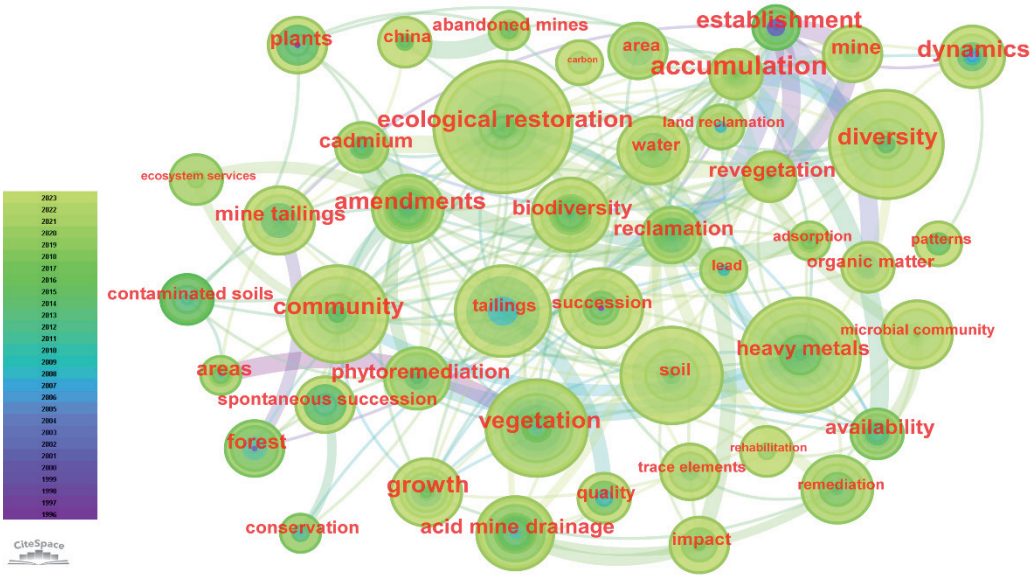

Fig. 8. Knowledge map of co-citation articles on the restoration of abandoned mines from 1996 to 2024.

Table 4. Top ten keywords with the strongest citation bursts during 1996-2024.

Keywords	Year	Strength	Begin	End	1996-2024
Natural revegetation	2001	2.70	2001	2008	
drainage	2001	2.48	2002	2005	
reclamation	2002	3.33	2011	2017	
Contaminated soils	2012	3.19	2012	2017	
Mine tailings	2001	2.42	2012	2017	
Spontaneous Succession	2013	2.69	2013	2015	
Remediation	2015	2.42	2015	2024	
Ecological restoration	2008	4.33	2017	2021	
water	2018	3.09	2018	2019	
Ecosystem services	2020	3.18	2020	2021	

* Hyphens indicate years ranging from 1996 to 2024, with grey hyphens denoting burst years, while black hyphens signify that the keyword was not a hotspot in the respective year.

This indicates that restoration methods dealing with abandoned mines and their risks tend to concentrate on natural revegetation, water, and soil, especially in mine tailings and coal-related contexts. Measures in these studies primarily address ecological restoration and involve chemical, microbial, phytoremediation, and landscape remediation methods to ensure stability and mitigate associated risks. As Chinese President Xi Jinping solemnly pledged at the 75th United Nations General Assembly in 2020 that China aims to peak its carbon dioxide emissions before 2030 and strive for carbon neutrality by 2060, research on the restoration of abandoned mines to harness their ecological benefits and utilize their spaces to achieve the dual-carbon strategy has garnered increasing attention since 2020, especially among Chinese scholars [19, 42].

Keyword Clustering Analysis

Clustering analysis is a crucial data mining method utilized to unveil hidden semantic themes within textual data. CiteSpace offers clustering capabilities, employing nouns or keywords extracted from the literature. In this research, the log-likelihood ratio algorithm was employed for keyword clustering, grouping keywords into thematic clusters and segmenting the research data into units, as illustrated in Fig. 9. Each cluster is named according to the predominant theme identified by the algorithm, and clusters are arranged by keyword count in descending order. The size of each unit reflects the number of articles, with a clustering module Q value of 0.6622 indicating a significant clustering structure (Q>0.3) [48]. The average silhouette value S is 0.8491, signifying reasonable clustering (S>0.5) and compelling clustering (S>0.7) [49, 63]. Given that the text data were retrieved based on abandoned mines, the cluster associated with abandoned mines was designated as Cluster #0.

