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Review Article

Research Frontiers in Ecological Restoration and Carbon Sequestration in Mining Areas: A Visual Analysis Using VOSviewer

Yulong Wang[1], Long Zhang[1], Guoyan Zhu[1], Chen Song[1], Longgang Zhang[2], Wei Chang[3], Kun Li[3], Xiaohui Wang[3, 4, *]

[1]Yichun Luming Mining Industry Limited Company, Yichun, China

[2]China Railway Environment and Technology Engineering Limited Company, Changsha, China

[3]Engineering Research Center of Agricultural Microbiology Technology, Ministry of Education, Heilongjiang Provincial Key Laboratory of Ecological Restoration and Resource Utilization for Cold Region, Heilongjiang University, Harbin, China

[4]Guangxi Institute of Botany, Chinese Academy of Sciences, Guangxi Zhuang Autonomous Region, Guangxi Key Laboratory of Karst Plant Conservation and Restoration Ecology, Guilin, China

Abstract

The functioning and progress of modern industrial systems are deeply reliant on mineral resources. While mining offers substantial economic and social gains, it also imposes notable environmental impacts. In the context of global climate change, sustainable mining and ecological restoration in mined areas are increasingly connected to carbon sequestration efforts. Enhancing carbon sink capacity in ecological restoration processes is crucial for achieving carbon neutrality. This study aims to review the current research landscape, identify key research areas, and explore future trends in this field. Relevant literature from the Web of Science was selected, key information extracted, and co-occurrence networks were mapped and analyzed using VOSviewer. Covering publications from 2000 to the present, the analysis spans 84 countries and regions, 1,184 institutions, 3,757 authors, and 858 papers. The main research areas include: (1) strategies for ecological and vegetative restoration of mining areas; (2) carbon sequestration processes in vegetation and soil in mining areas; (3) mechanisms for soil health restoration in mining areas; (4) the role of plants and microbes in pollution remediation; (5) importance of water resource management and wetland restoration in mining areas; and (6) ecological succession and biomass accumulation in mining area rehabilitation. This study highlights major contributors, countries, and institutions, elucidates research hotspots, and outlines directions for future development. By systematically summarizing research trends and hotspots in ecological restoration and carbon sequestration in mining areas, this work provides a valuable reference for researchers seeking to navigate and advance this dynamic field.

Keywords

Carbon Sequestration, Nutrient Cycling, Phytoremediation, Microbial Remediation

*Corresponding author: wangxiaohui_1996@163.com (Xiaohui Wang)

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1. Introduction

The mining industry is a vital pillar of China's economy, significantly influencing energy security, industrial growth, and regional economic stability. However, mining activities present severe environmental challenges, including land degradation, water and soil pollution, biodiversity loss, and greenhouse gas emissions [1, 2]. Mining operations often lead to extensive land disturbance, such as vegetation clearance, soil erosion, and topographic changes, which not only disrupt ecosystems but also reduce habitat availability and biodiversity [3]. Additionally, pollutants from extraction, smelting, transportation, and processing—such as dust, toxic gases, heavy metals, and tailings—adversely impact air, water, and soil quality [3]. Although some mines have implemented ecological restoration measures, restoring the original ecosystem remains difficult, time-consuming, and often limited in effectiveness. As carbon neutrality gains priority, the green transition of mining and ecological restoration have become essential.

Traditional physical and chemical remediation methods improve environmental conditions to some extent, but they are costly and often fail to restore the complexity and biodiversity of ecosystems [4]. By contrast, bioremediation, using diverse plants and microorganisms to rebuild disrupted ecosystems and remediate contaminated soils, offers an economical, effective, and sustainable alternative [5]. Bioremediation techniques improve the structure of degraded soils, increase organic matter, enhance water retention and nutrient availability, and support the growth of additional vegetation [6]. Methods like phytoremediation and microbial remediation help remove or stabilize heavy metals in soils through absorption, degradation, or transformation processes [7, 8]. This ecological approach improves the environmental quality of mining areas, creating opportunities for eco-tourism and sustainable development.

