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Review

Advancing Slope Stability and Hydrological Solutions Through Biocementation: A Bibliometric Review

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Abstract: Biocementation is an innovative and sustainable technique with wide-ranging applications in slope stabilization, watershed management, and erosion control. Despite its potential, comprehensive evaluations of its use in hydrology and geotechnical engineering are limited. This study addresses this gap through a bibliometric analysis of 685 articles (2013–2023) from the Scopus database, employing VOSviewer and RStudio to explore global research trends, key contributors, and emerging themes. The analysis reveals that China, the United States, and Japan are leading contributors to this field, with significant advancements in microbial-induced (MICP) and enzyme-induced calcium carbonate precipitation (EICP) techniques. These methods have demonstrated effectiveness in improving soil strength, reducing erosion, and enhancing hydrological properties such as infiltration, runoff control, and water retention. Co-occurrence analysis identifies interdisciplinary connections between geotechnics and hydrology, highlighting research clusters focused on biomineralization, erosion resistance, and durability. The findings underscore biocementation's pivotal role in addressing sustainability challenges by providing environmentally friendly alternatives to traditional soil stabilization techniques. This study not only maps the current research landscape but also offers valuable insights into the practical implications of biocementation for slope stability and hydrological management, laying the foundation for future advancements in sustainable engineering practices.

Keywords: biocementation; MICP; EICP; slope stabilization; erosion control; hydrology; sustainability; bibliometric analysis



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1. Introduction

Landslides disrupt transportation networks, damage infrastructure, and cause erosion and environmental degradation. Slope disturbances lead to land degradation and ecological damage [1,2]. Due to direct contact with the atmosphere, surface characteristics are progressively altered by climatic variations, making the surface more prone to soil loss and deterioration [3,4]. In some cases, malfunctioning road drainage systems

designed to collect runoff water can exacerbate slope failures or landslides. These issues demand solutions from both environmental and geotechnical engineers. Localized failures, like those affecting the road network in Laos, highlight the immediate impacts of slope instability [5]. Coastal areas are also vulnerable, with sand slopes facing severe erosion from waves, leading to coastal zone degradation [6]. Changes in rainfall patterns, such as longer dry periods, exacerbate issues like fugitive dust in riverbeds [7,8]. Figure S1 shows a significant crack running across an entire slope soil that underwent riprap stabilization, highlighting potential problems with the method. Traditional methods like retaining walls, dewatering, and soil replacement stabilize slopes but can be expensive and harm the environment (high energy use, water table disruption, chemical leaching). These challenges underscore the need for innovative and sustainable slope stabilization techniques.

The hydrological implications of slope instability are profound, as they directly impact watershed functions, groundwater recharge, and sediment transport into nearby water bodies. This interplay between soil mechanics and hydrological processes necessitates solutions that address both structural stability and hydrological balance [9]. Biocementation offers a novel approach to slope stabilization through two main techniques which include microbial-induced carbonate precipitation (MICP) and enzyme-induced carbonate precipitation (EICP). MICP primarily utilizes urease produced by naturally occurring microorganisms (i.e., *Sporosarcina pasteurii*), while EICP offers more flexibility by employing plant (*Canavalia ensiformis*)-derived urease [1,10]. Refs. [1,2] MICP and EICP ureolysis is a biochemical process where urea is enzymatically hydrolyzed by the urease enzyme sourced from plant or microbial sources into ammonia and carbon dioxide, leading to an increase in pH in the micro-environment [6]. This triggers the chemical reaction between the produced ammonia and dissolved carbon dioxide in the water, forming ammonium carbonate, which decomposes into carbonate ions and ammonium ions [3,4]. The carbonate ions react with calcium ions present in the surrounding environment, usually sourced from calcium chloride or calcium nitrate solutions, to form insoluble calcium carbonate (CaCO_3) precipitates [11,12]. These precipitates often take the form of calcite, vaterite, or aragonite crystals, which can bind soil particles together, enhancing their strength and stability [13].

Importantly, these biocementation methods influence the hydrological properties of soil, such as permeability, infiltration rates, and water retention capacity, offering dual benefits of enhanced slope stability and improved water management. In the biocementation process, CaCO_3 is metabolically precipitated in soil pores, cementing the soil matrix contacts and improving soil strength and stiffness [10,14]. Environmental temperature and pH conditions are crucial in determining the treatment efficiency. Temperature influences enzyme activity rate, while pH impacts enzyme structure and function [15]. Maintaining optimal conditions is essential for successful biocementation, highlighting the importance of environmental factors in slope stabilization and soil treatment. Fine-grained soils present challenges for MICP as bacterial cells struggle to move through these soils [16,17]. However, combining MICP and EICP can enhance biocement formation in soil. EICP can help overcome the limitations of MICP in fine-grained soils by providing an alternative pathway for CaCO_3 precipitation, leading to more effective soil stabilization [15]. Combining MICP with EICP broadens its applicability to diverse soil types.

The significance of slope improvement and soil treatment in preventing landslides, erosion, and other forms of slope instability cannot be overstated. These techniques play a crucial role in maintaining infrastructure integrity, preserving ecosystems, and ensuring public safety. Additionally, sustainable and eco-friendly techniques like biocementation and MICP are essential for addressing these challenges while minimizing environmen-

tal impacts [7,8]. Furthermore, by reducing sediment transport into water bodies, these techniques support hydrological resilience and improve water quality in slope-adjacent ecosystems. Biocementation offers numerous environmental benefits, including a reduced need for traditional stabilization methods that may have higher environmental impacts [18]. These techniques contribute to sustainable land management and ecosystem conservation by providing effective and environmentally friendly solutions to slope stabilization and soil treatment challenges [19]. In addition to their environmental benefits, biocementation and MICP also offer economic advantages. These techniques can result in cost savings compared to traditional improvement methods, particularly in the long term. Their economic feasibility and potential for cost-effective implementation make them attractive options for slope stabilization and soil treatment projects [20,21].

Several successful applications of biocementation and MICP in slope improvement soil treatment projects have been documented. These examples highlight the potential of biocementation and MICP for addressing slope instability and erosion-related challenges in various soil and environmental conditions. Ongoing research in biocementation is advancing slope improvement soil treatment. Researchers continue to explore innovative techniques and methods to improve these processes, making them more effective and applicable to a wider range of environments. For instance, studies have shown that EICP improves surface characteristics and erosion resistance in slope erosion control [22]. Similarly, research has investigated the potential of MICP in cold subarctic regions and clayey soils [23]. The effectiveness of MICP in mitigating suffusion and improving soil stability under seepage conditions has also been demonstrated [24,25]. New biogrout-ing methods have been explored, showing effectiveness against wave erosion in sandy slopes [26]. Furthermore, MICP has been shown to improve root/soil composites without harming vegetation [27]. Comparisons between the effectiveness of MICP and EICP in dune erosion control have been made [28]. Other researchers have used native microorganisms for bio-stabilization [8] or proposed bio-methods for rainfall infiltration control [29]. Studies have also focused on assessing the durability of slope stabilization methods [30,31] and using MICP for coastal protection [32] or industrial-grade chemicals for slope stabilization [33].

Recent studies demonstrate their efficacy in various contexts, including erosion resistance in sandy slopes, stability in clayey soils, and hydrological enhancements such as runoff reduction and water retention. Case studies highlight the potential of biocementation. For instance, CCEICP applications have shown success in mitigating shallow failures in cut slopes under artificial rain conditions, creating impermeable crusts and reducing infiltration [34]. Similarly, nano-bio-treated columns incorporating enhanced MICP and nano-SiO₂ have effectively improved the stability of clayey slopes under high centrifugal accelerations [35]. In coastal regions, MICP and EICP have been employed to protect sandy slopes from marine erosion, enhancing penetration resistance and extending the lifespan of treated areas despite dynamic environmental stressors [36]. Despite these advancements, key knowledge gaps persist. Questions remain regarding the long-term performance of biocementation under varied environmental conditions, its scalability for large-scale projects, and its economic feasibility compared to traditional methods [37,38]. Furthermore, understanding the interplay between soil type, treatment depth, and biocementation efficiency remains critical for optimizing applications in complex geotechnical and hydrological scenarios.

This study aims to address gaps in the current understanding of biocementation for slope stabilization and hydrological management by conducting a comprehensive bibliometric analysis of global research trends by examining 685 articles published between 2013 and 2023 from the Scopus database, which is an ideal source for bibliometric analysis due to its comprehensive coverage of scientific literature [39]. By using visualization mapping tools like VOSviewer (version 1.6.17) and RStudio (version 2021.09.1 “Ghost Orchid”), the study identifies leading contributors, emerging themes, and interdisciplinary connections. This review discusses the environmental sustainability of biocementation, its current applications, limitations, and future directions, thus fostering an understanding of biocementation’s potential to advance sustainable geotechnical practices and inform future research.

Biocementation represents a sustainable and innovative approach to slope stabilization and hydrological management. This study employs bibliometric analysis to uncover interdisciplinary research clusters, emerging trends, and gaps in the field. Unlike previous bibliometric studies, our work integrates co-occurrence mapping of keywords with an emphasis on sustainability and engineering practice. By systematically analyzing global research contributions, this study highlights underexplored connections between biocementation techniques and their applications in hydrological sustainability, providing unique insights for advancing slope stabilization methods.

2. Materials and Methods

2.1. Search Strategy and Keyword Selection

To examine global research advancements and trends in biocementation, the Scopus database was selected for its comprehensive coverage of high-quality, multidisciplinary scientific literature. The search query was designed to include diverse terms reflecting the intersection of geotechnics and hydrology, ensuring a thorough exploration of the field. The final bibliometric data were retrieved from Scopus on 13 March 2024. Multiple sets of keywords related to the field were selected to access relevant publications in the scientific database. The search command used was as follows: TITLE-ABS-KEY ((biocementation) OR (microbial AND induced AND carbonate AND precipitation) OR (enzyme AND induced AND carbonate AND precipitation) OR (MICP pathway) OR (EICP pathway) OR (biomineralization) OR (bio-cementation) OR (microbially AND enhanced AND calcite AND precipitation) OR (bacterially AND induced AND calcite AND precipitation) OR (bio-mediated AND calcification) OR (microbially induced calcite precipitation) OR (ureolysis) OR (biocalcification) OR (ureolytic bacteria) OR (plant urease) OR (microbial urease) AND (slope AND stabilization) OR (slope AND stabilization) OR (slope AND soil AND treatment) OR (soil AND slope AND bioconsolidation) OR (landslide AND mitigation) OR (soil AND surface AND runoff AND prevention) OR (earth AND retention) OR (slope failure) OR (slope erosion) OR (hillside instability) OR (slope degradation) OR (mass wasting) OR (slope collapse) OR (rockslide) OR (earthslide) OR (slope movement) OR (terrain instability) OR (soil slippage) OR (debris flow) OR (earthflow) OR (slope stability)). These keywords reflect the multidisciplinary nature of the field, intersecting geotechnical engineering and hydrology. The research highlights biocementation’s potential to improve slope stability while addressing critical hydrological challenges such as runoff control, sediment retention, and water infiltration, thereby promoting sustainable land and water management practices. The flow chart of the bibliometric steps used in this study is shown in Figure 1.