Analyzing Fig. 9, the network is segmented into nine clusters: Cluster #1 – restoration method, Cluster #2 – soil restoration, Cluster #3 – hydrology, Cluster #4 – land-use change, Cluster #5 – acid mine drainage, Cluster #6 – soil nutrients, Cluster #7 – vegetation succession, Cluster #8 – earthworms, and Cluster #9 – abandoned mine areas. These clusters encompass a substantial portion of the literature and depict the principal research subjects. Notably, the formulation and exploration of restoration methods (#1), especially those focused on soil restoration (#2), soil nutrients (#6), and vegetation succession to achieve land-use change (#4) in addressing abandoned mine issues, emerge as prevailing topics. These restoration methods directly impact the progress and stability of relevant restoration projects. Given the significant advantage of the vast potential and promising prospects for developing and utilizing underground space resources in abandoned mine areas (#9), there has been considerable scholarly attention towards the study of rock engineering restoration of underground spaces in abandoned mines to harness their underground space. In summary, research on abandoned mine restoration issues can be categorized into two main aspects: green ecological restoration, aimed at harnessing the ecological benefits of abandoned mines, and geotechnical engineering restoration, aimed at utilizing their underground space.

Keyword Timeline of Clusters

The timeline is derived from interactions and evolutionary relationships among keywords organized into clusters within a specific field. This method reveals the evolutionary trajectory and stage characteristics of the research field, offering insights into the historical evolution and the forefront topics of recent years. Fig. 10 presents the co-occurrence map of the keyword timeline for the restoration of abandoned mines from 1996 to 2024, illustrating the developmental directions and hotspots of this field from a temporal perspective.

Natural revegetation has been a significant focus throughout the entire duration of abandoned mine restoration research from 1996 to the present. As research progresses further, the methods of ecological restoration of abandoned mines continue to evolve and improve, incorporating chemical, microbial, phytoremediation, and landscape remediation approaches [22, 57, 71-77]. Since 2020, China has been at the forefront of research on restoration issues of abandoned mines, aligning with its national double carbon strategy, which prioritizes strategic deployment in various domains, including utilizing the underground space of abandoned mines for waste landfill, CO_2 sequestration, pumped storage, disposal of radioactive waste, gas storage, and energy storage [78-83]. This strategic alignment has presented both significant opportunities and challenges for in-depth exploration of the utilization and restoration of abandoned mines. Additionally, there has been a noticeable emergence of new keywords towards geotechnical engineering restoration since then, indicating a heightened focus and research interest in addressing the restoration of abandoned mine issues. This trend highlights increased attention and research efforts devoted to studying abandoned mine restoration projects, reflecting the adoption of diverse research content, methodologies, objects, and approaches, thus emphasizing the growing importance and interest in investigating the utilization of abandoned mines.