During mine restoration, vegetation and soil amendments can fix atmospheric carbon dioxide (CO_2) through photosynthesis and microbial activity, thereby reducing carbon emissions and restoring ecosystem functionality [9]. Above-ground vegetation plays a major role in carbon sequestration, as plants absorb atmospheric CO_2 through photosynthesis and store it in biomass [10]. Meta-analyses indicate that, under optimal vegetation types for specific climates, soil organic carbon sequestration potential can reach up to 12.86 Mt C per year [11]. Soil, as a significant carbon pool, enhances long-term carbon storage and creates stable carbon sinks by promoting microbial diversity and activity [12]. Furthermore, adding organic matter (e.g., compost, straw, and biochar) can significantly increase soil carbon content and enhance carbon sink potential, contributing to climate change mitigation and carbon neutrality objectives [13].

Against this backdrop, this study uses VOSviewer to analyze research trends in ecological restoration and carbon sequestration in mining areas, systematically synthesizing current findings. The study provides theoretical support for further research, policy development, and ecological restoration practices in mining regions.

2. Materials and Methods

2.1. Data Collection

To provide a comprehensive overview of international research trends in ecological restoration and carbon sequestration within mining areas, reliable data were sourced from the Web of Science Core Collection, a widely recognized authoritative database by the Institute for Scientific Information (ISI). The search was conducted using the query: TS= ("mining*" AND "Restoration*" AND "carbon*"), covering articles published between 2000 and 2024, in English, and limited to article-type documents. This search yielded 922 relevant articles (retrieved on August 24, 2024, at 13:40). We initially assessed each article's relevance to ecological restoration and carbon sequestration in mining contexts by reviewing titles and abstracts. When relevance could not be established through these means, full texts were reviewed for further screening. A final total of 858 articles was selected, authored by 3,757 contributors from 1,184 institutions across 84 countries or regions.

2.2. Data Processing

Using VOSviewer (version 1.6.16), we conducted a bibliometric analysis of the 858 selected articles to visualize trends and collaborations in the field. This analysis included temporal trends (annual publication counts), collaboration networks (authors, countries, and institutions), and research hotspots and frontiers (keyword co-occurrence). The network maps and charts generated show specific nodes representing key terms, such as countries, institutions, or keywords, with node size indicating research output.

3. Results and Analysis

3.1. Publication Trends

The annual publication trend provides insight into the field's development trajectory. From 2000 to the present, research on ecological restoration and carbon sequestration in mining areas has shown a steady upward trend, which can be divided into three phases. The initial phase (2007–2012) had fewer than 20 publications annually, reflecting the field's early stages. During the growth phase (2013–2018), the number of publications gradually increased as research interest expanded globally. Since 2019, a rapid growth phase has emerged, with publications projected to exceed 130 by 2024.

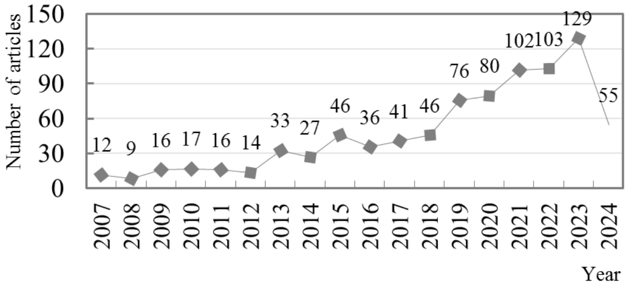

Figure 1. Annual publication volume in this field from 2000 to date.

3.2. Author Co-occurrence Analysis

The author collaboration network reflects the degree of cooperation within the research field. Since 2000, BAI Zhongke has been the most prolific author, with 19 publications (2.21% of total articles), followed by Pietrzykowski M and Bi Yinli with 15 and 13 publications, respectively. These authors, along with their collaborators, form three major research clusters that have driven the field's progress. However, numerous isolated nodes indicate independent research efforts or limited collaboration among some authors. Given the global and interdisciplinary nature of this field, expanding current partnerships to foster broader, deeper scientific collaborations is essential for future research.

