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Review

Progress of Mine Land Reclamation and Ecological Restoration Research Based on Bibliometric Analysis

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Abstract: The mining of mineral resources has caused serious damage to land and significant pressure on ecological environment. During the repairing of damaged land and degraded ecosystems, there have been many pieces of literature related to land reclamation and ecological restoration (LRER) that have emerged. To understand the progress and prospect of LRER research, it is necessary to sort out such pieces of literature, analyze the current research status, and forecast the future research directions. Here, Bibliometrix R-package was used to analyze 2357 articles, which were derived from the core database of Web of Science, to explore the development of LRER from 1990 to 2022. The results are as follows. (1) The annual scientific output results show that both the number of articles published on LRER and the number of articles annually citied were increasing gradually from 1990 to 2022. (2) High-frequency keyword analysis indicates that heavy metal (Cd, Pb) pollution remediation is a research hotspot. The cluster analysis (CA) and multiple correspondence analysis (MCA) show that there are two clusters in the current research of LRER, in which one surrounds heavy metal pollution and the other focuses on ecological restoration of mining areas. The two clusters correspond to the remediation and ecological restoration (rehabilitation) stages of stepwise ecological restoration, respectively. Thematic evolution analysis shows that, for more than 30 years, mine drainage and heavy metal pollution treatment, soil reconstruction (soil profile reconstruction, soil improvement), and vegetation restoration have been the focus of research. (3) Future research should focus on the relationship between mine ecological restoration and carbon sequestration and the relationship between ecological restoration and biodiversity in mine areas. In addition, LRER technology exchange, international cooperation, and industrialization are also main directions of development. Generally, in this study, metrology software (Bibliometrix R-package 3.1.4) from the literature was used to sort out the relevant literature on LRER over the past 30 years so as to provide reference for future research on LRER.

Keywords: mine; land reclamation and ecological restoration (LRER); research status; research directions; Web of Science; Bibliometrix

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1. Introduction

The mining industry is a large contributor to the global economy and has been developing since the industrial revolution [1]. The mining of metal minerals, non-metallic minerals, and organic minerals leads to many ecological and environmental problems, for example, land excavation and occupation, surface subsidence, soil erosion, desertification, land pollution, and biodiversity loss [2,3]. Open-pit mining can cause drastic disturbances to regional ecosystem and soil properties [4], resulting in a significant loss of soil nutrients (soil organic carbon, total nitrogen) [5]. Compared with open-pit mining, underground mining inevitably causes a large amount of land subsidence [6]. For example, underground coal mining with high ground-water level can cause many environmental problems, of which the most serious are subsidence and waterlogging [7]. In addition, mining is a significant source of soil heavy metal pollution [8].

In recent years, the United Nations (UN) Sustainable Development Goals (SDGs) for 2030 call for restoration of degraded terrestrial ecosystems (Goal 15) to "protect, restore and promote sustainable use of terrestrial ecosystems, . . . halt and reverse land degradation and halt biodiversity loss" [9]. The Convention on Biological Diversity (2016) called for the "restoration of degraded natural and semi-natural ecosystems, . . . as a contribution to . . . adapting to the effects of climate change, combating desertification and land degradation" [10]. In addition, the United Nations General Assembly has declared 2021–2030 as the Decade of Ecosystem Restoration [11]. A series of development goals and initiatives of the United Nations have put forward that it is urgent to restore various ecosystems, including mine ecosystems, to protect biodiversity and improve ecosystem stability and sustainability.

During the repairing of damaged land and degraded ecosystems, there are many pieces of research literature that have emerged, involving a lot of relevant terms, for example, ecological restoration, ecosystem restoration, mitigation hierarchy, eco-compensation (biodiversity, ecosystems), reclamation, rehabilitation, remediation, repurposing, revegetation, etc. [12,13]. According to Mine closure and reclamation—Vocabulary (ISO 20305:2020(E)—2020), reclamation (rehabilitation) is defined as "reinstating of disturbed land, associated with a mine or a mine feature to be safe, stable, non-polluting and consistent with the agreed post mining land use" [14]. The Society for Ecological Restoration's international standards (SER Standards), second edition, defines reclamation as "the process of making severely degraded land fit for cultivation or a state suitable for some human use" [13]. For ecological restoration, SER Standards have been proposed four times, and the latest one is that "ecological restoration is the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed" [13,15]. Classic ecological terminology regards rehabilitation, reclamation, and restoration as terms with similar goals [15]. Usually, reclamation is often used in the USA and UK, restoration is used in the UK sometimes, and rehabilitation is often used in Australia and Canada [16]. Remediation aims to remove degradation to achieve safe, stable, and non-polluting landscapes, and it is a precondition for ecological restoration, reclamation, or rehabilitation after mining [12]. Some scholars also believe that, except for restoration, reclamation, and rehabilitation, it is necessary to add a term "ecological reclamation" and define it [17]. From the above literature, it can be seen that there are many terms related to mine restorative practices, and their use in the academic community is quite chaotic. Although the terminology is different, the work content is quite similar or the same. In recent years, land reclamation and ecological restoration are often used side by side in many international academic conferences, for example, the first international symposium on LRER was held in Beijing, China, 2014, the second international symposium on LRER was held in Xi'an, Shaanxi, 2017, and the third international symposium on LRER was held in Xuzhou, Jiangsu, 2021. The convening of three international conferences indicates a trend towards gradually unifying terminology in this field. LRER is so important that it has become one of the academic research focuses. However, due to the large amount of terms in this field, the literature on LRER lacks systematic induction and sorting. How have scholars progressed in research on LRER so far? There should be more information to be obtained. Hence, relevant methods, such as the bibliometric method, are needed for literature analysis. Using bibliometrics for science mapping, we can answer three general types of research questions (the knowledge base, the research front, and the social network of scientific collaborations) [18].

Therefore, to clarify the development of existing research on LRER and to better grasp the future trend, in this study, the Bibliometrix R-package was used to systematically summarize and sort out the literature on LRER included in the core database of Web of Science between 1990 and 2022. The objectives of this study are as follows:

(1) To render a review of the research on LRER from 1990 to 2022 (dataset, sources, authors, and documents).

(2) To research the collaboration network feature among countries/institutions in the field.

(3) To analyze the current research status and explore future research directions of LRER.