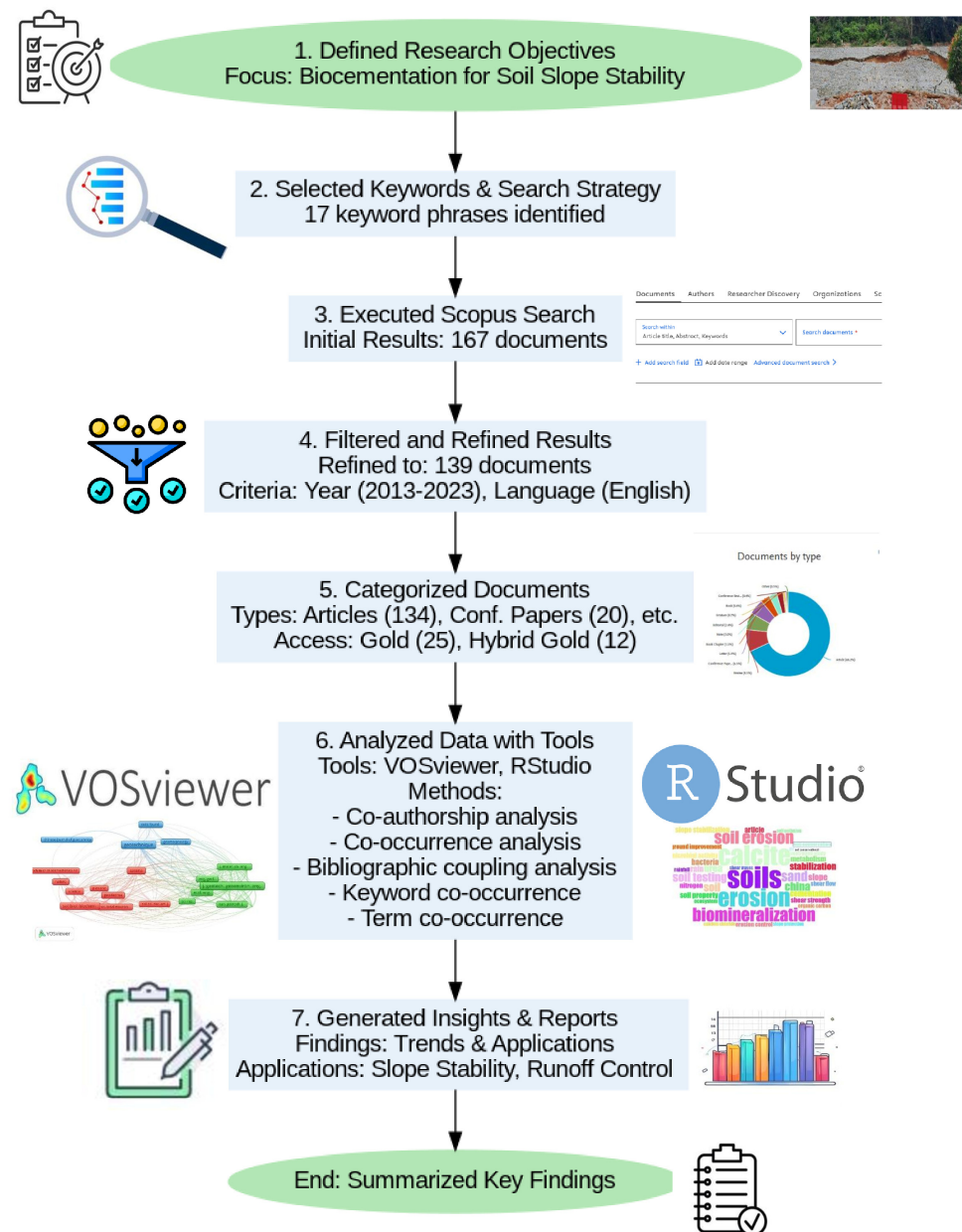


Figure 1. Flowchart of the methodology for data retrieval and bibliometric analysis on biocementation for slope stability.

2.2. Document Collection and Analysis

The search returned 167 documents, refined to focus on English language publications from 2013 to 2023 to ensure relevance and recency. These documents were categorized based on publication type and accessibility. This rigorous selection process ensured a valid dataset for analysis. Open-access publications were further sub-categorized into Gold (25), Hybrid Gold (12), Bronze (9), and Green (21). The documents were mostly published as articles (134), followed by conference papers (20). The remaining publications were classified as book chapters (6), reviews (5), conference reviews (1), and notes (1). These documents were written in English (152) and Chinese (15). After refining the search using the Scopus tool, the publication period was narrowed down to concentrate on documents published from 2013 to 2023, particularly those written in English. The detailed search query and steps are provided in Table S1.

2.3. Visualization Mapping Through VOSviewer and RStudio

The bibliometric tools VOSviewer and RStudio were chosen for their robustness in analyzing and visualizing bibliometric networks. VOSviewer, developed at Leiden University, was used to create co-authorship and keyword co-occurrence maps, with thresholds set to include only entities meeting specific criteria to enhance focus and relevance. RStudio facilitated data management, trend analysis, and visualization [40,41]. These tools provide established and reliable methods for descriptive bibliometric studies, making them ideal for exploring interdisciplinary research clusters and emerging trends. For country performance and relatedness, co-authorship and bibliographic coupling analyses were conducted. In co-authorship analysis, 18 of 28 identified countries met the threshold. For bibliographic coupling, 27 of 28 countries met the threshold. Author performance was analyzed through co-authorship and co-citation analyses. Out of 547 authors, 52 met the co-authorship threshold, and out of 12,468 cited authors, 131 met the co-citation threshold. Journal preference and performance were analyzed using VOSviewer through bibliographic coupling and co-citation. Out of 92 journals, 23 met the bibliographic coupling threshold, and out of 2720 journals, 27 met the co-citation threshold. For keyword and text data hotspots, both VOSviewer and RStudio were used. Co-occurrence analysis identified 474 keywords, with 41 meeting the threshold. Using Bibliometrix in RStudio, the top 50 keywords were identified. Co-occurrence analysis of text data identified 5078 terms, with 37 terms meeting the threshold. In VOSviewer, items such as authors, countries, journals, and keywords are analyzed within the network [42]. Thresholds are set to include only those entities meeting specific criteria, such as a minimum of one document and zero citations. This ensures a focus on relevant entities, while those not meeting the criteria are excluded. Absence from the analysis does not imply irrelevance but indicates the entities did not meet the specified thresholds. Higher thresholds can be used for a more focused analysis, though there are no mandatory guidelines. Once the thresholds are met, the analysis results can be obtained.

3. Results and Discussion

3.1. Publication and Citation Trends

The trends in publication and citation from 2013 to 2023 (Figure 2) highlight research related to slope or landslide stabilization through biocementation. In 2013, there were 4 publications with 608 citations, indicating strong initial interest and impact. In 2014, the number of publications dropped to 2 with 9 citations, suggesting a temporary decline or a shift in research focus. The trend picked up in 2015 with 5 publications and 115 citations and continued to increase in 2016 with 6 publications and 382 citations. The number of publications remained relatively stable in the following years, with fluctuations in citation counts indicating a resurgence of interest and continued exploration of biocementation as a viable method for slope stabilization.

The most significant increase in both publications and citations occurred in 2019, with 22 publications and 552 citations, marking a peak in research activity and impact during that year. This notable rise could be attributed to advancements in biocementation techniques, growing global awareness of the need for sustainable and eco-friendly slope stabilization methods, and heightened recognition of biocementation's dual benefits in enhancing soil stability and managing hydrological challenges. In subsequent years, the stable number of publications, despite variations in citation counts, reflects sustained interest in the field. This ongoing research effort underscores the interdisciplinary appeal of biocementation, particularly its relevance in addressing hydrological concerns such as runoff management, sediment control, and water retention in treated soils. Additionally, the field has likely benefited from the increased integration of biocementation research into broader discussions on climate resilience and sustainable land management practices.

This continued momentum indicates that biocementation remains a key focus area for researchers seeking innovative solutions to geotechnical and hydrological challenges. The growth in publications and citations on biocementation for slope stabilization is due to the rising demand for sustainable solutions. Advances in biocementation technologies have made the methods more effective. The field attracts researchers from different disciplines, and there is greater awareness of the need for disaster risk management. Additionally, more government support and funding for environmental projects have boosted research in this area.

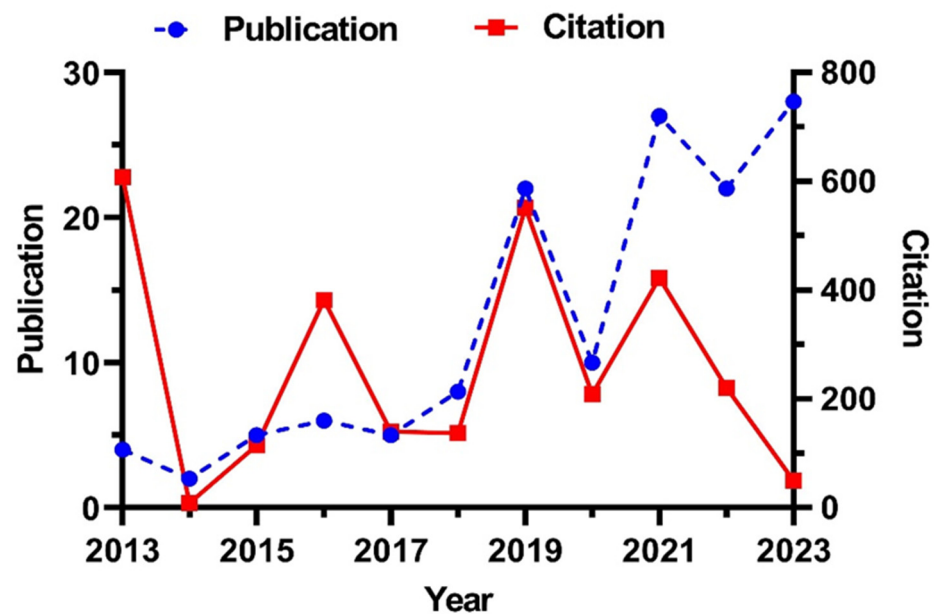


Figure 2. Publication and citation trend in the field from 2013 to 2023.

3.2. Global Distribution and Leading Countries

The performance of leading countries was analyzed, as shown in Figures 3, S2 and 4. In terms of publication output (Figure 3A), China leads with 73 publications, followed by the United States with 27 and Japan with 16. India, Australia, and the United Kingdom also made significant contributions with 10, 7, and 6 publications, respectively. Other countries such as Germany, Portugal, and Hong Kong also have notable representation, each contributing 5 or more publications. When considering the citations received by publications from each country (Figure 3B), China again leads with 1115 citations, indicating the impact of Chinese research in this field. The United States follows with 683 citations, and Japan with 405. India, Australia, and the United Kingdom also receive substantial citations, reflecting the recognition of their contributions to the field. Other countries such as Singapore, South Korea, and Nigeria also receive citations, indicating the global impact of their research efforts.

