RESEARCH ARTICLE

Bryophytes in slope ecological restoration: A review based on the CiteSpace tool

Yige Chen[1, 2], Wei Zhong[1, 2, *], JunfangCui[1, 2], Jialiang Tang[1, 2], Xuefeng Xiao[3]

[1]Institute of Mountain Hazards and Environment, Chinese Academy of Sciences, Chengdu, Sichuan, China. [2]University of Chinese Academy of Sciences, Beijing, China. [3]Chongqing Yitian Health and Wellness Industry Development Co., Ltd, Chongqing, China.

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Bryophytes with their unique ecological adaptability demonstrate significant potential in slope ecological restoration. This study systematically analyzed domestic and international literatures published between 2005 and 2025 on bryophyte-based ecological restoration using CiteSpace visualization tools with a focus on research hotspots, evolutionary trends, and engineering practices. The results showed that international studies predominantly emphasized fundamental ecological theories such as peatland restoration, biodiversity, and ecosystem functions, whereas domestic research prioritized applied technologies including rocky desertification control, heavy metal pollution remediation, and artificial cultivation. Bryophytes enhance ecosystem stability through multidimensional mechanisms including soil-water conservation, soil improvement, pedogenesis, and pollution monitoring. Future research should focus on standardizing bryophyte-based restoration technologies and evaluating cross-scale ecological effects to promote their broader applications in fragile ecosystems.

Keywords: *Bryophytes* (mosses); CiteSpace; biological crust; slope ecological restoration; soil-water conservation.

[*]**Corresponding author:** Wei Zhong, Institute of Mountain Hazards and Environment, Chinese Academy of Sciences, Chengdu, Sichuan 610213, China. Email: zhongwei@imde.ac.cn.

Introduction

As pioneer species in the transitional zone between aquatic and terrestrial environments, bryophytes are widely distributed across diverse geographical regions worldwide due to their unique ecological adaptability, particularly their ability to thrive in arid and impoverished areas. Globally, there are approximately 23,000 known species of bryophytes with China accounting for about one-tenth of this total [1]. As pioneer species, bryophytes support ecological succession through mechanisms such as promoting soil formation and nutrient cycling [2]. Although bryophytes are common, their small size has led to insufficient attention being paid to their economic and research value.

In recent years, ecological restoration in rocky desertification areas, especially in karst regions [3], as well as abandoned mining areas has highlighted the potential of bryophytes. Notably, after the earthquake in Jiuzhaigou, Sichuan, China, bryophytes successfully addressed the challenge of restoring bare rock slopes [4, 5], demonstrating their excellent adaptability to arid and impoverished environments. Further, the use of biological soil crusts including bryophytes

to improve hydrological, soil physicochemical, and biogeochemical cycles in desertified and mining areas shows considerable promise.

Despite growing interest, a comprehensive analysis of global research trends and the application of bryophytes in slope ecological restoration remains lacking. Current reviews often fail to distinguish between fundamental theoretical research and applied technological developments, particularly when comparing domestic and international research focuses. This study aimed to fill this gap by employing CiteSpace visualization tools to systematically review literatures from 2005 to 2025 to identify and compare research hotspots and evolutionary trends in bryophyte ecological restoration domestically and internationally, summarize the ecological functions of bryophytes in slope restoration, evaluate successful case studies of bryophyte application in restoration projects, and propose future research directions to enhance the application of bryophytes in the restoration of fragile ecosystems. This research provided valuable synthesis for researchers and practitioners, promoting the sustained development of bryophyte-based ecological restoration.

Materials and methods

Data sources

To comprehensively explore the application and progress of bryophytes in ecological restoration, an in-depth search and analysis were conducted in both international and domestic literature databases. Internationally, the Web of Science Core Collection database (https://www.webofscience.com) was explored with the keywords of "moss ecological restoration" or "bryophyte ecological restoration" in the period from 2005 to 2025. After strict manual screening to exclude non-academic and repetitive content such as conference papers, book reviews, and announcements, 235 high-quality articles were obtained and exported in plain text format for further analysis. Domestically, the China National Knowledge Infrastructure database (https://www.cnki.net) was employed with the theme "bryophyte ecological restoration" in the period 2005 to 2025. After multiple verifications and screenings, 53 articles were selected and exported in RefWorks format. All literature retrieval was completed on April 25, 2025, ensuring the timeliness and accuracy of the data.