2. Materials and Methods

The Bibliometrix R-package (http://www.bibliometrix.org (accessed on 1 January 2023)) provides a set of tools for quantitative research in bibliometrics and scientometrics [18]. Biblioshiny helps users perform relevant bibliometric and visual analysis on an interactive web interface and reduce the difficulty of literature analysis operations [19]. The Web of Science has the world's largest set of comprehensive academic resources with the most disciplines, covering more than 12,000 academic journals in natural sciences, engineering, biomedicine, social sciences, arts, humanities, and so on [20]. The Web of Science core database was used as the data source for retrieval, and the retrieval terms used were TS = ("ecological restoration" or "ecosystem restoration" or "reclamation" or "restoration" or "rehabilitation" or "revegetation" or "remediation" or "mitigation hierarchy" or "repurpose") and TS = ("mining industry" or "mining area" or "mining site" or "mine site" or "mined land"). The time span of the retrieval was set as 1990–2022. Literature types were limited to "Article", "Proceeding paper", "Review Article", "Early Access", and "Data Paper". The search language was English. After eliminating reduplicative and irrelevant data, a total of 2357 documents on LRER were obtained. The download data were converted to R data frame.

After data collection and conversion, the articles were analyzed using the Bibliometrix. Firstly, we analyzed the dataset, authors, sources, and documents on LRER, including annual scientific production, average citation per year, corresponding author's country, most relevant affiliations, most relevant sources, globally most cited documents, and high-frequency keywords, so as to give an overview of the research in that field from 1990 to 2022. Secondly, we analyzed cooperation between countries and institutions to find out the feature of a collaboration network. Finally, the conceptual structure, including topic dendrogram and thematic evolution, was analyzed to obtain the current research topics and future research directions for LRER (Figure 1).

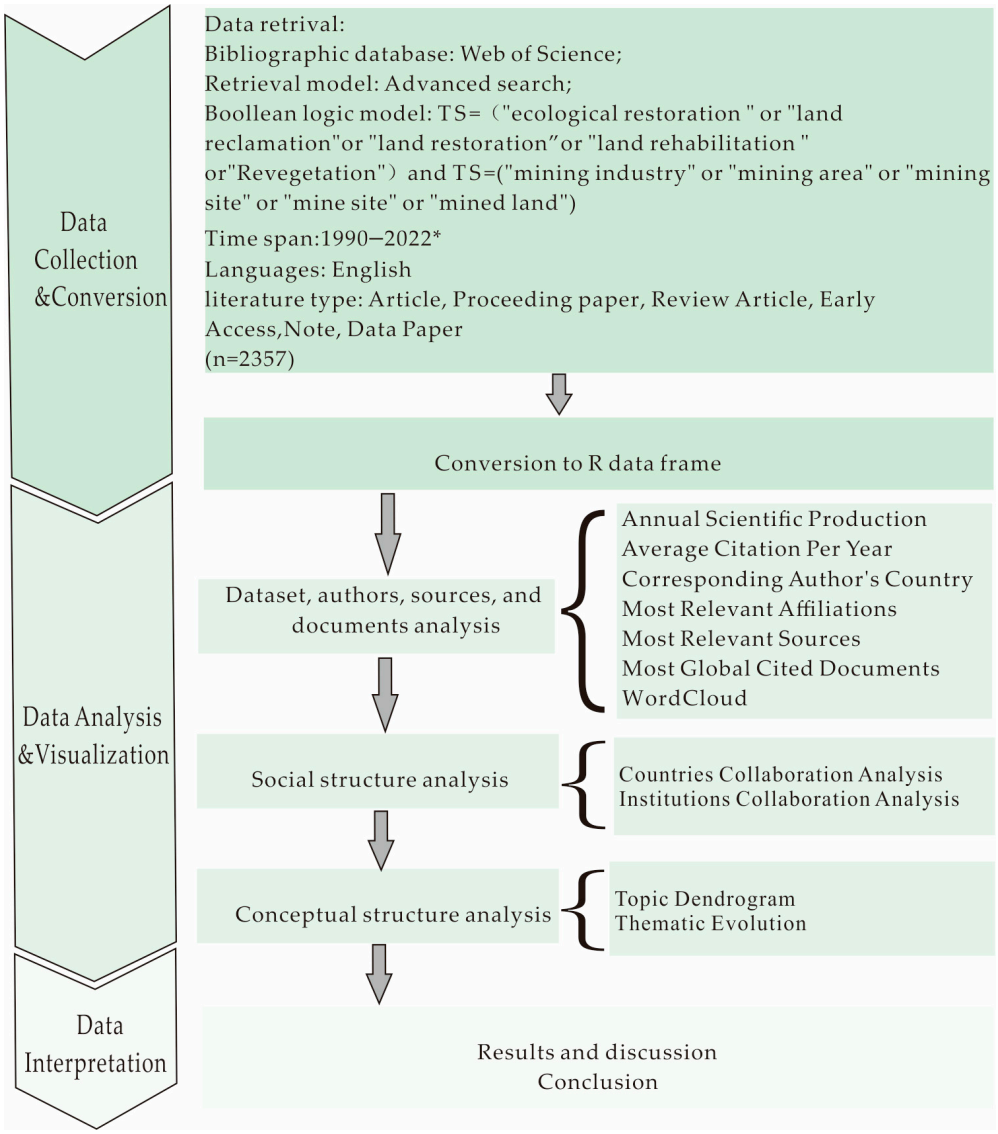


Figure 1. Technical flow of the Bibliometrics approach (* as of 15 January 2023).

3. Results and Analysis

3.1. Analysis of the Annual Scientific Production on LRER

The research progress on LRER can be obtained by counting the number of documents published each year. From 1990 to 2022, the number of papers published on LRER showed an increasing trend year on year (Figure 2), indicating that LRER attracted more and more attention of scholars. From 1990 to 2000, the total number of published relevant papers was 124, with an annual average number less than 20, accounting for only 7.47% of the total number. The annual growth of papers was low and slow, indicating, at that stage, the research on LRER was still in its infancy. Subsequently, between 2001 and 2014, published relevant papers increased significantly, with an average annual number of about 50, indicating that LRER research was closely related to socio-economic development during that period and more and more scholars paid attention to it. After 2015, the number of published relevant papers on LRER continued to increase significantly. In particular, the number of papers published in 2021 and 2022 reached 255 and 261, respectively. It can be seen that LRER has become a hotspot of current research.