Leading countries like China, the United States, and Japan focus on biocementation for soil stabilization and landslide mitigation for several reasons. These countries face challenges like soil erosion, landslides, and unstable slopes, often caused by urbanization, infrastructure development, and natural disasters. Biocementation offers a sustainable and environmentally friendly solution to these challenges by using natural processes to stabilize soil and prevent erosion [43]. Secondly, these countries have strong research and development capabilities, as well as advanced engineering and construction industries. This allows them to explore innovative solutions like biocementation and apply them to practical engineering projects. Additionally, there is a growing global focus on sustainable development and environmental conservation. Biocementation aligns with these goals

by offering a sustainable alternative to traditional soil stabilization methods, which often involve the use of chemical additives or mechanical reinforcement [44]. The interest of these leading countries in biocementation for soil stabilization or landslide mitigation can be attributed to their specific environmental challenges, research capabilities, and commitment to sustainable development.

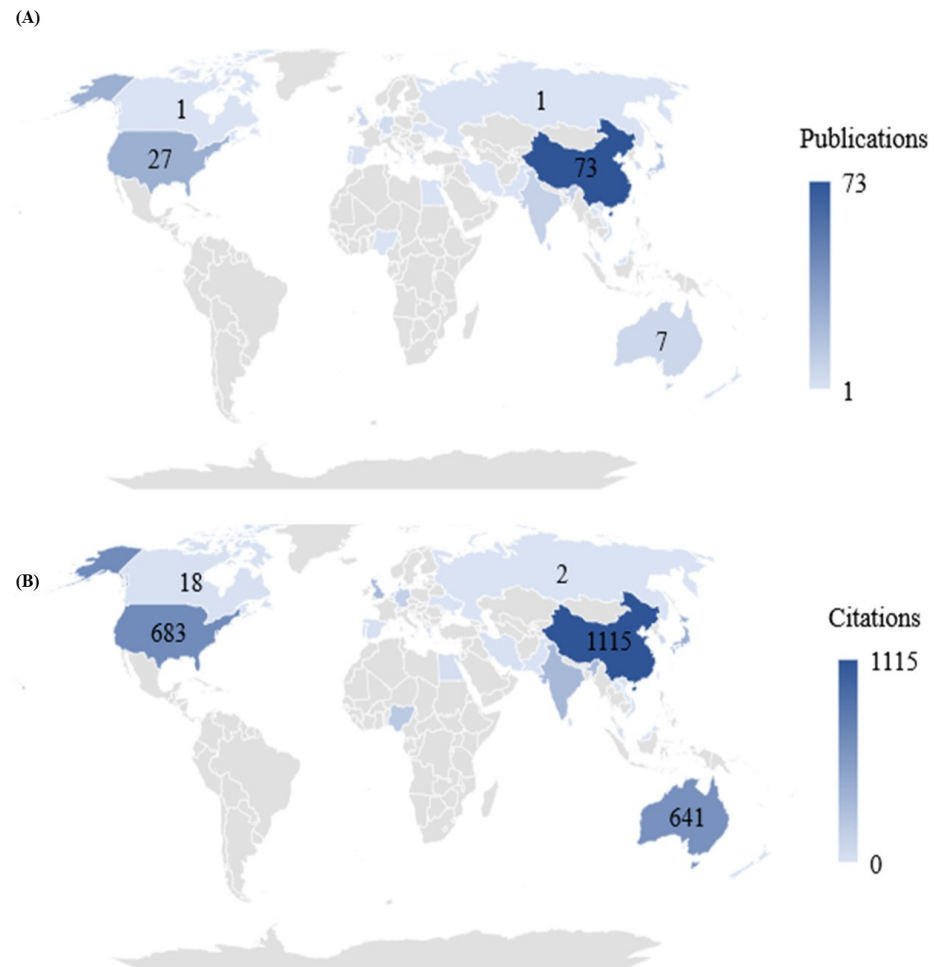


Figure 3. Global distribution of countries contributing to the field. (A) Publication; and (B) citations.

Co-authorship analysis of countries involved in research on slope or landslide stabilization through biocementation is depicted in Figure 4A. China emerges as the country with the highest link strength, with a total of 11 links and a total link strength of 27. This indicates strong collaboration and co-authorship among researchers from China in this field. China is followed by the United States, which has 6 links and a total link strength of 14, indicating a significant level of collaboration but less than that of China. The United Kingdom, Germany, and India also show notable levels of collaboration, with 7, 7, and 5 links, respectively. However, their total link strengths are lower compared to China and the United States. Japan, Australia, and Singapore exhibit moderate levels of collaboration, with 6, 2, and 2 links, respectively. Denmark, Hong Kong, New Zealand, Greece, Netherlands, South Korea, Sri Lanka, Iran, Laos, and Pakistan each show varying degrees of collaboration, with 3 or fewer links. These countries have relatively lower levels of collaboration compared to the previously mentioned countries.

Figure 4B illustrates a density visualization of bibliographic coupling analysis of countries engaged in research on a slope or landslide stabilization through biocementation. Australia emerges as the country with the highest link strength, with a total of 19 links

and a total link strength of 1386. This indicates strong bibliographic coupling among Australian research articles in this field. Australia is followed by China, with 25 links and a total link strength of 8854, indicating extensive bibliographic coupling among Chinese research articles. Other countries with notable levels of bibliographic coupling include the United States, with 21 links and a total link strength of 5051, and Japan, with 21 links and a total link strength of 3995. These countries exhibit significant levels of collaboration and interconnection in their research output. The United Kingdom, India, and Singapore also show considerable levels of bibliographic coupling, with 22, 22, and 19 links, respectively. These countries have strong connections among their research articles in this field. Other countries, such as Canada, Denmark, Egypt, Germany, Greece, Hong Kong, Iran, Laos, Malaysia, Netherlands, New Zealand, Pakistan, Portugal, South Korea, Spain, Sri Lanka, Switzerland, Taiwan, Ukraine, and Vietnam, exhibit varying degrees of bibliographic coupling, with fewer links compared to the previously mentioned countries.

China is at the forefront of biocementation research, driven by its urgent need to address geotechnical and hydrological challenges exacerbated by rapid urbanization and climate change. Recent studies showcase the innovative application of MICP in soil stabilization and erosion control. For example, Liu et al. [45] demonstrated that MICP significantly mitigates soil erosion during extreme rainfall events. Laboratory results revealed a 4.43-fold increase in soil penetration strength and a reduction of up to 92.6% in soil loss, while field trials confirmed the long-term durability of MICP treatments under natural rainfall conditions. These findings emphasize MICP's potential as a sustainable solution for protecting climate-vulnerable regions from soil degradation. Similarly, Gong et al. [38] highlighted the efficacy of MICP in managing erosion gullies within northeast China's black soil regions. Their research demonstrated a 22.22% improvement in soil strength and an 88.55% reduction in mass loss due to rainwater erosion, integrating slope protection plants into the strategy for enhanced sustainability.

Zhang et al. [46] extended these applications by conducting field trials on gravelly clay slopes in Fujian, demonstrating that non-sterilized MICP treatments not only reduced surface erosion but also enabled natural vegetation regrowth, highlighting its dual role in soil stabilization and ecological restoration. These examples underscore China's commitment to integrating biocementation into large-scale soil management practices, with a focus on mitigating the impacts of urban development and extreme weather events while addressing erosion in agriculturally critical regions. In the United States, biocementation research targets coastal erosion and the stability of soils under challenging environmental conditions. Hang et al. [47] evaluated MICP's potential in mitigating suffusion and enhancing the internal stability of silty sands under seepage conditions.

The findings revealed that biocemented soils exhibited superior resistance to particle migration and improved shear strength, significantly reducing instability risks in hydraulic structures. However, studies like Zeng et al. [48] also highlighted the challenges of applying MICP in heterogeneous soils, where preferential flow paths and uneven treatment limited its effectiveness. Such results underscore the need for tailored strategies, with numerical modeling emerging as a key tool for optimizing treatment uniformity. These efforts align with the broader application of EICP in coastal regions to combat wave-induced erosion and stabilize sandy slopes, demonstrating the adaptability of biocementation to diverse site-specific challenges. U.S. research thus emphasizes enhancing the scalability and uniformity of biocementation techniques, aiming to protect critical infrastructure and address vulnerabilities in coastal and flood-prone areas.

Japan's contributions to biocementation research reflect its focus on disaster risk reduction in seismically active and steep terrains. For instance, Phanvongsa et al. [34] demonstrated the effectiveness of casein-combined EICP in creating impermeable crusts

on cut slopes, which significantly reduced rainwater infiltration and prevented shallow slope failures. This technique is particularly valuable for maintaining road networks in mountainous regions prone to landslides. This study highlights Japan's emphasis on leveraging biocementation to mitigate geological risks while ensuring the ecological and structural resilience of its infrastructure [19].