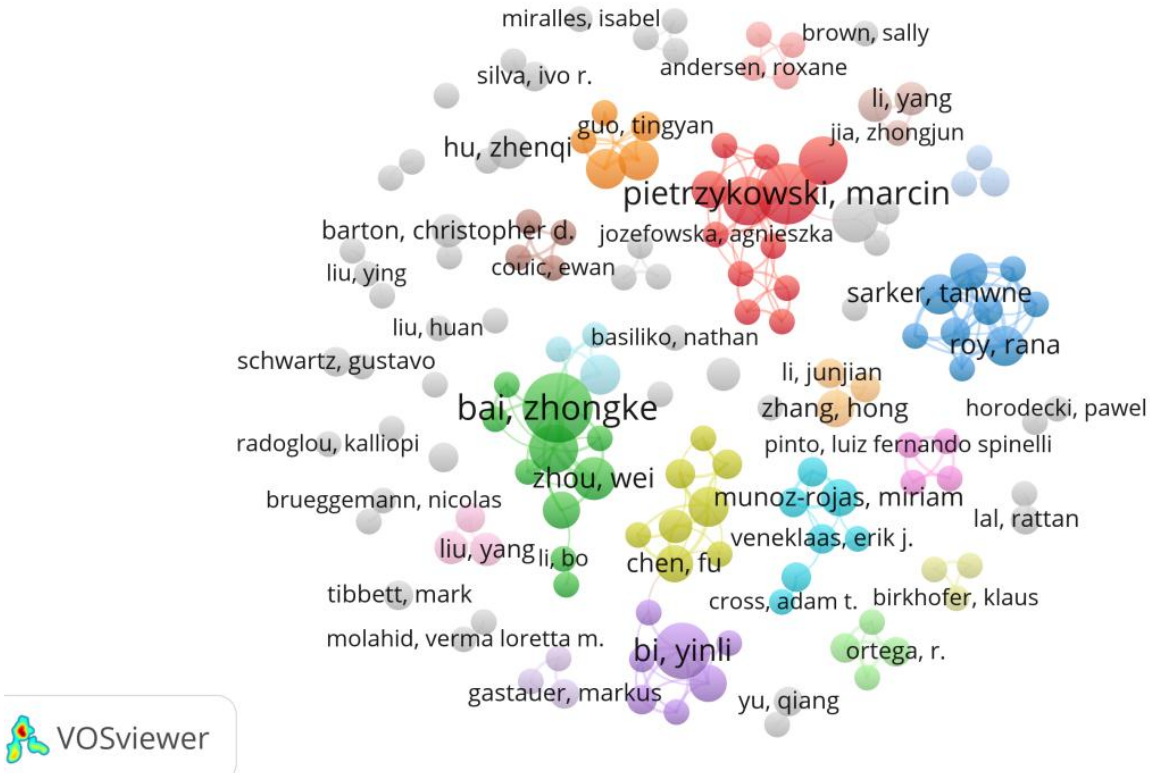

Figure 2. Co-occurrence network of authors in this field from 2000 to date.

3.3. Country/Region Co-occurrence Analysis

The network of publishing countries and regions reveals a complex landscape of global research collaborations. China and the United States are leading contributors, facilitating international academic exchange. European countries, such as Spain, France, Poland, and the Czech Republic, demonstrate close regional cooperation. Collaborative efforts between developed countries (e.g., the United States, Australia) and emerging markets (e.g., India, Brazil, South Africa) illustrate the field's inclusivity. Distinct color-coded clusters reflect regional research alliances, with European countries forming focused networks, while Asian countries often collaborate closely with China. Emerging economies like Brazil, South Africa, and Iran have increasingly active research initiatives, showing gradual integration into the global scientific network. Such international cooperation promotes knowledge exchange and advances technical innovation.