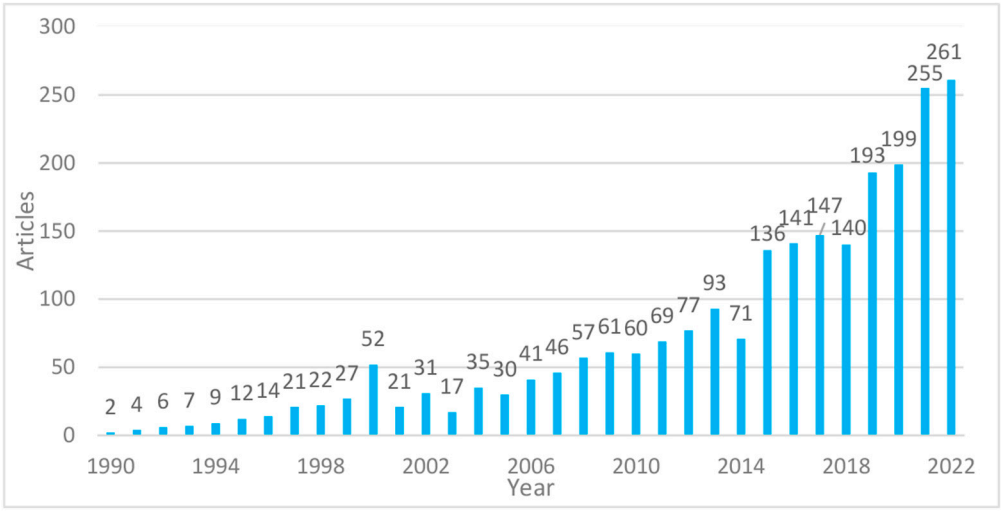


Figure 2. Numbers of relevant papers published each year from 1990 to 2022.

3.2. Analysis of Literature Citations on LRER

3.2.1. Annual Citation Rate

The annual average citation rate of pieces of literature on LRER is gradually increasing (Figure 3). The citation rate in 1990–2000 was very low (<1), indicating that the research was still in the initial stage of exploration and did not yet receive widespread attention of researchers. The average citation frequencies during 2001–2015 and 2009–2022 were 1.51 and 2.39, respectively. It peaked in 2018 (3.41). From 2018 to 2020, the citation frequency of the literature remained at a historical high level. In general, the number of citations has been increasing over time, indicating that the influence of LRER is increasing.

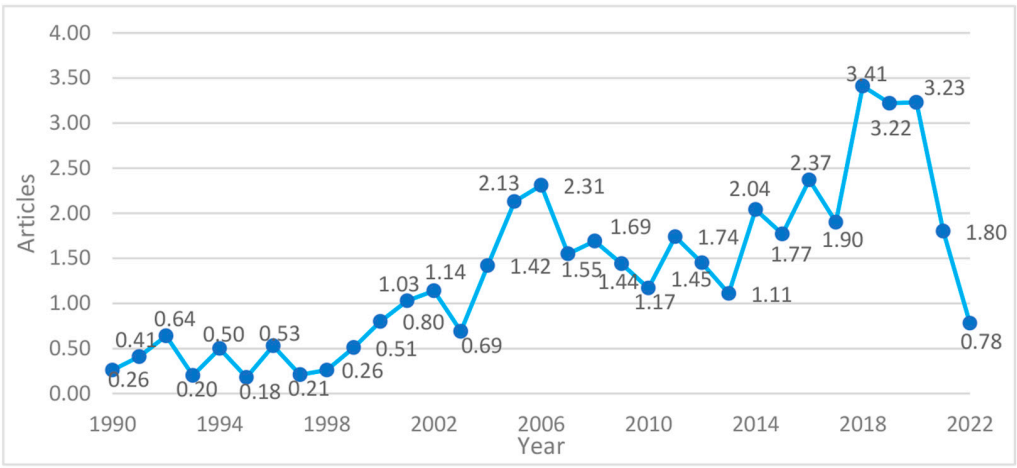


Figure 3. Average total citation rates per year on LRER from 1990 to 2022.

3.2.2. Analysis of Highly Cited Articles

Table 1 shows the top 10 most cited publications on LRER from 1990 to 2022. Among the literature related to LRER published from 1990 to 2022, the most frequently cited article in the world is the one titled Heavy Metal Removal Mechanism of Acid Mine Drainage in Wetlands: a Critical Review, published in Minerals Engineering by AS Sheoran and V. Sheoran [21] of Jai Jai Narain Vyas University, with 474 citations worldwide. Since about 1985, passive treatment has been used more and more frequently as a method for treating acid mine drainage [22]. In that article, the latest progress of passive treatment systems in constructed wetlands was reviewed, and suggestions were made for new trends in the development of passive treatment technology. The article further promoted the development of passive treatment technology for acid mine drainage. The second most

frequently cited article is Metal Contamination of Soils and Crops Affected by the Chenzhou Lead/Zinc Mine Spill (Hunan, China), published in Science of the Total Environment by Hongyu Liu et al. [23] of Hunan University, with 473 citations worldwide. The article showed that frequent mining activities caused heavy metal contamination in large areas of farmlands. The article pointed out that the heavy metal accumulation effect was not entirely depending on total element concentrations in soil. The article has important reference value for the research on remediation of heavy metal pollution in mines. The third most frequently cited article is Arsenic and Heavy Metal Pollution of Soil, Water and Sediments in a Semi-Arid Climate Mining Area in Mexico, with 296 citations worldwide [24]. The article assessed the impact of mining on environment and identified the main factors involved in the dispersion of arsenic and heavy metals under semi-arid conditions. It is of great significance to control arsenic and heavy metal pollution under semi-arid conditions.

Table 1. Top 10 most cited publications on LRER from 1990 to 2022.

Rank	Paper	DOI	Year	Journal	TC
1	SHEORAN AS, 2006, MINER ENG	10.1016/j.mineng.2005.08.006	2006	Minerals Engineering	474
2	LIU HY, 2005, SCI TOTAL ENVIRON	10.1016/j.scitotenv.2004.07.030	2005	Science of the Total Environment	473
3	RAZO I, 2004, WATER AIR SOIL POLL	10.1023/B:WATE.0000015350.14520.c1	2004	Water Air and Soil Pollution	296
4	LI MS, 2007, ENVIRON POLLUT	10.1016/j.envpol.2006.08.006	2007	Environmental Pollution	264
5	LI MS, 2006, SCI TOTAL ENVIRON	10.1016/j.scitotenv.2005.05.003	2014	Science of the Total Environment	264
6	YU HY, 2016, ENVIRON POLLUT	10.1016/j.envpol.2015.11.021	2006	Environmental Pollution	197
7	QIAO JT, 2018, CHEMOSPHERE	10.1016/j.chemosphere.2017.12.081	2018	Chemosphere	192
8	SHRESTHA RK, 2011, GEODERMA	10.1016/j.geoderma.2010.12.015	2011	Geoderma	173
9	RIOS CA, 2008, J HAZARD MATER	10.1016/j.jhazmat.2007.11.123	2008	Journal of Hazardous Materials	170
10	MACINTOSH DJ, 2002, ESTUAR COAST SHELF S	10.1006/ecss.2001.0896	2002	Estuarine Coastal and Shelf Science	169

3.3. Main Countries/Regions Conducting Research on LRER

According to our statistic (Table 2), the ten countries with the most publications on LRER are China, Australia, the USA, Canada, Germany, Poland, India, Spain, Brazil, and the UK. The publications of the top five countries accounted for 28.26%, 10.82%, 9.63%, 6.07%, and 3.52%, respectively, indicating those countries made the greatest contributions to the research on LRER. For example, in China, there are many studies on LRER in coal mining areas, and the research areas are mainly concentrated in ecologically fragile areas in Northwest China [4,25–44] and high water level areas in Eastern China [6,45–52]. The research focuses include reclamation of open-pit coal mines [8,38,39,53–58], reclamation of coal mining subsidence sites [7,51,59–77], and ecological restoration of coal gangue hills [78–80]. The research objects of LRER in the USA are extensive, from restoration of open pit coal mines to reclamation of various production and construction projects, and the research focuses are acid mine drainage treatment [81–83], soil reconstruction, and vegetation restoration [84,85]. Australia is in the top three countries with land areas impacted by mining, and it was a leader in land rehabilitation in the field of theory, application, demonstration, and communication late last century [86–88].