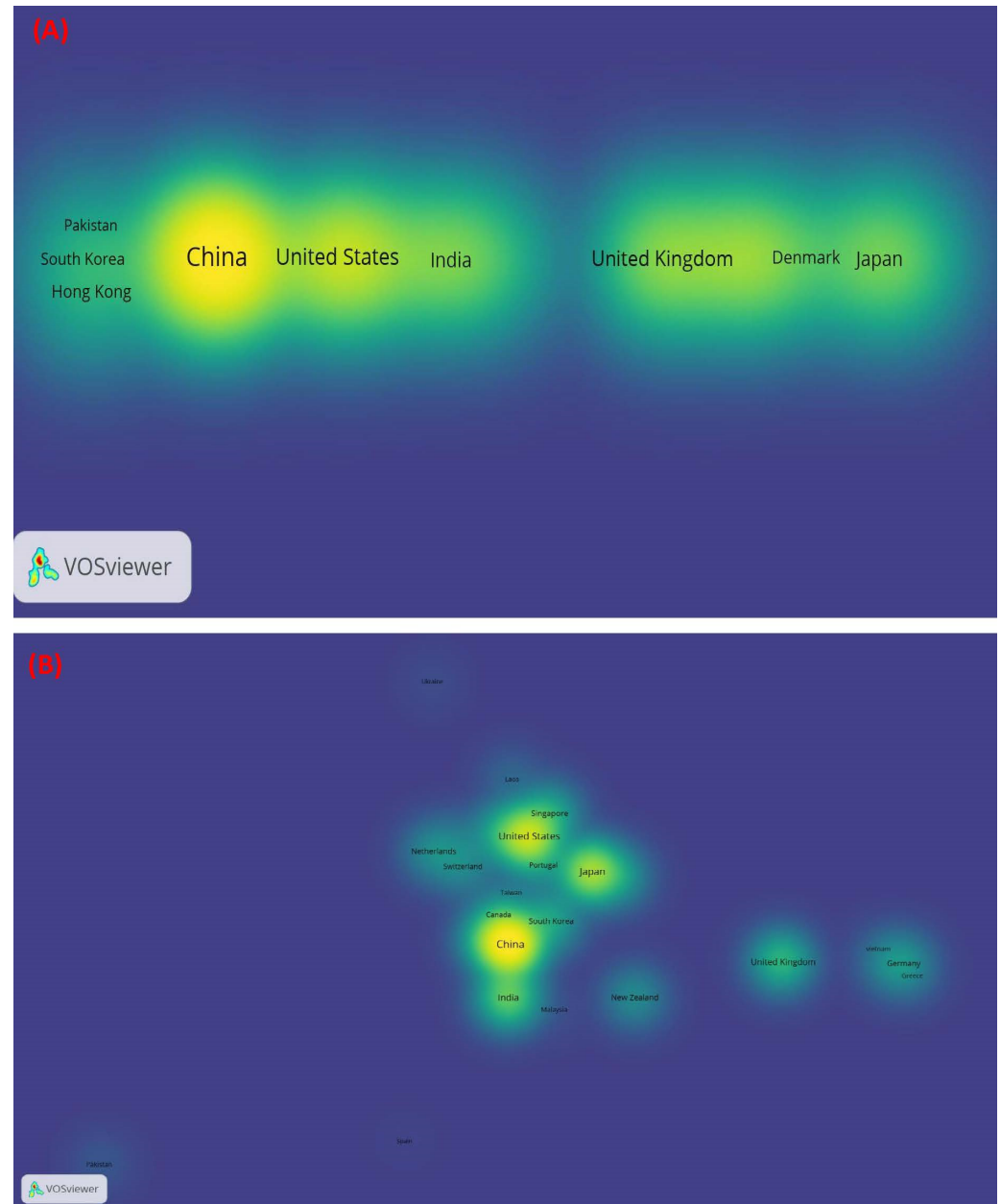


Figure 4. Density visualization mapping of VOSviewer analysis on countries collaboration. (A) Co-authorship analysis of countries available at <https://bit.ly/3vwUTjF> (accessed on 20 March 2024); (B) Bibliographic coupling of countries available at <https://bit.ly/3TSZeXT> (accessed on 20 March 2024). The VOSviewer density visualization graph uses a color gradient to represent the density of a particular metric. Blue indicates areas of low density or intensity, green represents mid-range density or intensity, and yellow signifies the highest density or intensity of relationships or connections in the dataset.

Furthermore, emerging research from India focuses on leveraging native microorganisms for biocementation, particularly in landslide-prone regions. Devrani et al. [49] isolated ureolytic bacteria from landslide sites in Uttarakhand, achieving superior soil strength

improvements compared to conventional strains. This localized approach enhances slope stability in hilly terrains and promotes the use of indigenous resources, aligning with sustainable development principles. By utilizing native bacterial strains, India addresses both the economic and environmental constraints of implementing biocementation, making it a cost-effective solution for stabilizing slopes in resource-limited settings [50]. Australia contributes to biocementation research by adapting techniques to improve soil stability in arid and semi-arid regions. Cheng et al. [51] demonstrated that MICP treatments under low soil saturation conditions enhanced crystallization efficiency and soil strength, making it an effective strategy for combating desertification and erosion. These findings are critical for optimizing biocementation processes in climates characterized by limited water availability. Australia's research advances the understanding of biocementation's application in improving soil properties under challenging environmental conditions, further expanding its potential for diverse geotechnical applications [29]. The findings from these leading research countries illustrate how bibliometric trends translate into practical applications. By addressing region-specific challenges, biocementation research demonstrates its versatility and adaptability as a sustainable solution for modern geotechnical and hydrological issues. These innovations have profound implications for engineering practice, enabling advancements in erosion control, slope stabilization, and infrastructure resilience while promoting environmentally sustainable development. As countries continue to tailor biocementation techniques to their unique challenges, the field is poised to play a critical role in addressing global environmental and structural vulnerabilities.

This review was able to identify several implications of collaboration networks among countries. The co-authorship analysis of countries (Figure 4A) highlights China's prominent role in global biocementation research, with the highest link strength (11 links, total link strength of 27). This strong collaboration network suggests that China is leveraging extensive academic and industrial partnerships to address its significant geotechnical challenges, such as landslides and soil erosion caused by rapid urbanization and climate variability [52]. China's collaborations with countries like the United States and Germany indicate a strategic effort to integrate advanced technologies and methodologies from leading research hubs. These collaborations likely enhance the scalability and efficiency of biocementation applications in diverse environmental contexts. The United States follows with 6 links and a total link strength of 14, signifying active but comparatively less extensive collaboration. The United States' involvement reflects its interest in sustainable engineering practices and its ability to provide robust technical contributions, particularly in integrating biocementation into broader geotechnical solutions [53]. The United Kingdom, Germany, and India exhibit moderate levels of collaboration, with 7, 7, and 5 links, respectively. These networks likely represent targeted partnerships that align with specific regional challenges, such as slope stabilization in areas prone to heavy rainfall (e.g., the Western Ghats in India) or addressing soil stability issues in Europe [37]. The presence of smaller networks involving Denmark, Greece, and Sri Lanka, with fewer links, underscores the growing global awareness and adoption of biocementation techniques. These emerging networks can play a pivotal role in adapting this technology to niche geotechnical problems or underrepresented geographical regions. Countries with limited links may face barriers, such as funding constraints or access to advanced research facilities. However, they present opportunities for future capacity-building initiatives, such as multilateral research programs and knowledge-sharing platforms.

The bibliographic coupling analysis (Figure 4B) provides insights into thematic and methodological alignment across countries [54]. While China demonstrates extensive bibliographic coupling (25 links, total link strength of 8854), Australia's leading position in bibliographic coupling strength (19 links, total link strength of 1386) indicates a strong

thematic alignment among its researchers. This suggests that Australian research is heavily focused on environmental sustainability and the adaptation of biocementation in unique soil and climatic conditions, such as those found in coastal or arid regions [55]. Other leading contributors, such as the United States (21 links, total link strength of 5051) and Japan (21 links, total link strength of 3995), highlight the growing interconnectedness of global research. The United States bibliographic coupling reflects its focus on developing innovative biocementation applications for slope stabilization and erosion control. Japan's contributions, closely aligned with its geological challenges (e.g., landslide-prone mountainous terrains), underscore its commitment to advancing precise biocementation techniques [56]. The significant bibliographic coupling among countries such as the United Kingdom, India, and Singapore (22, 22, and 19 links, respectively) reflects their shared focus on foundational and applied research in biocementation [57–59]. For example, India's contribution to bibliographic coupling may be tied to its need for cost-effective solutions for rural and semi-urban areas facing soil stability challenges.

These collaboration networks and bibliographic couplings demonstrate the field's growing maturity and global relevance. The patterns of co-authorship and coupling reflect the increasing interdisciplinary nature of biocementation research, integrating geotechnics, microbiology, and hydrology. Moving forward, fostering stronger international collaborations, especially involving underrepresented countries, can bridge knowledge gaps and accelerate the development of locally adapted solutions [60]. Programs such as joint research grants, student exchanges, and open-access publications can further democratize access to biocementation technologies. In practice, the interconnectedness revealed in bibliographic coupling highlights the potential for standardized methodologies, which can be adapted to diverse environmental conditions. This alignment facilitates the transfer of knowledge, ensuring that advances in one region can be effectively applied in another. For instance, Australia's expertise in addressing hydrological implications of biocementation could complement China's focus on scaling these technologies for large infrastructure projects.

3.3. Top Performing Authors

The leading authors in the field of slope or landslide stabilization through biocementation are identified based on their research output and citation impact, as shown in Tables 1 and S2. Among them, Gowthaman Sivakumar from the University of Jaffna, Kawasaki Satoru, and Nakashima Kazunori from Hokkaido University have each contributed 8 documents with 251 citations, indicating a significant impact in the field. He Jia from Hohai University and Miao Linchang from Southeast University in Nanjing, China, have each produced 5 documents with 119 and 96 citations, respectively, demonstrating a strong research presence. Sun Xiaohao from The Hong Kong Polytechnic University, Wang Hengxing from Southeast University, and Hang Lei from Hohai University have also made notable contributions, with 5 documents and 96 citations each. Wu Linyu from Southeast University and Chu Jian from Nanyang Technological University have each contributed 4 documents, with Wu Linyu having 72 citations and Chu Jian having 95 citations. The authors mentioned are from Sri Lanka, Japan, China, Hong Kong, and Singapore.

The top authors from these countries are likely working in the field of slope or landslide stabilization through biocementation due to the prevalent issues of slope instability and landslides in their respective regions, driving their interest in developing innovative solutions to address these challenges. In Sri Lanka, the central highlands are prone to landslides due to heavy rainfall, deforestation, and improper land use practices, leading to significant economic and human losses [61]. In Japan, mountainous regions experience frequent landslides, exacerbated by earthquakes and typhoons. China faces similar challenges, especially in regions like Sichuan and Yunnan, where rapid urbanization and infrastructure development

increase the risk of landslides [62]. Hong Kong's steep terrain and high population density make it vulnerable to landslides, particularly during the rainy season [56]. These issues highlight the need for effective slope stabilization techniques like biocementation.

Table 1. Leading authors in the field.

Authors	Number of Documents	Number of Citations	Affiliation
Gowthaman Sivakumar	8	251	University of Jaffna
Kawasaki Satoru	8	251	Hokkaido University
Nakashima Kazunori	8	251	Hokkaido University
He Jia	5	119	Hohai University
Miao Linchang	5	96	Southeast University
Sun Xiaohao	5	96	The Hong Kong Polytechnic University
Wang Hengxing	5	96	Southeast University
Hang Lei	4	113	Hohai University
Wu Linyu	4	72	Southeast University
Chu Jian	3	95	Nanyang Technological University

The bibliographic data analysis conducted in RStudio identified 483 unique authors, with a total of 660 appearances across all documents. Among these, there was only one author of single-authored documents, while the majority, 482 authors, contributed to multi-authored documents. The collaboration among authors was evident, with an average of 0.288 single-authored documents per author and an average of 3.47 authors contributing to each document. The collaboration index, calculated at 3.52, indicates a significant level of cooperation among authors, with an average of 4.75 co-authors per document. This signifies a high level of collaboration among authors, indicating a collective effort and shared expertise in contributing to the field, leading to a diverse range of perspectives and insights in the research output.

The results from Figure 5A, a visualization mapping of VOSviewer analysis on author collaboration, reveal the authors with the highest link strengths in co-authorship analysis. He Jia emerges as the author with the highest link strength, with 18 links and a total link strength of 22, indicating extensive collaboration with other authors. Hang Lei and Xiao Yang follow closely behind, with 12 links and 16 links, respectively, showing significant collaboration in their research. Van Paassen Leon A., Chu Jian, and Gao Yufeng also demonstrate strong collaboration, with 11, 10, and 8 links, respectively. Other authors, such as Dubey Anant Aishwarya, Mukherjee Abhijit, Ravi K., and Lu Huaming, also exhibit notable levels of collaboration, with 7 links each. These findings indicate a strong collaborative network among authors in the field of slope or landslide stabilization through biocementation, suggesting an active and interconnected research community.