Literature mapping

CiteSpace (https://citespace.podia.com) is a knowledge graph analysis tool developed on the Java platform, offering powerful data mining and visualization functions, which enables the extraction of academic value from multidimensional information elements such as authors, research institutions, keywords, and references. This study used CiteSpace version 6.4.R1 to conduct an in-depth analysis of the literature on bryophyte ecological restoration. Co-occurrence maps were applied to display clusters of high-frequency keywords and their emergence, providing a comprehensive understanding of the current status, evolutionary trends, and hotspots in bryophyte ecological restoration research both domestically and internationally.

Analysis of case studies

Recent case studies underscored the versatile applications of bryophytes in restoration ecology. Examples included the rewetting and reintroduction of *Sphagnum* mosses for restoring degraded peatlands in Canada (ca. 2000) with key metrics such as *Sphagnum* cover, water table dynamics, and soil stability; the optimization of laboratory cultivation protocols for Mediterranean moss species in Portugal (2021), focusing on growth rate of cover and responses to temperature and photoperiod; and the recent strategic selection of rapidly establishing biocrust mosses and lichens for dryland rehabilitation in the Great Basin, USA, emphasizing reproductive rate and establishment mechanisms. Complementing these, a detailed investigation in the post-earthquake landscape of Jiuzhaigou National Nature Reserve (Sichuan, China) with the field sampling in 2019 quantitatively assessed

functional traits of three dominant moss crusts including *Racomitrium japonicum*, *Hypnum plumaeforme*, and *Plagiomnium ellipticum* by measuring carbonic anhydrase activity, dissolution rate, carbon sink potential, soil consolidation capacity, and water retention rates. Collectively, these efforts highlighted the importance of species-specific functional traits, precise environmental controls, and quantifiable performance indicators in designing effective bryophyte-based restoration strategies across diverse biomes and disturbance regimes.

Results and discussion

Global research hotspots and trends in bryophyte ecological restoration

The annual number of publications reflected the development trends of research on bryophytes in ecological restoration. During the statistical period from 2005 to 2024, research related to bryophyte ecological restoration showed an overall upward trend. From an international perspective, the number of relevant publications went through three distinct phases. The period from 2005 to 2012 was the initial phase with a relatively small number of publications, and the total annual output remaining below ten articles; 2013 to 2020 was the development phase with fluctuating growth in the number of publications and an average annual output of approximately eleven articles; and 2021 to 2024 was the rapid growth phase, peaking in 2023 with twenty-five publications. Domestically, the publication history was divided into two stages. From 2005 to 2017, a nascent stage with fewer than three publications per year; and from 2018 to 2023, a rapid growth phase with the number of publications increasing from three in 2018 to ten in 2023. Data for 2025 was not included in the analysis because literature retrieval was conducted in 2025.