Additionally, the numbers of single-country publications (SCP) and multiple-country publications (MCP) were used to determine the level of international cooperation. China has the highest number of articles (666), the highest MCP (564), and the highest SCP (102). The collaboration network of 50 countries (Figure 4) publishing articles on LRER was drawn to demonstrate the status and level of cooperation between countries. The radius of the circle is used to reflect the number of articles published by each country, and

the thickness of the lines between countries is used to indicate the degree of cooperation between countries. Clearly, there is more collaboration among China, the USA, Australia, Canada, and the UK, especially between China and the USA and between China and Australia. As countries attach importance to the issue of LRER, promoting national and regional cooperative research has become a consensus.

Table 2. Top 10 countries in terms of the literature numbers on LRER.

Rank	Country	Number of Articles	Single-Country Publications (SCP)	Multiple-Country Publications (MCP)
1	China	666	564	102
2	Australia	255	189	66
3	USA	227	204	23
4	Canada	143	118	25
5	Germany	83	68	15
6	Poland	75	69	6
7	India	73	66	7
8	Spain	69	50	19
9	Brazil	64	49	15
10	UK	50	38	12

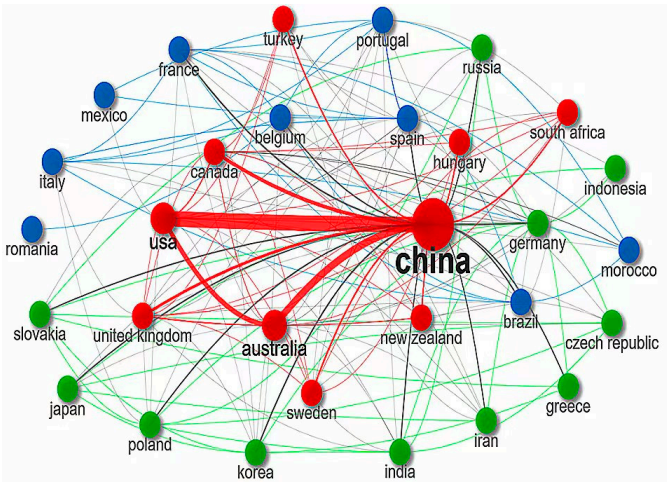


Figure 4. Collaboration network of countries publishing articles on LRER.

3.4. Main Institutions Conducting Research on LRER

The top ten LRER research institutions were determined according to their publication quantities (Table 3), and they are China Univ Min and Technol, Univ Queensland, China Univ Geosci, Univ Western Australia, Curtin Univ, China Univ Min and Technol Beijing, Univ Chinese Acad Sci, Key Lab Land Consolidat and Rehabil, Univ Cagliari, and Univ Quebec Abitibi Temiscamingue.

China Univ Min and Technol published 133 articles in that field, followed by the Univ Queensland with 98 articles, and China Univ Geosci with 84 articles. Among the top ten research institutions, five are from China and three are from Australia, indicating China and Australia attach great importance to LRER research.

The collaboration network of 50 institutions is shown in Figure 5. It can be seen that institutional cooperation is mainly carried out within the same country, for example, the cooperation between Univ Western Australia and Curtin Univ happened in Australia. The two research institutions of LRER, China Univ Min and Technol and China Univ Geosci, have more cooperation with other research institutions in China. Compared with the level of institutional cooperation within the same countries, the level of international institutional cooperation is still low.

Table 3. Top 10 research institutions related to LRER.

Rank	Research Institution	Country	Number of Articles
1	The China Univ Min and Technol	China	133
2	Univ Queensland	Australia	98
3	China Univ Geosci	China	84
4	Univ Western Australia	Australia	70
5	Curtin Univ	Australia	46
6	China Univ Min and Technol Beijing	China	42
7	Univ Chinese Acad Sci	China	36
8	Key Lab Land Consolidat and Rehabil	China	33
9	Univ Cagliari	Italy	27
10	Univ Quebec Abitibi Temiscamingue	Canada	27

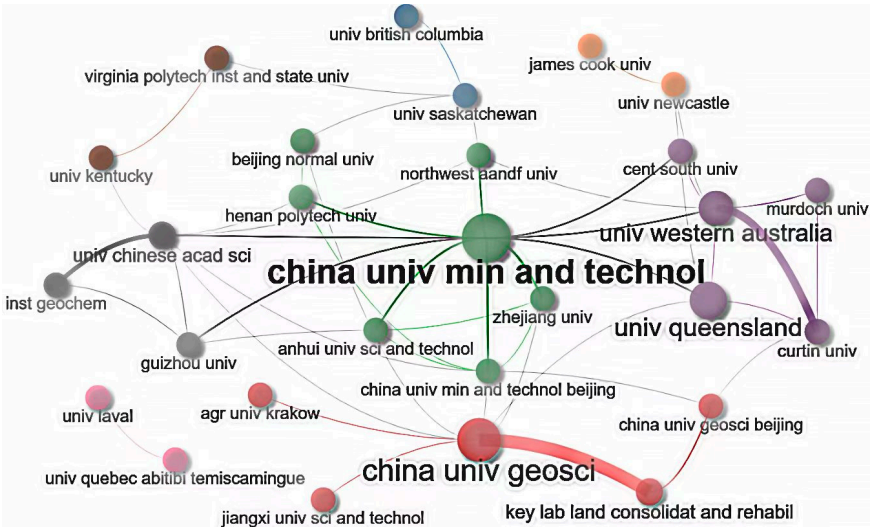


Figure 5. Collaboration network of main institutions on LRER.