The results from Figure 5B, a co-citation analysis of cited authors, highlight the authors with the highest link strengths based on their citations. DeJong J.T., Chu J., and Soga K. emerge as the top authors with the highest link strengths, each with 127 links and total link strengths of 20,743, 18,979, and 13,317, respectively. This indicates that their works are frequently cited together in the field, suggesting a strong influence and recognition of their contributions. Montoya B.M., Van Paassen L.A., and Cheng L. also show significant link strengths, each with 127 links and total link strengths of 12,416, 10,859, and 10,381, respectively. Other authors such as Xiao Y., Kawasaki S., Liu H., and Nelson D.C. also demonstrate notable link strengths, indicating their works are frequently cited in conjunction with other authors in the field. These findings suggest a cohesive body of literature and a strong network of influential authors in the field of slope or landslide stabilization through biocementation.

The co-authorship analysis of authors and co-citation analysis of cited authors are two methods used to evaluate author relationships and influence in a specific field [42]. Both methods aim to identify key authors who are actively collaborating or frequently cited, indicating their impact on the field. However, they differ in the way they measure author relationships and influence. Co-authorship analysis of authors looks at the number of times authors have collaborated on publications, indicating the strength of their collaborative network [63]. In Figure 5A, authors like He Jia, Hang Lei, and Xiao Yang exhibit high link strengths, suggesting extensive collaboration with other authors. This method helps identify authors who are actively contributing to the field and are part of a connected research community. On the other hand, co-citation analysis of cited authors examines how often authors are cited together in publications, indicating the strength of their influence and recognition in the field. Authors like DeJong J.T., Chu J., and Soga K. have high link strengths, as shown in Figure 5B, suggesting that their works are frequently cited together. This method helps identify authors whose work has had a significant impact on the field and is often considered foundational or influential. While both methods provide valuable insights into author relationships and influence, co-authorship analysis focuses on collaborative networks among authors, while co-citation analysis highlights the influence and recognition of authors' work in the field.

The contributions of leading authors in the field of biocementation have significantly advanced our understanding of microbial- and enzyme-induced soil stabilization techniques. Each researcher's work demonstrates the potential of biocementation to address diverse geotechnical and hydrological challenges while promoting sustainable practices. For instance, Gowthaman Sivakumar, Kawasaki Satoru, and Nakashima Kazunori have been instrumental in exploring cost-effective methods for applying MICP for slope stabilization [31,64]. Their collaborative work on the Hokkaido expressway focused on augmenting indigenous bacteria and utilizing low-grade chemicals to achieve substantial cost reductions without compromising performance. Their studies achieved soil UCS of up to 820 kPa while cutting treatment costs by 96% [64]. These findings highlight a scalable approach for implementing MICP in large-scale infrastructure projects, particularly in regions with economic constraints. The use of low-grade chemicals and indigenous bacteria not only reduces costs but also minimizes environmental impact, making it a feasible alternative to traditional methods. He Jia's research has furthered the application of EICP by combining it with fiber reinforcement for cohesive soils. His studies demonstrated that incorporating glass and steel fibers into EICP treatments improved erosion resistance under rainfall and surface runoff, with steel-fiber-treated samples reducing particle erosion by 98.11% [65]. The fiber/calcium carbonate net structure significantly enhances the mechanical properties of treated soils, offering a durable solution for protecting highway embankments. This approach also supports crack repair, ensuring long-term structural stability against dynamic weather conditions.

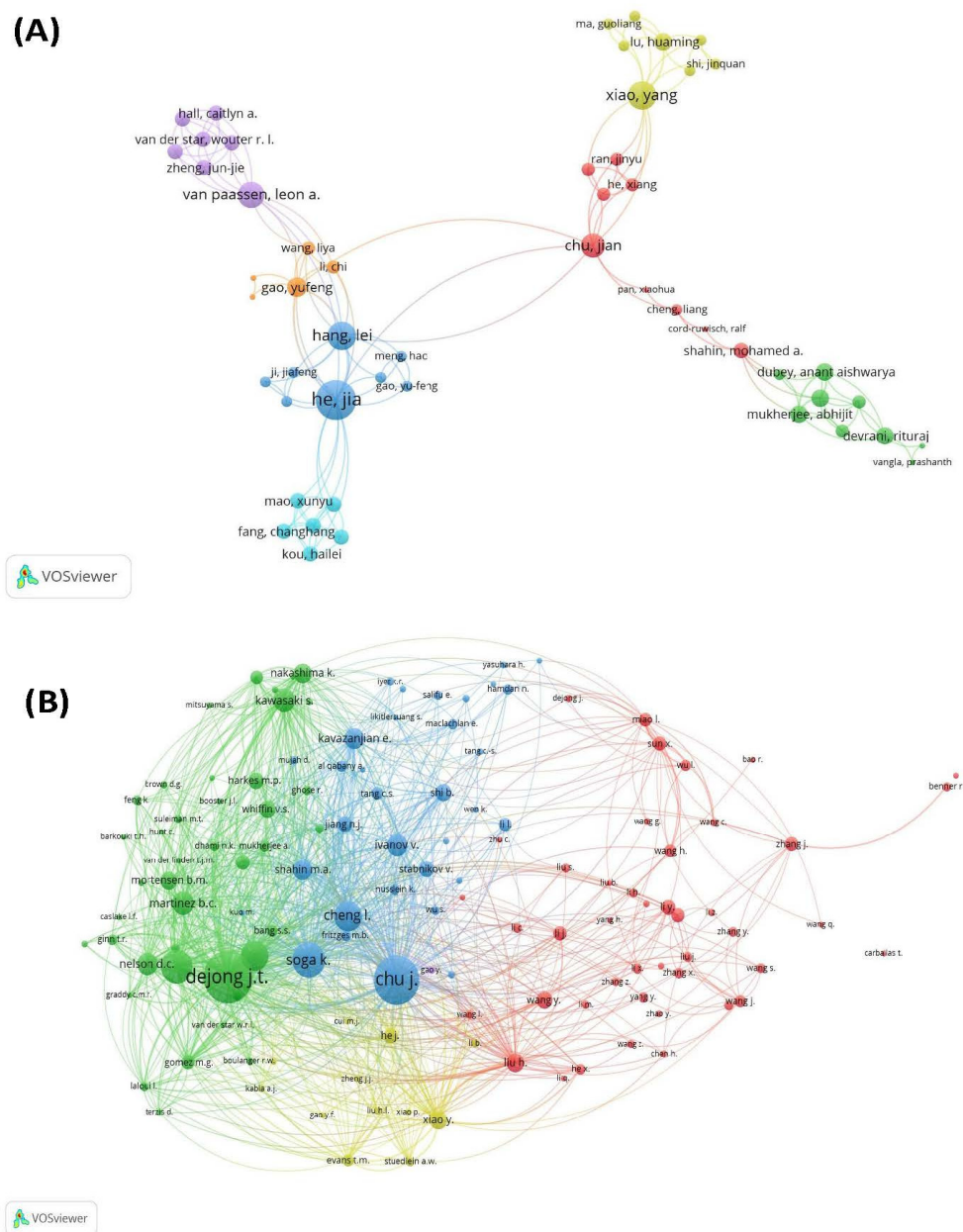


Figure 5. Networking visualization mapping of VOSviewer analysis on author collaboration. (A) co-authorship analysis of authors; and (B) co-citation analysis of cited authors. The maps are available online at <https://bit.ly/4a79oKf> (accessed on 20 March 2024) and <https://bit.ly/4asNLDR> (accessed on 20 March 2024).

Sun Xiaohao, Miao Linchang, Wang Hengxing, and Wu Linyu developed the MEMCP method to mitigate foreshore erosion, demonstrating that optimized bacterial suspension and urease solution ratios significantly improved slope stability and reduced soil loss during tidal cycles [66]. This highlights the adaptability of biocementation for marine and estuarine applications. Their work showcases the adaptability of biocementation for marine and estuarine applications, where tidal forces and soil heterogeneity pose significant challenges. Chu Jian applied MICP to control rainwater infiltration, reducing landslide risks and maintaining soil permeability during light rainfall. His method strengthens treated soils against heavy rainfall while supporting ecosystem sustainability [29]. Hang Lei explored biocementation for desert sands, showing increased solution concentration and treatment temperature improved erosion resistance. His work demonstrated durability under extreme wetting/drying and freeze/thaw cycles, validating MICP's use in

arid climates [67]. Together, the contributions of these authors underscore the diverse applications of biocementation across varied environmental and geotechnical challenges. Their innovations in combining biocementation with Supplementary Materials, optimizing chemical treatments, and tailoring techniques for specific environmental conditions provide a foundation for advancing sustainable soil stabilization practices globally.

3.4. Top Publishing Avenues

Valuable insights into the top ten preferred publication venues in the research field, along with other relevant metrics, are provided in Tables 2 and S3. *Geotechnical Special Publication* emerges as the most prolific publishing spot, with 9 publications and a total of 121 citations. This is a platform of the American Society of Civil Engineers (ASCE) that publishes selected conference proceedings. *Acta Geotechnica* follows closely, with 5 documents and 198 citations. Other notable journal platforms include *Science of the Total Environment*, with 4 documents and 84 citations, and *Journal of Geotechnical and Geoenvironmental Engineering*, with 3 documents and 72 citations. The remaining journals in the list are *Applied Sciences* (Switzerland), with 4 documents and 9 citations, *Advances in Civil Engineering*, with 3 documents and 29 citations, *Bulletin of Engineering Geology and the Environment*, with 3 documents and 19 citations, *Journal of Soils and Sediments*, with 3 documents and 64 citations, *Nongye Gongcheng Xuebao/Transactions of the Chinese Society of Agricultural Engineering*, with 3 documents and 32 citations, and *Sustainability* (Switzerland), with 3 documents and 14 citations. The publishing avenues listed in Table 2 are published by a variety of publishers, including the ASCE, Springer Nature, Multidisciplinary Digital Publishing Institute, Elsevier, and Hindawi, with h-indexes ranging from 41 to 317, CiteScores from 0.8 to 16.6, and quartile rankings from not yet assigned to Q1, indicating their visibility and influence in the field of slope or landslide stabilization through biocementation. These metrics suggest that researchers prefer high-impact journals with strong reputations to ensure their work is widely read and cited.

Table 2. List of top publishing avenues in the field.