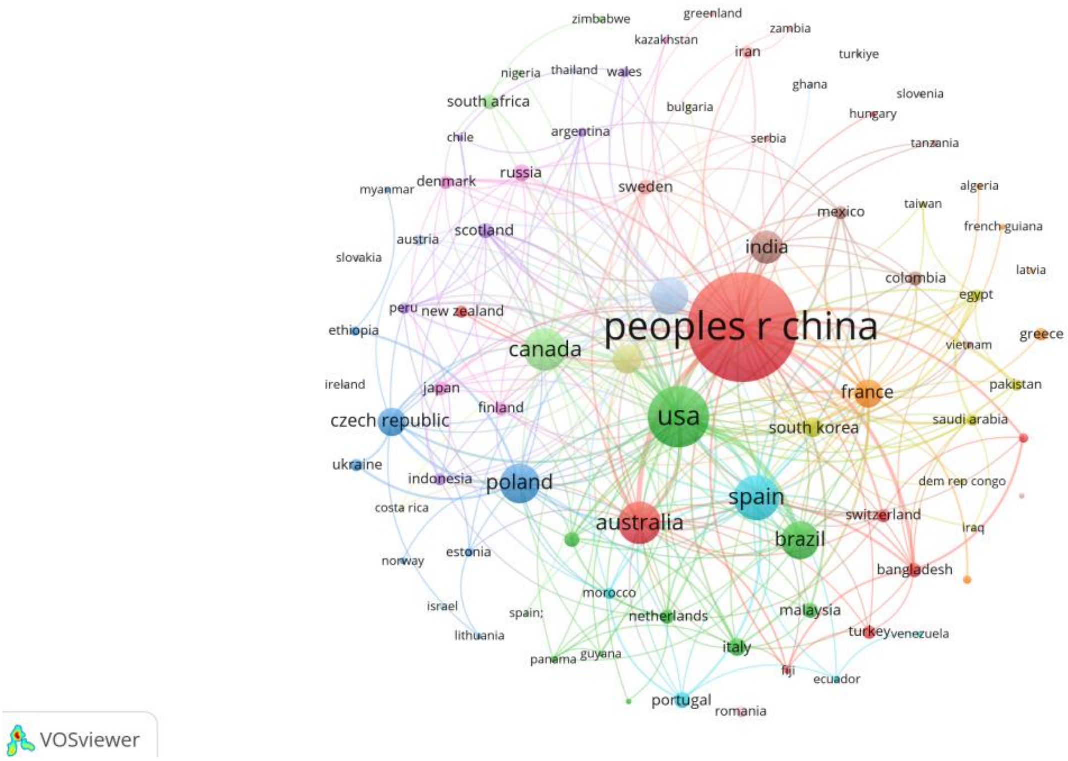

Figure 3. Co-occurrence network of countries/regions in this field from 2000 to present.

3.4. Institutional Co-occurrence Analysis

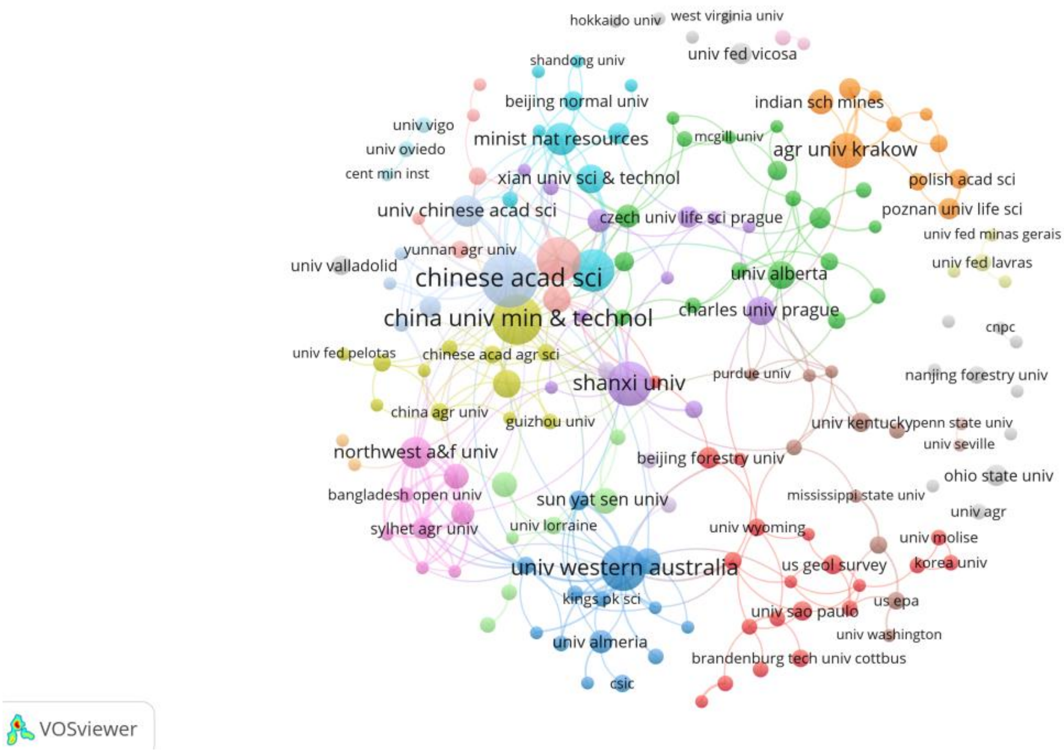

Figure 4. Co-occurrence network of institutions in this field from 2000 to date.