3.5. Research Categories on LRER

A bibliometric analysis was carried out on the literature disciplines of LRER research with the data from Web of Science to explore the main research areas. It can be seen that the field of ecological restoration involves multiple disciplines (Figure 6), including environmental science, engineering environment, water resource, etc. Among the research disciplines related to LRER, environmental science is the principal category, accounting for 46.6% of the total, followed by engineering environment (13.9%), water resources (10.7%), mining mineral proceedings (10.6%), ecology (10.4%), geosciences multidisciplinary (10.4%), soil science (8.9%), green sustainable science technology (5.45%), and environmental studies (5.3%). There are also other categories involved, such as geochemistry geophysics, remote sensing, plant science, and public environmental occupational health; however, none of their percentages are higher than 5%. The most attention is paid to environmental science and engineering environment, and in these two disciplines there are the most extensive publications. The key issues are related to soil and water pollution by heavy metals in mining areas, especially the pollution of heavy metals such as Cd and Pb, heavy metal phytoremediation, and vegetation reconstruction. Water resource is concerned in terms of the discharge and treatment of acidic water containing heavy metals in mining areas and the pollution of river water. The discipline of ecology focuses on topics such as mining damage to ecosystems, impacts on ecosystem services, biodiversity conservation, and ecosystem spontaneous succession.

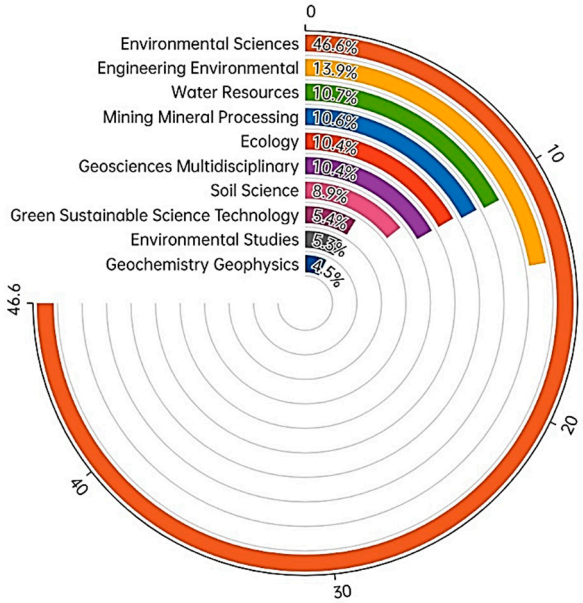


Figure 6. Main research categories on LRER.

3.6. Main Journals on LRER

The most abundant journals that publish research articles on LRER are shown in Table 4. The top ten journals are from The Netherlands, USA, Germany, UK, and Switzerland. The main journals according to the number of LRER articles are Science of the Total Environment, Environmental Science and Pollution Research, and Restoration Ecology. The journal with the most published articles is Science of the Total Environment, which has a JCR division of Q1 in 2022 and an impact factor of 10.753. It published 74 articles related to LRER in total from 1990 to 2022. The second is Environmental Science and Pollution Research, which has a JCR division of Q2 and an impact factor of 5.190. It published 53 articles related to LRER in total from 1990 to 2022. The third is Restoration Ecology, which has a JCR division of Q2 and an impact factor of 4.181. It published 51 articles related to LRER in total from 1990 to 2022.

Table 4. Top 10 journals in terms of the literature quantity on LRER.

Rank	Journal	Country	Journal Citation Report (JCR)	Impact Factor (If)	Articles
1	Science of the Total Environment	The Netherlands	Q1	10.753	74
2	Environmental Science and Pollution Research	Germany	Q2	5.190	53
3	Restoration Ecology	United States	Q2	4.181	51
4	Ecological Engineering	The Netherlands	Q2	4.379	46
5	Journal of Cleaner Production	United States	Q1	11.072	44
6	Environmental Earth Sciences	Germany	Q2	3.119	41
7	Journal of Environmental Management	England	Q1	8.910	41
8	Sustainability	Switzerland	Q2	3.889	41
9	Chemosphere	England	Q1	8.943	36
10	Remote Sensing	Switzerland	Q1	5.349	29

3.7. Hot Research Topics and Trends on LRER

3.7.1. High-Frequency Keyword Analysis

Keywords are a high-level summary of research contents [89]. The cloud map of the top 50 keywords related to LRER is shown in Figure 7. The larger the keyword font in the figure, the higher the frequency of occurrence. As seen from Figure 7, the high-frequency keywords

that appear include "heavy-metals", "mining area", "soil", "remediation", "accumulation", "reclamation", "restoration", "water", "growth", "pollution", "cadmium", "vegetation", "diversity", and so on. As it shows, the scope of research on LRER is very wide. For a long time, the discharge of mineral acidic wastewater has often led to heavy metal pollution [21], especially Cd and Pb pollution. Remediation aims to remove degradation to achieve safe, stable, and nonpolluting landscapes, and it is a pre-requisite for ecological restoration, reclamation, or rehabilitation after mining [12]. Soil occupies an important position in the ecosystem because it provides the environment with places where various plants, soil, animals, and microorganisms grow. Soil heavy metal pollution remediation is the key to LRER, and it is also a current research hotspot. Vegetation cover provides a cost-effective and environmentally sustainable method for stabilizing the bare area and minimizing the pollution problem, and the growth of plants (biomass, growth rates, and biomass of nodules) is the focus of research [90–92]. The objective of LRER is to assist the recovery of the ecosystem, thus terms such as accumulation, vegetation, and growth are also high-frequency keywords on LRER.

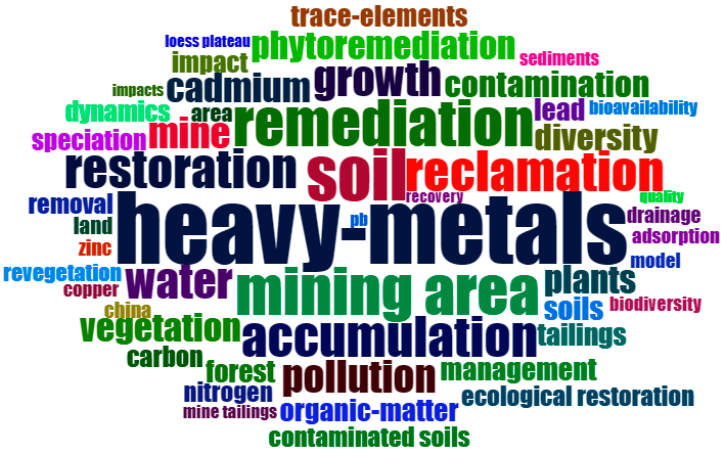


Figure 7. Cloud map of high-frequency keywords on LRER from 1990 to 2022.