Publishing Avenues	Number of Documents	Number of Citations	CiteScore 2022
<i>Geotechnical Special Publication</i>	9	121	0.8
<i>Acta Geotechnica</i>	5	198	8.7
<i>Applied Sciences</i> (Switzerland)	4	9	4.5
<i>Science of the Total Environment</i>	4	84	16.6
<i>Advances in Civil Engineering</i>	3	29	3.4
<i>Bulletin of Engineering Geology and the Environment</i>	3	19	7.3
<i>Journal of Geotechnical and Geoenvironmental Engineering</i>	3	72	6.9
<i>Journal of Soils and Sediments</i>	3	64	7.1
<i>Nongye Gongcheng Xuebao/Transactions of the Chinese Society of Agricultural Engineering</i>	3	32	3.4
<i>Sustainability</i> (Switzerland)	3	14	5.8

VOSviewer was used to identify the bibliographic coupling of publishing spots in the field, as shown in Figure 6A. *Acta Geotechnica* and *Geotechnical Special Publication* have the highest total link strength, with 807 and 533 total link strengths, respectively, indicating

strong connections with other journals in the field. *Journal of Geotechnical and Geoenvironmental Engineering* and *Journal of Soils and Sediments* also have high total link strengths, with 442 and 422, respectively, indicating their prominence in the field. *Science of the Total Environment* is another noteworthy journal, with a high total link strength of 393. This suggests that it covers a wide range of topics related to geotechnical engineering and is well-regarded in the field. Other journals such as *Advances in Civil Engineering*, *International Journal of Geomechanics*, and *Journal of Materials in Civil Engineering* also show strong connections with other journals, with total link strengths of 414, 399, and 390, respectively, indicating their influence in the field.

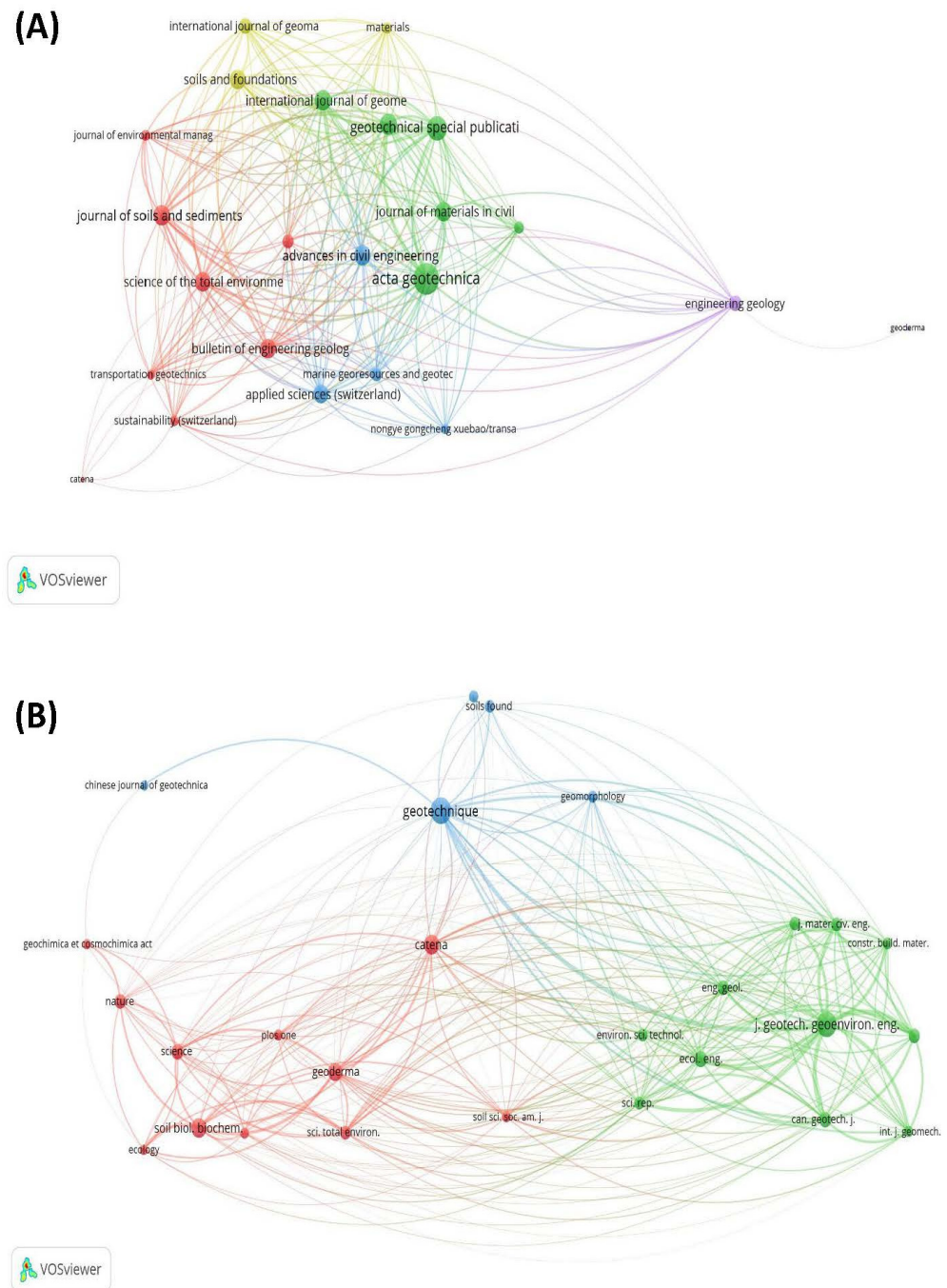


Figure 6. Visualization mapping of VOSviewer analysis on journals in the field. **(A)** bibliographic coupling of journals; and **(B)** co-citation analysis of cited journals. The maps are available online at <https://bit.ly/3IUHpBn> (accessed on 20 March 2024) and <https://bit.ly/43yxTgS> (accessed on 20 March 2024).

The co-citation analysis of cited journals determined via VOSviewer is shown in Figure 6B. *Geotechnique* emerges as the most highly co-cited journal, with a total link strength of 1847 and 167 citations. This indicates that *Geotechnique* is highly influential in the field and papers published in this journal are frequently cited alongside other key journals. *Journal of Geotechnical and Geoenvironmental Engineering* also shows a high total link strength of 4155 and 149 citations, further highlighting its significance in the field. *Soil Biology and Biochemistry*, *Catena*, and *Geoderma* are also highly co-cited journals, with total link strengths of 1201, 1106, and 1269, respectively. These journals likely cover topics that are closely related to each other and are often cited together in research articles. *Ecological Engineering*, *Canadian Geotechnical Journal*, and *Science* also show strong co-citation patterns, indicating their importance in the field. Furthermore, *Acta Geotechnica* and *Nature* are also among the top co-cited journals, with total link strengths of 1764 and 510, respectively. This suggests that these journals are frequently cited alongside other influential journals in the field, indicating their impact on geotechnical engineering research.

Bibliographic coupling and co-citation analysis are methods used to assess relationships among publishing avenues in a given field, each aiming to pinpoint influential and respected platforms with different approaches [42]. For instance, *Acta Geotechnica* and *Geotechnical Special Publication* in Figure 6A exhibit strong link strengths, suggesting substantial shared references and thematic alignment. This method identifies publishing platforms with similar research areas or frequent citations. In contrast, co-citation analysis gauges how often two or more publishing platforms appear together in citations, indicating thematic congruence or intellectual kinship. *Geotechnique* stands out in Figure 6B, signifying frequent co-citation with other pivotal journals. This method identifies journals regarded as influential or foundational. Although both approaches shed light on journal relationships, they differ. Bibliographic coupling spotlights direct connections via shared references, while co-citation analysis captures indirect connections via citations in other papers. Moreover, bibliographic coupling may reveal more direct intellectual bonds, whereas co-citation analysis may encompass broader thematic associations.

Research on biocementation has been published in leading journals such as *Geotechnical Special Publication*, *Acta Geotechnica*, and *Science of the Total Environment*. These studies explore various aspects of MICP and related techniques, advancing their application in slope stabilization, erosion control, and sustainable engineering practices. Several studies address the role of MICP in improving slope stability and mitigating landslides. In *Geotechnical Special Publication*, Shilpi et al. [37] used numerical modeling to explore MICP's efficacy in stabilizing homogeneous slopes under varying geometric and soil conditions. Their findings showed significant landslide risk reduction and proposed practical design charts for effective implementation. Similarly, in the *Bulletin of Engineering Geology and the Environment*, Wang et al. [68] demonstrated the effectiveness of biotreated sand embankments under rainfall scouring. Their study revealed that MICP significantly improved erosion resistance and delayed failure times, with results validated through finite element modeling. Together, these studies highlight MICP's potential for slope stabilization, emphasizing its adaptability to different slope geometries and environmental conditions.

MICP applications in coastal and riverbank settings are a prominent focus. In *Science of the Total Environment*, Dubey et al. [69] investigated biocementation and bio-polymer composites to mitigate erosion along riverbanks. The bio-composite approach reduced erosion rates fourfold compared to untreated soils and offered a sustainable alternative with reduced ecological impact. The *Journal of Geotechnical and Geoenvironmental Engineering* featured Sun et al. [66], who applied the MEMCP method to stabilize foreshore slopes. Their optimized bacterial suspension and urease solution ratios enhanced surface strength and minimized soil loss during tidal cycles. Similarly, in *Sustainability* (Switzerland), Huang

et al. [70] utilized MICP spray irrigation to reinforce sandy coastal slopes, demonstrating reduced sand loss and improved stability under simulated rainfall. These studies collectively showcase the adaptability of biocementation for erosion control in coastal and riparian environments.

MICP's utility extends beyond conventional soil stabilization to protect cultural heritage sites and address unique engineering challenges. In *Advances in Civil Engineering*, Liu et al. [71] investigated the impact of rainfall-induced erosion on sandy slopes treated with MICP and found that while high-concentration MICP-treated slopes demonstrated significant strength and smoother surfaces post-erosion, they had lower resistance to erosion compared to cement-treated slopes. In *Applied Sciences* (Switzerland), Nayanthara et al. [72] focused on reinforcing nearshore sandy soils using locally isolated *Sporosarcina* sp. Their research demonstrated significant strength improvements in treated sands while maintaining hydraulic properties, making it suitable for erosion control in sensitive ecological zones. Innovations combining MICP with other materials are increasingly explored for enhanced performance. In the *Journal of Soils and Sediments*, Sun et al. [73] demonstrated that the addition of polyvinyl acetate to MICP treatments significantly improved loess slope stability and reduced soil loss during rainfall. This hybrid approach offers a promising solution for regions prone to erosion. Meanwhile, *Acta Geotechnica* featured Hang et al. [47], who investigated MICP's impact on the internal stability of silty sands under seepage conditions. Their study highlighted the method's ability to enhance shear strength and resist suffusion, making it a viable solution for hydraulic systems and geotechnical structures prone to instability. Finally, in *Nongye Gongcheng Xuebao/Transactions of the Chinese Society of Agricultural Engineering*, Shao et al. [74] investigated microbial mortar as a protective covering for silt slopes. Their results demonstrated improved resistance to rainfall erosion and enhanced water stability, offering a sustainable alternative for silt slope protection. The study emphasizes the coupling effect of microbial crust strength and soil permeability in resisting raindrop splash and surface flow erosion. These journals have facilitated significant advancements in biocementation, from slope stabilization to coastal erosion control and cultural heritage preservation. By addressing diverse geotechnical challenges, these studies underscore MICP's versatility and highlight opportunities for its sustainable application across various engineering domains.