The Chinese Academy of Sciences and China University of Mining & Technology appear as dominant nodes, reflecting their central roles in this research area. Both institutions have produced significant contributions and established extensive collaborative networks. Shanxi University and the University of Western Australia are also notable nodes, indicating their strong influence and broad collaborations within the field. Multiple international collaboration networks are visible, with institutions like the University of Western Australia, University of Alberta, and Agricultural University of Krakow showing significant ties with Chinese institutions. Clusters, such as those involving China Agricultural University and Northwest A&F University, indicate robust domestic collaborations within China. In Europe, the Polish Academy of Sciences and Agricultural University of Krakow have formed a regional network, underscoring the importance of localized partnerships. Institutions such as Beijing Forestry University and the US Geological Survey exemplify cross-disciplinary collaborations across fields like ecology, soil science, and geology, highlighting the field's multidisciplinary and globalized nature.

3.5. Citation Co-occurrence Analysis

The citation network highlights interdisciplinary knowledge flow, with core journals like Science of the Total Environment, Ecological Engineering, Environmental Science and Pollution Research, Chemosphere, and Journal of Environmental Management as central nodes. These journals frequently publish influential work on ecological restoration, pollution remediation, and soil and water management. Their high citation rates reflect their role in disseminating core research findings and advancing field knowledge. Journals such as Plant and Soil and Forests demonstrate the intersection of ecology and plant sciences, while Sustainability and Journal of Cleaner Production emphasize environmental management and sustainable development. Smaller, region-specific journals (e.g., Polish Journal of Environmental Studies) focus on localized issues and contribute to integrating regional insights into the global knowledge system. By fostering cross-disciplinary citation, these core journals support the diversity and growth of the research field.