3.7.2. Cluster Analysis (CA) and Multiple Correspondence Analysis (MCA) of High-Frequency Keywords

CA is one of the main methods for analyzing multivariate data [93]. The CA results of high-frequency keywords are shown in Figure 8. In this study, keywords are clustered into two categories. The first is mainly related to "heavy metals", "soil amendments", "mine tails", "biochar", "toxicity", etc. This type of research focuses on heavy metal pollution in metal mine wasteland and tailings, especially the remediation of heavy metal pollution in soil by biochar, which is a current research hotspot [94,95]. The second is mainly related to "organic matter", "organic carbon", "nitrogen", "vegetation", "succession", "quality", "diversity", etc. This type of research focuses on soil organic carbon, nitrogen, natural succession, vegetation reconstruction, biodiversity, etc. Since the major problems of land after mining include physical properties (structure, stability, moisture), nutrition (macronutrients, micronutrients), and toxicity (pH, heavy metals, salinity) [96,97], research on LRER is also mainly conducted on those aspects.

MCA is an unsupervised learning algorithm for visualizing the patterns of large and multidimensional categorical data [98]. The results of MCA on keywords are shown in Figure 9, where there are two clusters on the figure, one is centered on heavy metals, and the other is centered on restoration. CA and MCA of high-frequency keywords show that, currently, there are two clusters in LRER research, one is heavy metal pollution caused by mining, and the other is ecological restoration in mining areas, especially soil reconstruction and vegetation restoration.

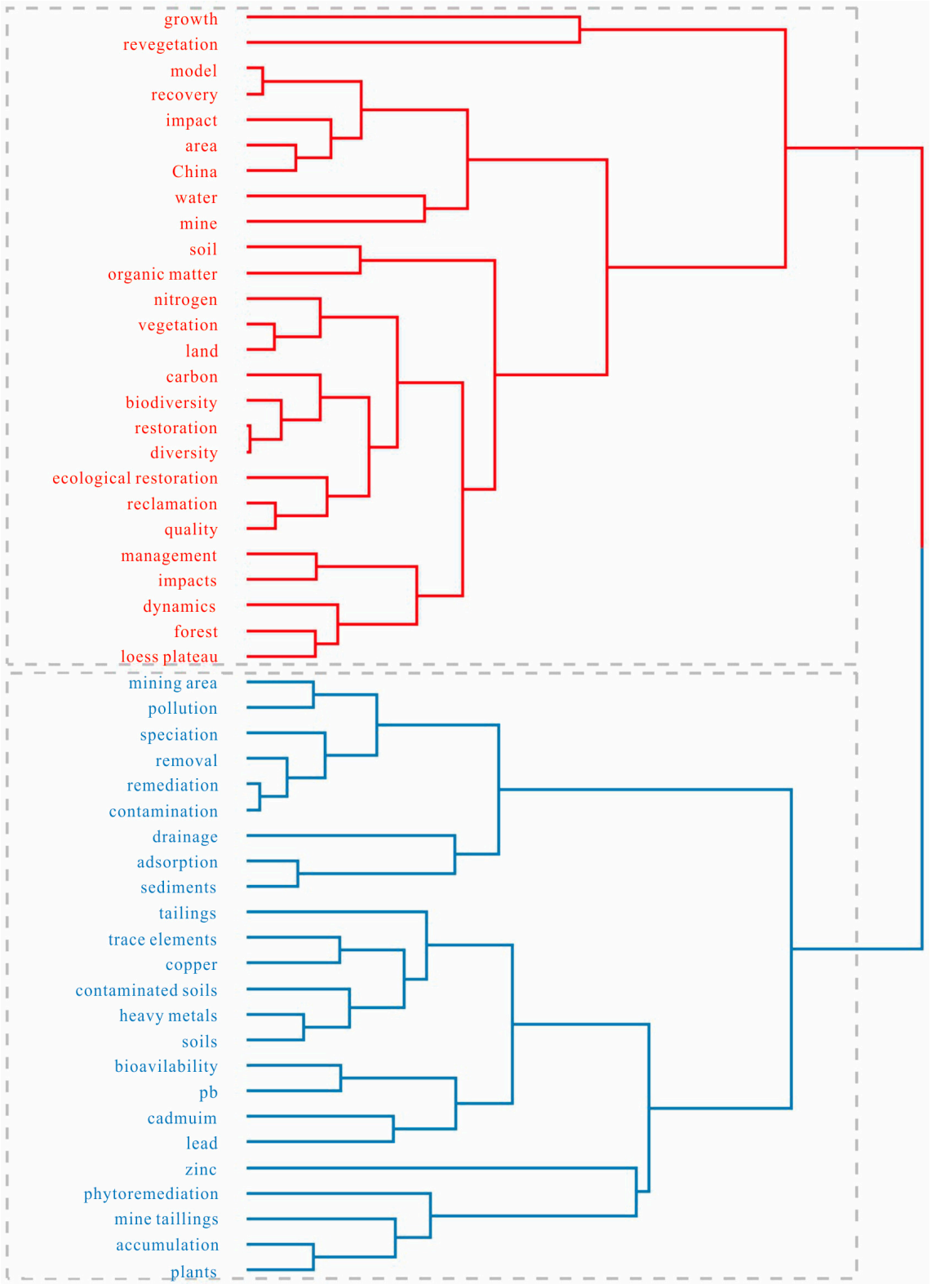


Figure 8. Dendrogram of keywords on LRER from 1990 to 2022.