3.5. Co-Occurrence Analysis of Keywords and Text Data

VOSviewer was used to analyze author keywords and text data (titles and abstracts), as shown in Figure 7. Co-occurrence analysis involves examining the frequency of keywords and phrases appearing together in publications, providing insights into common themes and topics in the field. Table 3 highlights the top 10 author keywords, indicating a strong focus on "MICP", "erosion", and "biocementation". These keywords suggest a significant interest in using biological processes to stabilize soil and mitigate erosion. The presence of keywords like "biomineralization" supports the idea that researchers are exploring innovative and sustainable approaches to soil stabilization through the formation of minerals by bacteria. The clustered keywords in Figure 7A represent distinct themes within the field. Cluster 1 (Red) highlights durable slope surfaces achieved using indigenous bacteria and low-grade chemicals, showcasing interest in sustainable stabilization and erosion control. This theme highlights the growing emphasis on environmentally friendly engineering solutions that leverage local resources, which is particularly relevant for regions with limited access to high-purity chemicals or advanced infrastructure. Similarly, Cluster 2 (Green) relates to biocementation and biocement, emphasizing the use of biological processes to improve soil stability. Keywords such as "soil improvement" and "native bacteria" in this

cluster suggest that researchers are increasingly exploring site-specific applications that integrate local microbial strains and soil conditions into treatment designs.

Cluster 3 (Blue) centers on erosion, permeability, and shear strength, reflecting the importance of understanding and improving the mechanical properties of treated soils. The inclusion of microbial terms like “*Bacillus megaterium*” and “*Sporosarcina pasteurii*” underscores the pivotal role of bacterial activity in enhancing soil stability. Meanwhile, Cluster 4 (Yellow) highlights processes such as MICP and EICP, focusing on their biochemical mechanisms with keywords like “urease activity” and “CaCO₃”.

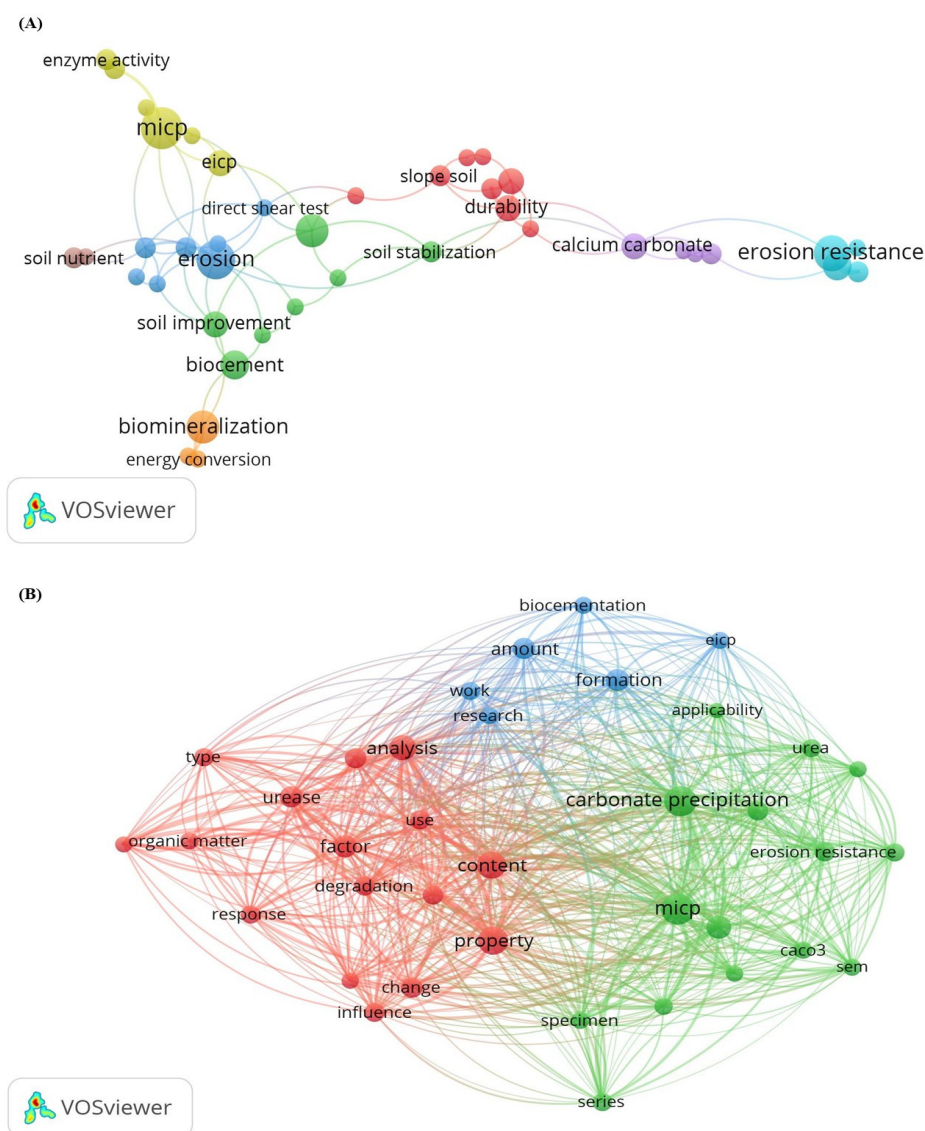


Figure 7. Visualization mapping analysis was performed using VOSviewer for (A) co-occurrence of author keywords; and (B) co-occurrence of text data in the field. The maps are available online at <https://bit.ly/3PFVtm1> (accessed on 20 March 2024) and <https://bit.ly/3vpMhLL> (accessed on 20 March 2024).

This cluster suggests a significant effort to optimize these processes for greater efficiency and consistency, addressing key challenges in scaling biocementation techniques for field applications. Clusters 5 (Purple) and 6 (Turquoise) draw attention to applications in specific and challenging environments. Cluster 5, which includes keywords like “erosion resistance”, “sandy slope”, and “calcareous sand”, highlights practical solutions for slope stabilization in areas prone to soil erosion, particularly in coastal regions. Clus-

ter 6 (Turquoise) addresses erosion under wave action, surface erosion, and penetration resistance, with a focus on erosion-resistant materials for coastal slopes. These clusters underline the need for research that addresses region-specific challenges and demonstrates biocementation's adaptability to diverse environmental conditions.

The less commonly discussed themes in Clusters 7 (Brown) and 8 (Chocolate) reveal the broadening scope of biocementation research. Cluster 7 explores biomineralization in interdisciplinary contexts, with keywords like "energy conversion" and "oxygen evolution reaction", suggesting its potential applications in renewable energy and functional material development. Cluster 8 focuses on soil nutrients and cut slopes, indicating a growing interest in combining soil stabilization with agricultural and construction applications. These themes point to emerging opportunities for integrating biocementation into wider sustainability efforts, such as improving soil fertility in degraded lands or stabilizing slopes in infrastructure projects.

Table 3. List of top 10 author keywords identified by the VOSviewer program.

Keyword	Occurrence	Links	Total Link Strength
MICP	9	8	10
Erosion	8	12	14
Erosion resistance	7	4	9
Biocementation	6	6	6
Biomineralization	6	4	6
Biocement	5	3	3
Sandy slope	5	4	9
Calcium carbonate	4	7	7
Durability	4	6	9
EICP	4	4	4

The co-occurrence analysis not only identifies established research priorities but also highlights underexplored and emerging directions that are shaping the future of biocementation research. Author keywords such as "low-grade chemicals", "indigenous bacteria", and "native bacteria" reflect a growing shift toward sustainable and cost-effective solutions that leverage locally available resources. This focus aligns with global sustainability goals, particularly in regions with limited access to high-purity reagents or advanced infrastructure. Utilizing indigenous bacteria not only enhances the ecological compatibility of treatments but also minimizes the risks associated with introducing non-native strains, thereby promoting localized and environmentally conscious applications [64,75,76]. The inclusion of "wave action" and "calcareous sand" underscores the increasing relevance of addressing specific environmental and soil conditions, particularly in coastal areas where erosion and soil movement are exacerbated by dynamic forces. These keywords highlight the need for tailored biocementation solutions that can withstand extreme environmental stressors while maintaining cost and material efficiency. For instance, optimizing the CaCO_3 precipitation process for calcareous sands in coastal regions could significantly enhance erosion resistance and shoreline protection efforts [77,78].

Emerging themes such as "energy conversion" and "soil nutrients" reveal the interdisciplinary potential of biocementation to address broader sustainability challenges. The use of biomineralization in energy-related applications, including developing functional materials for catalysis and energy storage, represents an exciting convergence of geotechnical engineering and materials science. Similarly, integrating biocementation into soil management

practices for agricultural lands could improve both mechanical stability and soil fertility, offering dual benefits in regions prone to nutrient depletion and erosion [79–81]. Furthermore, the attention to “slope surface” and “penetration resistance” highlights the importance of improving field-scale applications. Methods such as sprayable biocementation solutions could be optimized to maximize coverage, penetration depth, and durability, ensuring their practical viability in diverse settings. For soils like loess, which are highly porous and prone to collapse, tailored stabilization approaches are essential to address their unique challenges, particularly in regions with significant loess deposits like China and Central Asia [82,83]. In dynamic coastal environments, combining biocementation with physical reinforcements, such as geosynthetics or vegetative barriers, could enhance the resilience of slopes exposed to wave action. Standardizing methods for measuring key metrics like penetration resistance and shear strength will also be crucial for ensuring the consistency and comparability of results across studies, further advancing the field’s applicability.

The visualization mapping analysis in Figure 7B was conducted using VOSviewer to examine the co-occurrence of text data in the field. It found three different cluster groups. In Cluster 1 (Red), the research work appears to focus on the analysis and impact of various factors related to MICP and soil erosion. Terms like property, analysis, factor, urease, and enzyme activity suggest a detailed examination of the properties and influencing factors of MICP. Additionally, terms like soil erosion, change, degradation, and impact indicate a concern researchers have with the effects and responses to erosion in soils treated with MICP. The cluster also includes terms like use, response, and type, which may relate to the practical applications and categorization of MICP methods and materials. Organic matter and soil samples are also mentioned, indicating a focus on the environmental aspects and practical testing of MICP in different soil types. In Cluster 2 (Blue), the focus is more on the practical aspects and outcomes of MICP and biocementation. Terms like improvement, erosion resistance, slope surface, and shear strength suggest a focus on enhancing the durability and stability of slopes using MICP. The presence of terms like urea, cementation solution, CaCO_3 , and biocementation indicates a focus on the materials and methods used in MICP applications. The cluster also includes terms like specimen, SEM (scanning electron microscopy), and series, suggesting a focus on experimental setups and analysis techniques in MICP research. Finally, Cluster 3 (Green) appears to focus on the formation and quantity of carbonate precipitation in MICP. Terms like formation, amount, and surface strength suggest a focus on understanding the processes and outcomes of carbonate precipitation in MICP-treated soils. The cluster also includes terms like work and applicability, indicating a broader perspective on the practical implications and future directions of MICP research.