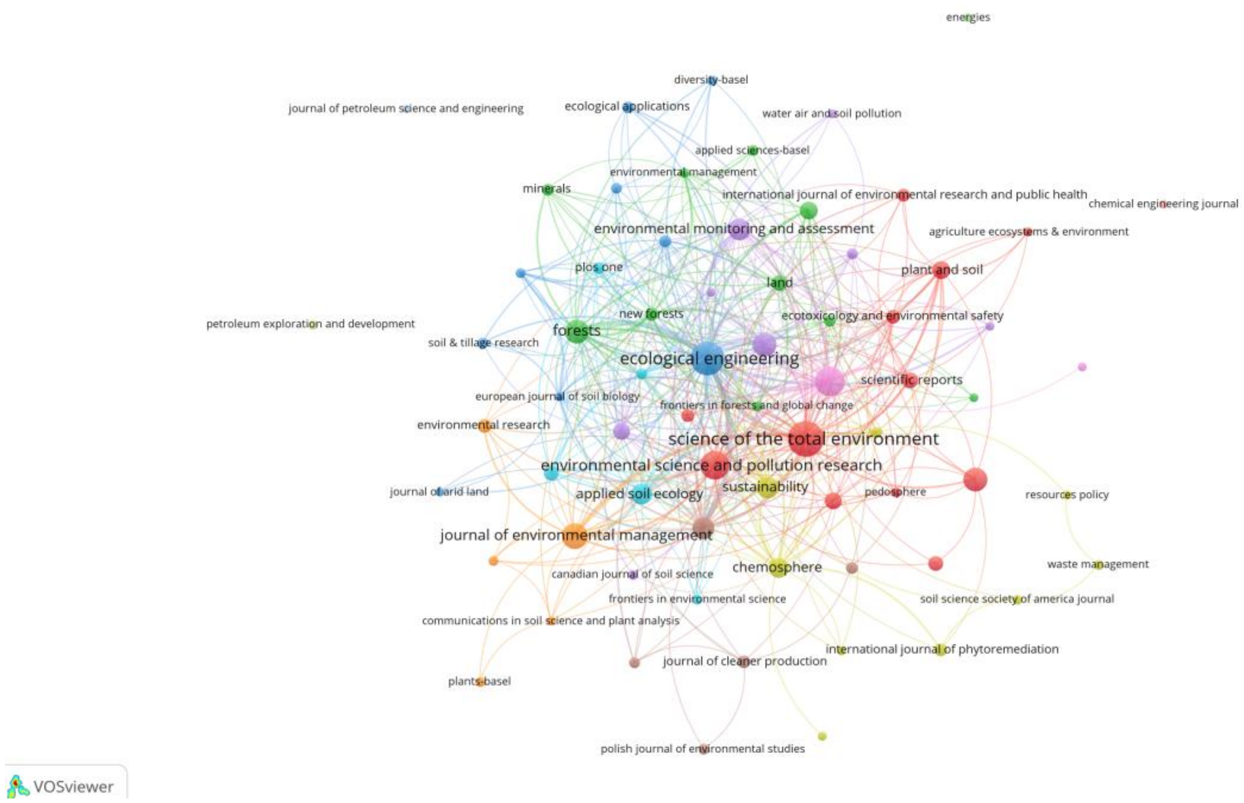

Figure 5. *Citation co-occurrence network of this field from 2000 to date.*

3.6. Citation Co-occurrence Analysis

The keyword co-occurrence network is divided into seven clusters, representing a total of 390 nodes and 12,869 connections. Excluding one relatively independent cluster, the main research foci can be summarized as follows: (1) strategies for ecological and vegetative restoration of mining areas; (2) carbon sequestration processes in vegetation and soil in mining areas; (3) mechanisms for soil health restoration in mining areas; (4) the role of plants and microbes in pollution remediation; (5) importance of water resource management and wetland restoration in mining areas; and (6) ecological succession and biomass accumulation in mining area rehabilitation. These clusters highlight the field's complexity and offer directions for future research in mining area ecological restoration.