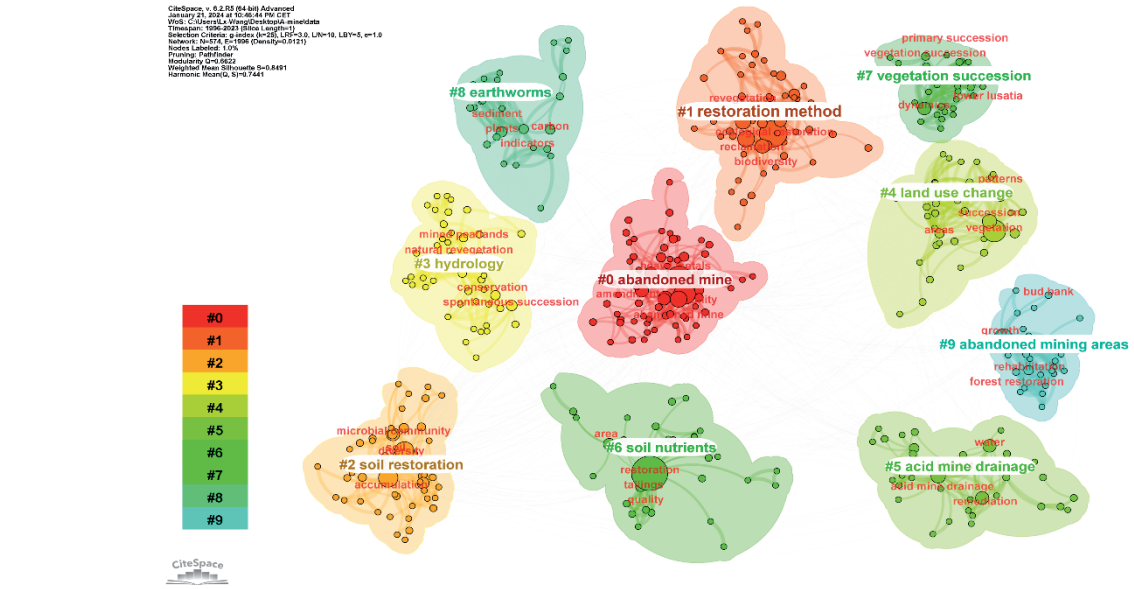

Fig. 9. Main clusters in the domain of the restoration of abandoned mines.

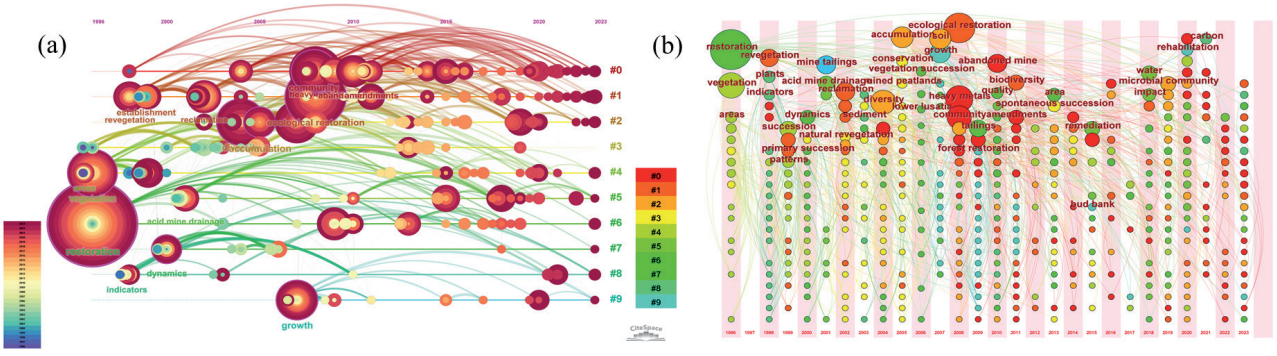

Fig. 10. Keywords co-occurrence timeline of main clusters. a) the form of line;b) the form of zone.

Discussion

Current Research Hotspots

Through the analysis and examination of key countries, research institutions, and their collaborative networks, it becomes clear that Chinese research institutions and scholars have played a pivotal role in advancing the study of abandoned mines restoration. Chinese President Xi Jinping solemnly announced to the world at the 75th United Nations General Assembly that China strives to peak its carbon dioxide emissions by 2030 and endeavors to achieve carbon neutrality by 2060, leading to an increasing number of projects on the restoration and utilization of abandoned mines [19]. This has injected new vitality and research focus into the study of abandoned mines, making it a key issue attracting worldwide attention and research. Co-occurrence analysis and clustering analysis based on keywords reveal that current research is focused on two main aspects. Firstly, there is a significant emphasis on the ecological restoration of abandoned mines through chemical, microbial, phytoremediation, and landscape remediation means. This aspect holds paramount importance in abandoned mine restoration, directly impacting the development and stable operation of such projects. Additionally, there is a growing emphasis on the utilization of underground spaces in abandoned mines for geotechnical engineering restoration. Although relatively small compared to the former, research in this direction has become a hotspot and frontier in the field of abandoned mine restoration, attracting more attention and further research from scholars in the future.

Further Research Prospects

By examining keywords and clustering terms within the domain of abandoned mine restoration, and by extensively reviewing cited literature, this study presents future research focal points and recommendations for the advancement of this field as follows:

(1) Currently, there are numerous abandoned mines worldwide, each with varying causes, natural conditions, environmental issues, and complexities. During the restoration process, it is crucial to consider the interactions among different ecological factors and adapt strategies accordingly. Therefore, there is an urgent need to propose and unify an evaluation system for restoration methods that can address the diverse environmental conditions of abandoned mines. This evaluation system would comprehensively assess various restoration methods, aiding in the selection of appropriate restoration modes and techniques.