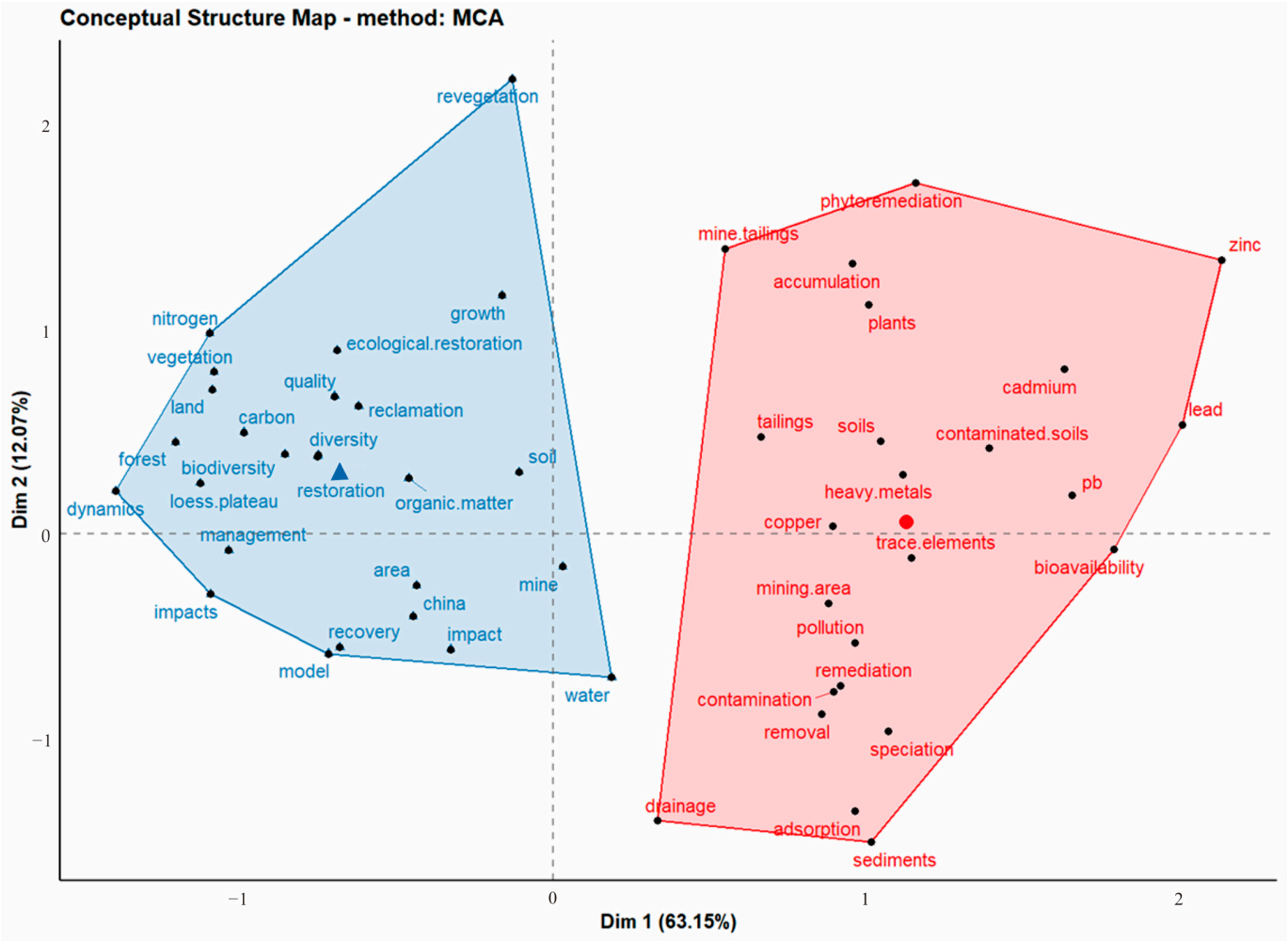


Figure 9. Word map of keywords on LRER from 1990 to 2022.

3.7.3. Thematic Evolution Analysis

In the past 30 years, the research direction on LRER has had both continuity and development. Figure 10 shows the chronological order of the evolution of various themes. Connections between keywords are indicated by gray lines connected to various rectangular colored shapes. Before 2000, the research on LRER was in its infancy, and researchers began to explore topics such as reclamation, rehabilitation, and acid rock drainage (acid mine drainage) treatment. From 2001 to 2014, the contents of LRER research were gradually enriched, mainly involving land reclamation, mine site rehabilitation, mine site restoration, the impact of mining and reclamation on soil physical and chemical properties (especially bulk density), and heavy metals pollution, especially mercury (Hg) and arsenic (As) contamination. The research on LRER from 2015 to 2020 mainly focused on reclamation, mine site restoration, phytoremediation, heavy metals, reforestation, etc. In the past two years, the research on LRER has focused on heavy metals and their pollution, arbuscular mycorrhizal fungi microbial restoration, mine vegetation restoration, and coal gangue ecological restoration. Overall, for more than 30 years, mine acid wastewater treatment and heavy metal pollution control, soil reconstruction (soil profile reconstruction, soil improvement), and vegetation restoration have been the key topics of research.

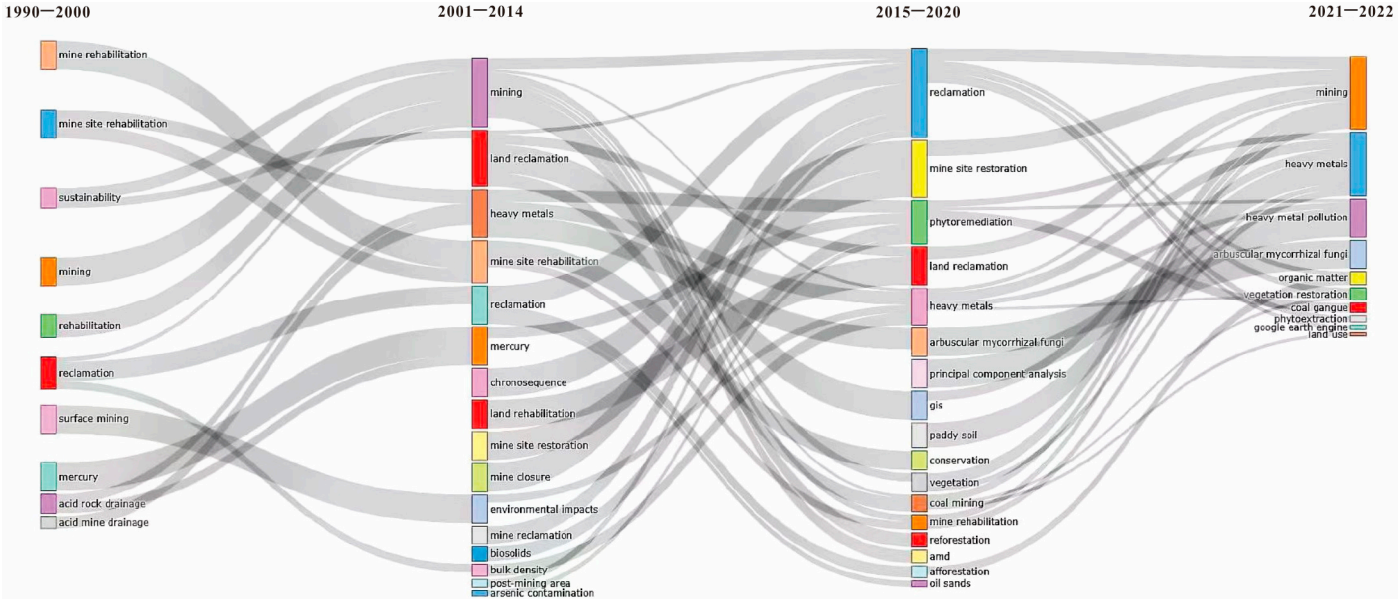


Figure 10. Thematic evolution on LRER.