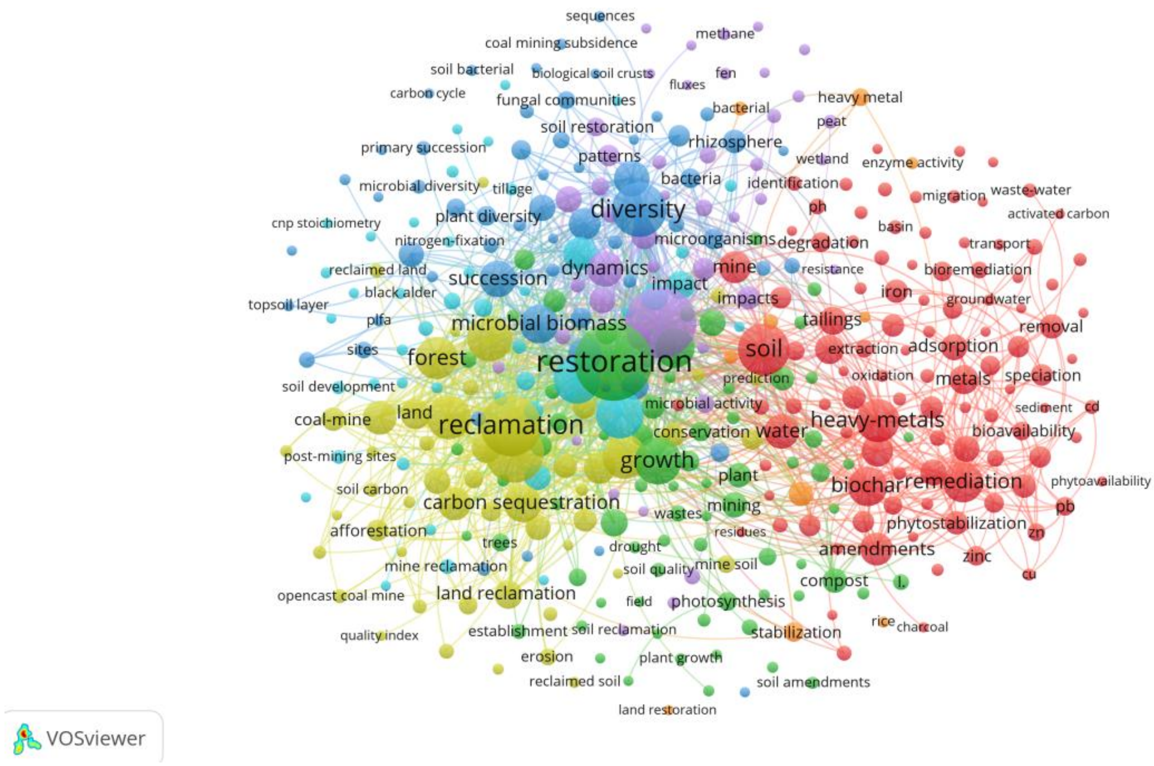

Figure 6. *Co-occurrence network of keywords in this field from 2000 to date.*

4. Discussion

4.1. Strategies for Ecological and Vegetative Restoration of Mining Areas

Restoration of mining ecosystems and vegetation, integral to carbon cycling and ecological repair, supports biodiversity enhancement and carbon sequestration. "Reclamation" and "Restoration" appear as dominant terms, underscoring the prominence of ecosystem rehabilitation in mining restoration research. Initial steps require comprehensive assessment of ecological degradation and specific remediation plans. Addressing primary disturbances such as mining, pollution, and invasive species removal is essential [14, 15]. Soil, vegetation, and hydrological conditions are then rehabilitated through both natural and artificial replanting techniques. Utilizing native, drought-resistant species optimizes vegetation resilience and longevity [16]. Monitoring and adaptive management of invasive species, pests, and controlled grazing are necessary to maintain restored systems [17]. By establishing ecological corridors, connectivity across fragmented areas can improve carbon sequestration efficiency, enhancing carbon capture within restored landscapes [18].

4.2. Carbon Sequestration Processes in Vegetation and Soil in Mining Areas

Carbon sinks, which store atmospheric CO_2 through natural or engineered processes, rely heavily on vegetation and soil. Vegetative carbon sequestration, particularly through reforestation and wetland restoration, is a primary strategy in mining areas [19]. For less polluted sites, productive or ornamental plantings offer viable sequestration options, such as hemp crops in lignite post-mining regions, which enrich soil organic matter [20]. Soil carbon, primarily sourced from plant residues and root exudates, is also crucial [22]. Soil amendments, including crop residue retention and reduced tillage, increase soil carbon capture and prevent erosion [23]. Biochar, derived from pyrolyzed agricultural waste, enhances soil structure and moisture retention, boosting carbon sequestration efficiency [24]. Effective carbon capture depends on long-term land use and ecosystem management policies, which are vital for mitigating climate change impacts.

4.3. Mechanisms for Soil Health Restoration in Mining Areas

Restoring soil health is fundamental to ecosystem recovery in mining areas. "Soil," "Heavy Metals," and "Biochar

Remediation" reflect the focus on soil restoration, especially in remediating heavy metal contamination. Heavy metals pose significant risks to crop growth and human health through food chains. "Soil Amendments" and "Stabilization" indicate common remediation strategies, such as chemical stabilization with lime or biochar [25]. While physical and chemical methods stabilize pollutants, they are costly and less suitable for high-contamination areas. Biological approaches, favored for cost-effectiveness and scalability, are increasingly preferred for long-term solutions in contaminated soils.

4.4. The Role of Plants and Microbes in Pollution Remediation

Biological remediation, encompassing phytoremediation and microbial remediation, is crucial in mitigating mining pollution. Plants absorb and stabilize heavy metals, with hyperaccumulators effectively removing contaminants from soil [26, 27]. Local species are often prioritized for resilience, such as *Mallotus* species in China's lead-zinc mining areas [28]. Microbial remediation leverages specific microorganisms to transform or immobilize metals, minimizing their environmental threat [7]. "Microbial Biomass" and "Rhizosphere" highlight the relevance of microbial communities in improving plant growth and soil health [29]. Collaborative plant-microbe interactions further enhance remediation by supporting mutual nutrient exchanges and promoting stable metal sequestration. Amendments like organic fertilizers and compost improve soil quality and metal binding [30, 31], while biochar provides stable carbon structures that mitigate metal mobility and toxicity [13]. This synergy underscores the efficacy of biological remediation for both pollutant removal and carbon sequestration in mining contexts.

4.5. Importance of Water Resource Management and Wetland Restoration in Mining Areas

Mining site restoration requires an integrated approach, including soil, vegetation, and water resource management [32]. "Water," "Wetland," and "Methane" illustrate the significance of water management, especially in wetland restoration for ecological recovery. Proper water resource management supports dust suppression, irrigation, and wastewater treatment while conserving resources for sustainable restoration [33]. Rehabilitating damaged water systems such as rivers and aquifers fosters biodiversity and ecosystem health [34]. Wetland restoration, in particular, regulates microbial communities and greenhouse gas flux, notably reducing methane emissions. Consequently, wetland ecosystems enhance the stability and biodiversity of mining areas, supporting ecosystem resilience [32].