(1) Keyword clustering analysis

Keywords represent the essence of paper, and those with high frequency and strong centrality reflect research hotspots in a field. Keyword clustering techniques provided insights into the latest research frontiers and emerging trends in bryophyte ecological restoration. The keyword clustering analysis conducted using CiteSpace for domestic and international studies demonstrated that, internationally, research on bryophyte ecological restoration was extensive with in-depth studies on peatland restoration. Among the sixteen research clusters, two were specifically dedicated to core *Sphagnum* issues with one on *Sphagnum* establishment and the other on regenerating *Sphagnum*, both closely related to peatland ecological restoration, highlighting their importance. Notably, international research tended to focus more on theoretical exploration such as studies on functional roles aimed at understanding the functions of ecosystem components and their interactions, plant-environment relationships focusing on interaction patterns between plants and the ecological environment, and ecosystem engineers, examining the profound impacts of key species on ecosystems. Domestically, research on bryophyte ecological restoration technologies and practice attracted significant attention. Among the five clusters, ecological restoration, slope restoration, and heavy metal treatment were closely related, while the other two clusters focused on the characteristics of bryophytes and their response mechanisms to various environmental factors (Figure 1). Analysis of keyword frequency revealed significant differences as well as commonalities between domestic and international research hotspots in bryophyte ecological restoration. Domestically, "rocky desertification" appearing 6 times and "heavy metals" appearing 4 times were high-frequency keywords, reflecting the academic recognition of bryophytes' unique value in accelerating rock weathering and promoting soil formation in Karst regions, as well as their potential in adsorbing heavy metals. The frequent appearance of keywords such as "artificial cultivation" (3 times) and "bacterial community" (3 times) indicated domestic efforts to transition from laboratory theory to practical engineering applications. In contrast, international research emphasized theoretical

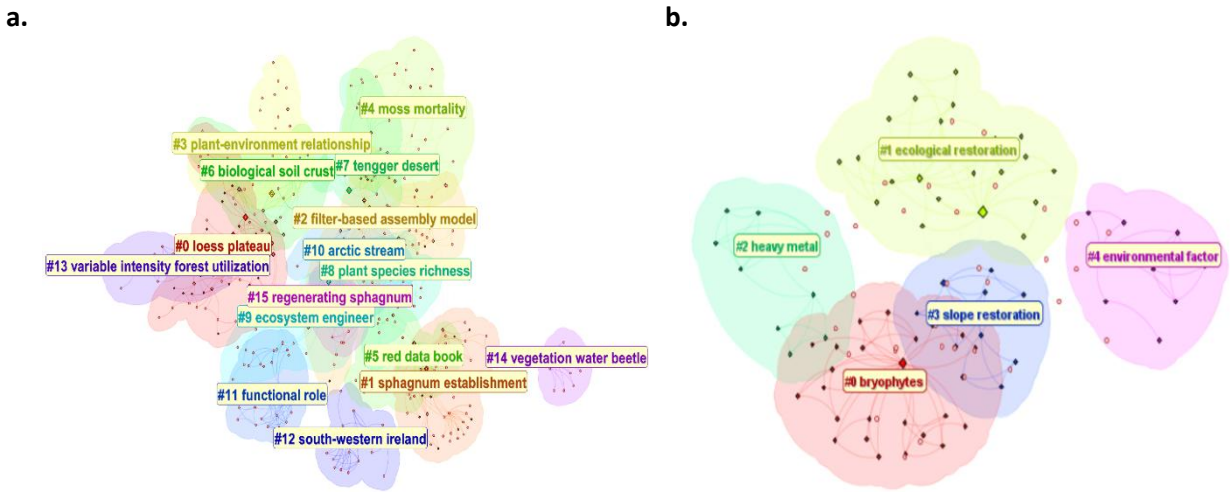

Figure 1. Keyword clustering analysis of bryophyte ecological restoration research across international (**a**) and Chinese (**b**) literatures.

exploration with high-frequency terms such as "Biodiversity" (29 times), "Diversity" (48 times), and "Dynamics" (22 times) highlighting a deep concern for ecosystem complexity, dynamic evolution, and biodiversity conservation. The widespread use of keywords like "vegetation" (34 times) and "community" (31 times) further underscored the importance of the structure and function of entire ecosystems in international research. Notably, both domestic and international research showed strong interest in the relationship between bryophytes and soil. Domestically, "biological crust" (3 times) was a key keyword, while internationally, "biological soil crusts" (38 times) received considerable attention, demonstrating the close relationship between bryophytes and soil and their critical role in ecological restoration.