(2) Presently, the methods and techniques used for ecological restoration of abandoned mines have become more diverse and refined, with vegetation ecological restoration being recognized as one of the most effective techniques. However, current research often focuses on studying the effects of individual methods on mines restoration. Single techniques may not achieve optimal results; hence, there is a need for research on the combined effects of multiple restoration methods to fully utilize synergies in practice.

(3) With the introduction of the double carbon strategy, the utilization of underground space in abandoned mines for landfilling, CO_2 storage, pumped storage, disposal of radioactive waste, and gas storage has become a research hotspot and frontier. However, ecological restoration of mines and geotechnical engineering restoration have often evolved into separate, non-intersecting subjects. There is an urgent need to develop a comprehensive, green, and systematic mines restoration system that integrates interdisciplinary ecological restoration and geotechnical engineering restoration in parallel.

Limitations

While this study employs a literature data-driven visualization approach, certain constraints should be acknowledged. The analysis relies exclusively on data from Web of Science Core Collection, which may not fully align with results from alternative databases such as Scopus or Google Scholar. Furthermore, the search parameters were confined to particular elements – namely, titles, abstracts, and keywords – potentially omitting relevant studies. Another limitation stems from the inclusion of only

The knowledge mapping visualization also presents challenges, as it processes extensive bibliometric data. For clarity and focus, the interpretation prioritized the most salient patterns and statistically significant findings. Nevertheless, this research serves as a valuable introductory resource, offering an accessible overview for scholars entering this domain.

Conclusions

In this study, a scientometric analysis of 393 research articles using CiteSpace software was conducted to review research on the restoration of abandoned mines from 1996 to 2024. The analysis encompassed publication quantity and trends, national and institutional collaboration networks, co-cited references, journal co-occurrence, keyword co-occurrence, and clustering. Knowledge maps were generated and analyzed, leading to the following conclusions:

(1) Collaboration Network Analysis: China holds a dominant position in global restoration of abandoned mines research, with strong connections to other countries. Chinese scholars contributed to 29.63% of publications, with the Chinese Academy of Sciences leading with 18 articles. The authorship network as a whole displays a dispersed pattern with small-scale aggregations, suggesting close communication and collaboration within research teams, but limited collaboration between teams.

(2) Citation analysis: Ecological Engineering, Science of Total Environment, Restoration Ecology, and Chemosphere are the highest cited journals, reflecting strong co-citation relationships. The most cited article, "Effects of mineral-solubilizing microbial strains on the mechanical responses of roots and root-reinforced soil in external-soil spray seeding substrate" by Chong Li et al. [60] suggested that the addition of a mineral-solubilizing microbial strain to the external-soil spray seeding substrate could help plants strengthen the soil and positively enhance its effects to achieve the ecological restoration of abandoned mines.

(3) Keyword co-occurrence analysis: "ecological restoration" emerges as the most frequent keyword over the past two decades. Rational restoration of abandoned mines is crucial for engineering safety, making it a hot topic. With the introduction of the double carbon strategy, the utilization of underground space in abandoned mines for landfilling, CO_2 storage, pumped storage, disposal of radioactive waste, and gas storage has become a research hotspot and frontier.

(4) In the analysis of Clustering, main clusters identified include #1 – restoration method, #2 – soil restoration, #3 – hydrology, #4 – land-use change, #5 – acid mine drainage, #6 – soil nutrients, #7 – vegetation succession, #8 – earthworms, and #9 – abandoned mine areas, representing current research topics.

(5) In terms of future research prospects, the abundance of abandoned mines worldwide, each with unique challenges, underscores the need for a unified evaluation system for restoration methods. Such a system would accommodate diverse environmental conditions and guide the selection of appropriate techniques. While vegetation restoration is widely recognized, current research often overlooks the synergistic effects of combined methods. Investigating these synergies is crucial for optimizing restoration outcomes. Furthermore, the utilization of abandoned mines' underground space for various purposes, driven by the double carbon strategy, is a burgeoning research area. However, the separation of ecological and geotechnical restoration realms presents a challenge. Integrating interdisciplinary approaches is imperative for developing a comprehensive, green, and systematic mines restoration framework.

In conclusion, this study offers a thorough examination of research on abandoned mines, pinpointing key topics and outlining future directions for further exploration in the restoration of abandoned mines.

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Conflict of Interest

The authors declare no conflict of interest.

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