4.6. Ecological Succession and Biomass Accumulation in Mining Area Rehabilitation

Biomass accumulation, a marker of ecosystem health and carbon cycling, signifies ecological succession and carbon storage capacity. "Primary Succession" and "Coal-mine" associated with "Reclamation" underscore interest in studying succession from bare land to mature vegetation cover [35]. Biomass accumulation indicates plant community establishment and ecosystem stability, with "Biomass" and "Plant Growth" marking key indicators of rehabilitation success. Plant and microbial growth restore ecosystem functions, including hydrological regulation and nutrient cycling [36]. Biomass-focused approaches in restoration efforts support both ecological recovery and climate mitigation, facilitating sustainable mining area rehabilitation.

5. Conclusions

Research on ecological restoration and carbon sequestration in mining areas reveals several key trends and characteristics. Publication volume in this field has increased, with China leading the contributions, largely through the Chinese Academy of Sciences, while Science of the Total Environment remains the most frequently cited journal. Keyword network analysis identifies six primary research focuses: (1) strategies for ecological and vegetative restoration of mining areas; (2) carbon sequestration processes in vegetation and soil in mining areas; (3) mechanisms for soil health restoration in mining areas; (4) the role of plants and microbes in pollution remediation; (5) importance of water resource management and wetland restoration in mining areas; and (6) ecological succession and biomass accumulation in mining area rehabilitation.

Given the growing global concern over climate change, research in mining area restoration and carbon sequestration plays a critical role in mitigating emissions and restoring ecological balance. Future studies should prioritize the following areas:

1) Multiscale Monitoring and Assessment Technologies: Leverage satellite remote sensing and drone technology for multiscale, long-term monitoring of ecosystem recovery and carbon sequestration. Big data and AI-driven analysis can identify key trends, optimize sequestration strategies, and predict restoration outcomes.
2) Multifunctional Ecosystem Restoration: Consider multiple ecosystem services—carbon sequestration, soil and water conservation, and biodiversity preservation. Exploring combined ecological engineering and natural restoration approaches can enhance resilience and stability of restored mining ecosystems.
3) Technological Innovation and Practical Application: Integrate biotechnology with ecological engineering,

utilizing novel materials and cost-effective restoration techniques to improve plant carbon sequestration and soil carbon storage, enhancing overall restoration efficiency.

4) Climate-Adaptive Restoration Strategies: Develop restoration strategies resilient to climate change by selecting drought-resistant native species, optimizing water management, and implementing dynamic management systems to ensure restoration stability under extreme conditions.
5) Carbon Sequestration Mechanism and Model Optimization: Further investigate carbon inputs, storage, and release mechanisms within mining ecosystems. Develop optimized sequestration models tailored to specific mining conditions to forecast sequestration potential and create targeted restoration strategies.
6) Policy Support and International Collaboration: Promote policies and regulations that support mining ecosystem restoration and carbon sequestration, strengthening global collaboration for technology sharing and management expertise, advancing global efforts in ecosystem restoration.
7) Integrating Socioeconomic and Ecological Benefits: Assess the economic benefits of mining ecosystem restoration to support ecotourism and agricultural development, fostering community involvement and ensuring long-term social sustainability.

Focusing on these critical areas will enhance the contributions of mining ecosystem restoration and carbon sequestration research to achieving carbon neutrality, restoring ecological balance, and driving sustainable development.

Abbreviations

CO_2 Carbon Dioxide

Author Contributions

Yulong Wang: Conceptualization, Data curation, Formal Analysis, Investigation, Software, Supervision, Validation, Visualization, Writing – original draft

Long Zhang: Data curation, Formal Analysis, Investigation, Software

Guoyan Zhu: Validation, Visualization

Chen Song: Data curation, Methodology

Longgang Zhang: Formal Analysis

Wei Chang: Writing – review & editing

Kun Li: Writing – review & editing

Xiaohui Wang: Conceptualization, Funding acquisition, Writing – review & editing

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Data Availability Statement

The data is available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflicts of interest.

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