(2) Keyword emergence analysis

By using CiteSpace, the emergence of keywords was visualized to track changes in research directions. The keyword emergence map revealed differences in research hotspots and trends between domestic and international ecological studies. International research consistently emphasized fundamental ecological issues, while domestic research was more policy-driven and focused on applied topics. Thematically, international research revolved around basic ecology with long-term high-frequency appearances of keywords such as "species richness" and "vegetation", reflecting sustained attention to biodiversity and vegetation dynamics. The emergence of interdisciplinary themes like "enzyme activity" indicated the growing prominence of soil microbial research. In contrast, domestic research was more oriented toward practical applications with localized and applied issues dominating. The frequent appearance of keywords such as "heavy metal", "rocky desertification", and "soil and water conservation" reflected China's urgent need to manage ecologically fragile areas amid rapid industrialization (Figure 2).

Through keyword cluster analysis and high-frequency keyword statistics of research on bryophyte ecological restoration both domestically and internationally using CiteSpace, the study revealed that research in this field exhibited both commonalities and differences. Researchers worldwide consistently emphasized the interaction mechanisms between bryophytes and soil. In international studies, "biological soil crusts" appeared 38 times, while domestically, "biological crust" was mentioned 3 times, indicating that the critical role of bryophytes as core components of biological soil crusts in soil

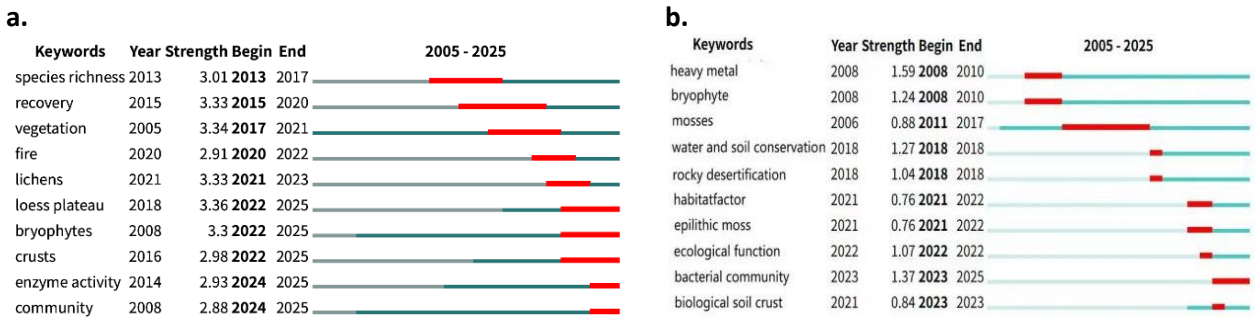

Figure 2. Keywords of moss ecological restoration research internationally (**a**) and domestically (**b)** (2005-2025).

stabilization, water retention, and nutrient cycling had been widely recognized. This commonality stemmed from the unique ecological adaptations of bryophytes, which included that their rhizoid systems could effectively stabilize surface soil, and their leaf structures could intercept precipitation and reduce runoff, thus giving them direct practical value in addressing global ecological problems such as desertification and soil erosion. In contrast, international research tended to focus more on theoretical exploration of ecological mechanisms. High-frequency keywords such as "biodiversity" (48 times) and "dynamics" (22 times) reflected in-depth investigations into ecosystem complexity, dynamic succession, and biodiversity conservation. In studies on peatland restoration, international scholars used species interaction network models to reveal the regulatory role of bryophyte communities in carbon cycling and water balance. Domestic research, however, was more application-oriented with high-frequency keywords like "rocky desertification" (6 times) and "heavy metal" (4 times), highlighting a focus on practical issues such as rocky desertification control and heavy metal pollution remediation. This divergence likely stemmed from differing regional ecological pressures, distinct research evaluation systems, and varying historical depths of bryological data accumulation.