4. Discussion

Before 2004, there were few studies on LRER. From 2005 to 2014, the number of relevant publications increased steadily. A big increase of relevant articles occurred from 2015 to 2022, especially in 2021 and 2022. A series of actions, such as UN SDGs for 2030, the Convention on Biological Diversity, and the UN Decade of Ecosystem Restoration 2021–2030, have greatly promoted research on LRER. In addition, the three consecutive International Symposiums on LRER held in 2014, 2017, and 2021 promoted academic exchanges and strongly promoted international cooperation in LRER [99].

LRER is closely related to the development and utilization of mineral resources. Therefore, countries that contributed more publications on LRER are also those that have rich mineral resources and pay more attention to ecological and environmental issues, such as China, Australia, USA, Canada, and Germany. In recent years, the number of articles published by Chinese scholars gradually increased. Since 2012, China has put the construction of ecological civilization in a prominent position. China's adherence to the green development strategy and strict laws and regulations (such as the Land Reclamation Regulations, the Implementation Measures for Land Reclamation Regulations) have made ecological and environmental protection a hard constraint for mine development. As a result, the number of research institutions on LRER in China has also increased. The field of LRER involves categories such as environmental science, engineering environment, water resources, mining mineral proceeding, ecology, etc., showing a trend of multidisciplinary development. There are many kinds of periodicals that publish articles about land reclamation and ecology, mainly focusing on environmental science and ecology, earth science, and engineering technology, which are related to the research content and direction of LRER.

For the heavy metal pollution in metal mine wasteland and tailings, the remediation of heavy metal pollution in soil by biochar is a current research hotspot [94,95]. For energy mines, such as coal mines, more attention is paid to terrain remodeling [100], soil profile reconstruction and improvement [4,101], revegetation [102–104], dynamic reclamation methods for subsidence band [105], and biodiversity [106], and that is why more articles on LRER are published in popular journals of environment and ecology. The CA and MCA of high-frequency keywords show that the current LRER research has two clusters, one is around heavy metal pollution (Cd, Pb, etc.), and the other is around ecological restoration in mining areas, including soil reconstruction and vegetation restoration. Renee E. Young et al. [12] put forward the idea of stepwise ecological restoration in 2022. The idea of stepwise ecological restoration is to use three restorative modes for different levels of

ecosystem degradation, i.e., environmental remediation for seriously degraded ecosystems, ecological rehabilitation for moderately degraded ecosystems, and ecological (even natural) restoration for slightly degraded ecosystems. It can be seen that current LRER research is in different stages of stepwise ecological restoration, i.e., remediation stage and ecological restoration (rehabilitation) stage. The analysis results of high-frequency keywords are consistent with the theory of stepwise ecological restoration [12]. From this perspective, it is also necessary to carry out stepwise ecological restoration based on targets and end goals for post-mining recovery of ecosystems with different degrees of degradation [107].

Thematic evolution analysis shows that mine acid wastewater treatment and heavy metal pollution control, soil reconstruction (soil profile reconstruction, soil improvement), and vegetation restoration have been the focus of research for more than 30 years. Judging from the three consecutive international conferences on LRER held in 2014, 2017, and 2021, soil reconstruction and landform remodeling, solid waste and acidic water treatment, reclamation and ecological restoration of coal mining subsidence, open-pit mine reclamation and ecological restoration, and restoration of contaminated land are also hot topics. The UN SDGs for 2030, the Convention on Biological Diversity, the UN Decade of Ecosystem Restoration 2021–2030, and other international initiatives have brought opportunities and challenges to the field of LRER. For mine ecosystems, as one of the degraded ecosystems, the future LRER should not only focus on traditional hotspots such as soil reconstruction and landform remodeling, solid waste and acid water treatment, mining subsidence and ecological restoration, open pit mine reclamation and ecological restoration, and polluted land restoration, but also focus on the relationship between LRER and carbon sequestration and the relationship between LRER and biodiversity. In addition, from the analysis of the national cooperation network and institutional cooperation network of LRER, it can be seen that the international cooperation is mainly concentrated among countries such as China, the USA, and Australia; the current international cooperation among other countries is not so frequent, and institutional cooperation is mainly carried out within the same country. Therefore, the technical exchanges and international cooperation should be strengthened. A series of ecological restoration goals and initiatives of the UN also require the cooperation of all countries.

Insufficiencies and recommendations. Articles retrieved through the core database of Web of Science in this study are only a subset of the research field of LRER. For example, some articles published in international conferences on LRER and national reclamation societies (societies of ecological restoration) of different countries are included by EI and ISTP, but not by SCI. In addition, setting the search language to English also blocks articles published in other languages. For example, there are many articles written by experts on reclamation in China, and some articles are written in Chinese, which are missed in the search. Therefore, future bibliometric research should include articles from different databases and languages for more comprehensive analysis.

5. Conclusions

In this study, an R runtime environment was set up and the Bibliometrix software packages (version 3.1.4) were used to systematically summarize and sort out the literature on LRER. The trends in publications, major research journals, institutions, countries, research hotspots, and themes were analyzed, and the future research directions were discussed.

The annual scientific output results show that the number of articles published on LRER and the number of annual average citations increased gradually from 1990 to 2022. China, Australia, the USA, Canada, and Germany made the greatest contribution to the research on LRER.

There is more collaboration among China, the USA, Australia, Canada, and the UK, especially between China and the USA as well as between China and Australia. The technical exchanges and international cooperation should be strengthened. There are five Chinese institutions ranking top ten on LRER research. China attaches great importance to LRER research. The field shows the interdisciplinary development trend of environmental

sciences, engineering environment, mining resources, proceedings, and ecology. The top five prolific journals are Science of the Total Environment, Environmental Science and Pollution Research, Restoration Ecology, Ecological Engineering, and Journal of Cleaner Production. The globally most cited articles focus on passive treatment of contaminated acid wastewater, phytostabilization of mine tailings, and biochar on mine tailings.

Currently, there are two major concerns of LRER, one is heavy metal pollution caused by mining, and the other is ecological restoration in mining areas, especially soil reconstruction and vegetation restoration. Those two major concerns of LRER correspond to different stages of stepwise ecological restoration, i.e., remediation stage and ecological restoration (rehabilitation) stage. The mine acid wastewater treatment, heavy metal pollution control, soil reconstruction (soil profile reconstruction, soil improvement), and vegetation restoration are the focus of research. In addition to traditional reclamation hotspots, future LRER should also focus on the relationship between LRER and carbon sequestration as well as the relationship between LRER and biodiversity. In addition, technology exchanges, international cooperation, and industrialization of LRER should be strengthened in the future.

We try to sort out the research status quo, dig out the research hotspots, forecast the future research trends, and provide references for future research on LRER.

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Abbreviations

CA	Cluster analysis
LRER	Land reclamation and ecological restoration
MCA	Multiple correspondence analysis
MCP	Multiple-country publications
SCP	Single-country publications
SDGs	Sustainable Development Goals

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