Ecological functions of bryophytes in slope restoration

Based on keyword clustering analysis and the literature review, China placed great importance on the application of bryophytes in slope restoration. The literature analysis showed that bryophytes played four key roles in slope ecological restoration including water and soil conservation, soil improvement, promotion of soil formation, and pollution indication. Bryophytes exhibited multidimensional and synergistic ecological functions in water and soil conservation. Through mechanisms such as physical interception of precipitation [6], water conservation [7], erosion resistance [8, 9], and soil structure improvement [10-13], they effectively enhanced the structural and functional stability of degraded ecosystems. As "miniature soil engineers," bryophytes contributed multidimensionally to soil improvement through the regulation of biogeochemical cycles [14-16], microbial synergy [17, 18], and soil structure optimization [19]. As "ecological pioneers at the rock-soil interface", bryophytes played an irreplaceable role in weathering and soil formation through mechanisms such as physical interception [20], biochemical weathering [21], and crust-layer construction [22-24]. As "natural pollution sensors", bryophytes demonstrated high sensitivity, broad-spectrum detection capability, and high spatial resolution advantages in environmental pollution monitoring due to their unique physiological characteristics and ecological adaptability [25-27].

Case studies of bryophyte ecological restoration projects

The significant potential of bryophytes in ecological restoration has gained recognition through numerous successful applications in ecological restoration practices both domestically and internationally. In the United States, a restoration project employed a combination of passive and active restoration methods. Passive restoration relied on natural dispersal, while active restoration involved introducing moss fragments or spores, supplemented by physical barriers such as burlap coverings to reduce soil erosion [28]. This approach resulted in the rapid proliferation of mosses and lichens, improving soil stability and suppressing invasive plants. Before restoration, the area was characterized by arid conditions degraded by fire or grazing, lacking a biological crust. After restoration, the biological crust was restored, promoting the native plant community reestablishment and reducing soil erosion. In Spain, researchers developed a laboratory cultivation method for mosses under controlled temperature and photoperiod using an organic horticultural substrate without fertilizer [29]. The cultivated mosses were transplanted to degraded areas or urban green spaces, achieving over 60% moss coverage within 5 - 8 weeks. The mosses showed linear growth at low temperature of 15°C but declined at higher temperatures from 20 to 25°C. Before restoration, the degraded areas lacked vegetation cover with unstable soil. After restoration, the rapid formation of a moss layer significantly improved soil stability. In Canada, a peatland restoration project involved rewetting sites, covering them with a straw protective layer, and artificial sowing of *Sphagnum* fragments to optimize microclimate and moisture conditions [30]. This method achieved *Sphagnum* coverage exceeding 50%, restoring peat accumulation function. Vascular plant diversity significantly increased after 3 - 4 years. Before restoration, the peatland was exposed after mining and unable to recover naturally. After restoration, the *Sphagnum* layer was re-established with gradual recovery of ecosystem functions including carbon storage and hydrological regulation. In China, following the Jiuzhaigou earthquake in Sichuan province, researchers screened three superior moss species including *Racomitrium japonicum*, *Hypnum plumaeforme*, and *Plagiomnium ellipticum*, which were suitable for bare rock slope greening and established demonstration plots [4, 5]. The project achieved an average moss coverage of 80% in the plots, providing a practical basis for large-scale restoration. Before restoration, extensive bare rock was exposed after the earthquake, causing severe damage to the natural landscape. After restoration, mosses gradually covered the bare rock, effectively restoring the natural landscape.

Conclusion

This study comprehensively reviewed the research progress on bryophytes in slope ecological restoration from 2005 to 2025 using the CiteSpace visualization tool and found that significant differences existed between domestic and international research on bryophytes with international studies focusing on fundamental ecological theories such as peatland restoration, biodiversity maintenance, ecosystem functions and domestic research emphasizing practical applications like rocky desertification control, heavy metal pollution remediation, artificial cultivation techniques, demonstrating a balanced combination of theory and practice. Bryophytes possessed rich ecological functions. Through multiple mechanisms such as water and soil conservation, soil improvement, promotion of soil formation, and pollution monitoring, they provided strong support for ecosystem stability. As "miniature soil engineers" and "natural pollution sensors," bryophytes had achieved remarkable results in arid area management, degraded peatland restoration, and post-earthquake bare rock slope engineering. Although application examples of bryophytes in ecological restoration were increasingly abundant, research on technical standardization remained inadequate, and a comprehensive

evaluation system for cross-scale ecological effects needed improvement. These factors, somewhat, hindered the large-scale application of bryophytes in fragile ecosystems.

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