The analysis of underexplored and developing terms in biocementation research provides critical insights into future directions for the field. Emerging areas of focus suggest a shift toward addressing practical challenges, optimizing material applications, and enhancing the sustainability and durability of MICP techniques. The presence of terms such as EICP and erosion resistance indicates a growing interest in enzyme-based approaches as an alternative to MICP. EICP offers advantages such as faster reaction times and fewer environmental restrictions, making it a promising solution for applications requiring rapid stabilization, particularly in regions prone to extreme weather events [84]. Future studies should explore the integration of EICP with Supplementary Materials like fibers and bio-polymers that can enhance soil erosion resistance while maintaining sustainability [85]. Terms like applicability, specimen, and work suggest a growing emphasis on translating laboratory findings into real-world engineering applications. While small-scale experiments have demonstrated the efficacy of MICP and EICP, challenges remain in scaling these methods for use in large infrastructure projects [86]. Future research should address issues such as the uniform distribution of treatments, economic feasibility, and compatibility with existing

construction practices. The development of guidelines and tools, such as design charts and simulation models, will be instrumental in bridging the gap between research and practice.

The analysis of 474 author keywords in RStudio, focusing on the top 50 frequently used keywords, reveals key focus areas in the field (Figure 8A). Keywords like “calcium carbonate”, “calcite”, and “carbonate precipitation” highlight the emphasis on CaCO_3 mineralogy and chemistry in soil stabilization and biomineralization. Terms such as “erosion”, “soil erosion”, “slope stability”, and “slope stabilization” indicate a focus on erosion control, geotechnical aspects, and the use of CaCO_3 for improving soil mechanics. The interest in “enzyme activity” and “microbial activity” reflects the role of bacteria and enzymes in biomineralization for sustainable soil improvement. The presence of “China” suggests significant research contributions from this region. Other keywords like “sand”, “cementing (shafts)”, and “ground improvement” point to construction and geotechnical engineering practices. Environmental considerations are shown by “rain” and “rainfall.” Keywords like “compressive strength”, “shear strength”, and “shear flow” focus on the mechanical properties of treated soils. “Organic carbon”, “nitrogen”, and “ecosystem” suggest ecological implications and nutrient dynamics. “Soil testing” and “soil mechanics” indicate experimental and theoretical approaches to soil behavior and treatment efficacy.

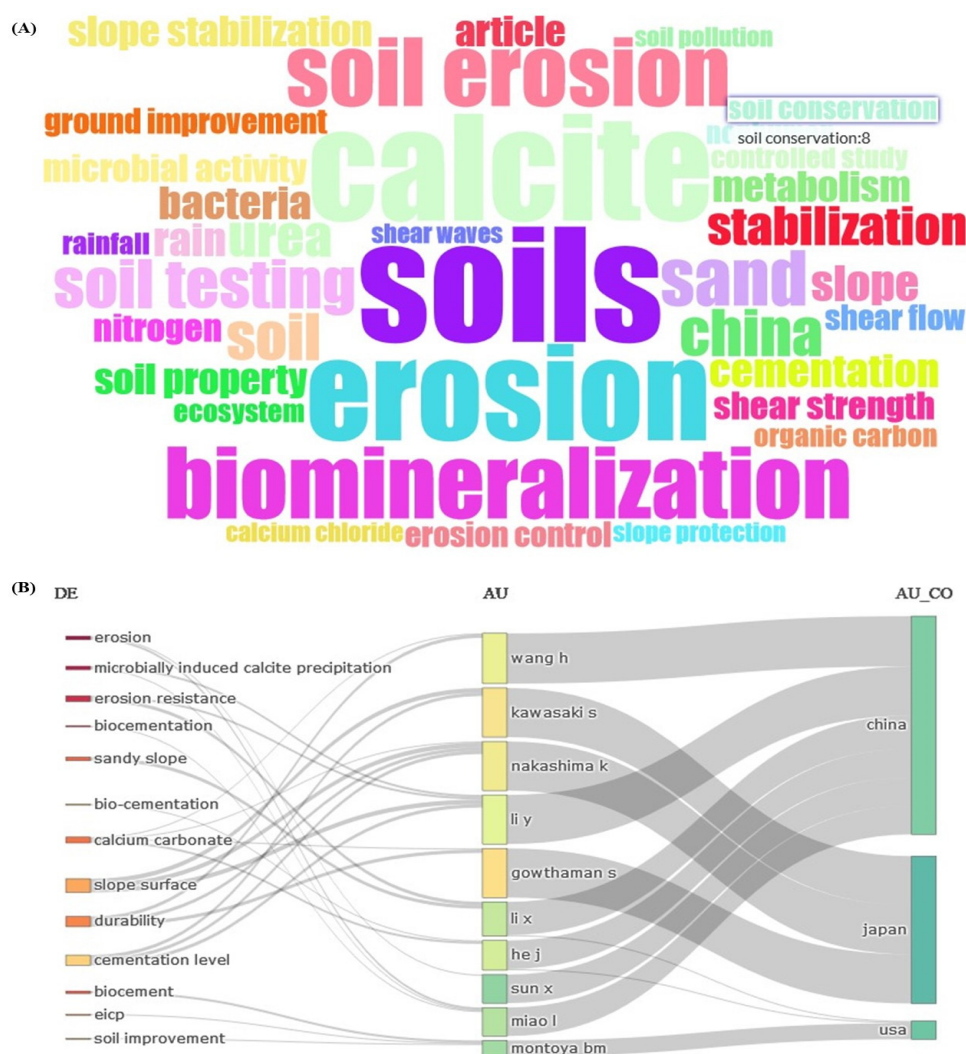


Figure 8. RStudio analysis of bibliographic data on author keywords. (A) Word cloud of the top 50 most frequently used keywords; (B) Three-field plot showing the highest frequency author keywords (on the left), authors (in the center), and countries (on the right), generated from text file analysis using RStudio.

The relationship between major keywords, authors, and countries (Figure 8B) identifies three key countries: China, Japan, and the United States. China is linked with authors such as Wang H. [84], Li Y. [36], Li X. [87], He J. [22], Sun X. [73], and Miao L. [73], and keywords like slope surface, CaCO₃, durability, sandy slope, erosion resistance, biocementation, MICP, and erosion. Japan is associated with Kawasaki S. [31], Nakashima K. [19], and Gowthaman S. [23], linked to keywords like slope surface, cementation level, MICP, biocementation, durability, and CaCO₃. The United States is connected by Montoya B.M. [88], Li X. [87] (also associated with China), and He J. [22] (also associated with China), sharing keywords like “biocement”, “EICP”, “CaCO₃”, “slope surface”, “erosion resistance”, and “soil improvement”. RStudio’s analysis (Figure 8B) highlights the global research landscape, with China, Japan, and the United States playing prominent roles. The focus of China on practical applications such as soil stabilization and erosion control is evident from its association with keywords like “slope surface”, “CaCO₃”, and “erosion resistance”.

Biocementation is closely linked to hydrological factors, which significantly impact soil and water management. Keywords like “rain” and “rainfall” highlight the environmental conditions under which biocementation processes occur. Precipitation influences the effectiveness and longevity of biocemented soils; heavy rainfall can lead to increased water infiltration and erosion, making biocementation crucial for enhancing soil cohesion and preventing washout. Hydrological conditions also play a key role in microbial activity essential for biocementation. Soil moisture content directly affects enzyme activity and the formation of CaCO₃, improving MICP EICP and resulting in more stable, durable soils. Additionally, understanding the interaction between hydrology and biocementation is critical for slope stability and erosion control. In regions with high rainfall and steep slopes, biocementation can substantially reinforce soil structure, reducing susceptibility to erosion and landslides and improving overall land stability in vulnerable areas.

3.6. Top Important Co-Cited References and Bibliographic Coupling of Documents

The visualization mapping of co-citation analysis of cited references in the research field is presented in Figure 9. The analysis reveals clusters of cited references that are closely related based on their co-citation patterns. In this study, A total of 5 different clusters were identified by VOSviewer. Cluster 1 (Green) comprises studies that looked into various aspects of MICP and its applications in soil stabilization and related fields. Al Qabany et al. [89] examined the impact of chemical concentration, using urea/calcium chloride solutions, on the CaCO₃ precipitation pattern in MICP-treated sand samples. Hamdan and Kavazanjian [90] demonstrated the efficacy of EICP in mitigating fugitive dust emissions, offering a sustainable alternative in arid environments where conventional methods are often ineffective or costly. Cheng et al. [91] proposed a unique approach to cementing sandy soils in marine environments using MICP, relying solely on seawater as the calcium source for calcite formation. ASTM [92] outlined standardized procedures for making and curing concrete test specimens under field conditions, providing essential requirements for concrete specimen preparation in construction projects. Jiang and Soga [93] investigated the potential of MICP for controlling internal erosion in gravel/sand mixtures, using large column tests to explore erosion characteristics and hydro/mechanical behaviors of MICP-treated soils. Whiffin [94] studied MICP’s ability to reduce soil permeability and increase shear strength, focusing on urea hydrolysis by urease-producing bacteria to form calcite. Chu et al. [95] explored MICP for producing biocementitious material for soil stabilization, investigating the feasibility of using commercially available technical-grade reagents for MICP studies. Omoregie et al. [96] examined the feasibility of using technical-grade reagents for MICP studies, demonstrating that low-cost growth media can be used to cultivate ureolytic bacteria for MICP field-scale trials. Lastly, Al Qabany et al. [97]

investigated the optimal use and efficient control of *Sporosarcina pasteurii* for inducing CaCO_3 precipitation in open environments, focusing on changing treatment factors to enhance chemical efficiency in MICP.

Cluster 2 (Red) focuses on erosion control and slope stabilization using MICP and related biogeotechnical strategies. Salifu et al. [98] emphasized the importance of adopting efficient and eco-friendly measures to stabilize slopes and prevent erosion in estuaries. To simulate tidal cycles, they constructed laboratory microcosms and studied the causes of erosion and failure in sandy foreshore slopes. MICP was applied to selected slopes, significantly improving slope stability and reducing sediment erosion. Omoregie et al. [6] investigated the use of locally isolated *Sporosarcina pasteurii* bacteria for soil improvement. The authors optimized cultural conditions for urease production and conducted biocementation tests, demonstrating the potential of these bacteria to enhance the strength of poorly graded soils. Danjo T. and Kawasaki S. [99] explored sand cementation using *Pararhodobacter* sp for coastal sand improvement. Their study established conditions for achieving significant unconfined compressive strength in sand specimens, contributing to the development of bio-stimulation techniques for coastal areas. Zhang et al. [100] addressed soil erosion in karst regions, studying the effects of slope gradient and length on runoff and soil loss. Their findings provide insights into soil conservation measures in karst regions. Van Paassen et al. [101] conducted a large-scale experiment on biogrouting, a biological ground improvement method using microorganisms to induce carbonate precipitation in granular soils. The approach provides insights into controlling bacterial activity for engineering applications. DeJong et al. [102] discussed bio-mediated improvement systems, focusing on bio-mediated calcite precipitation of sands.

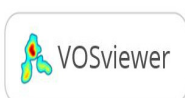
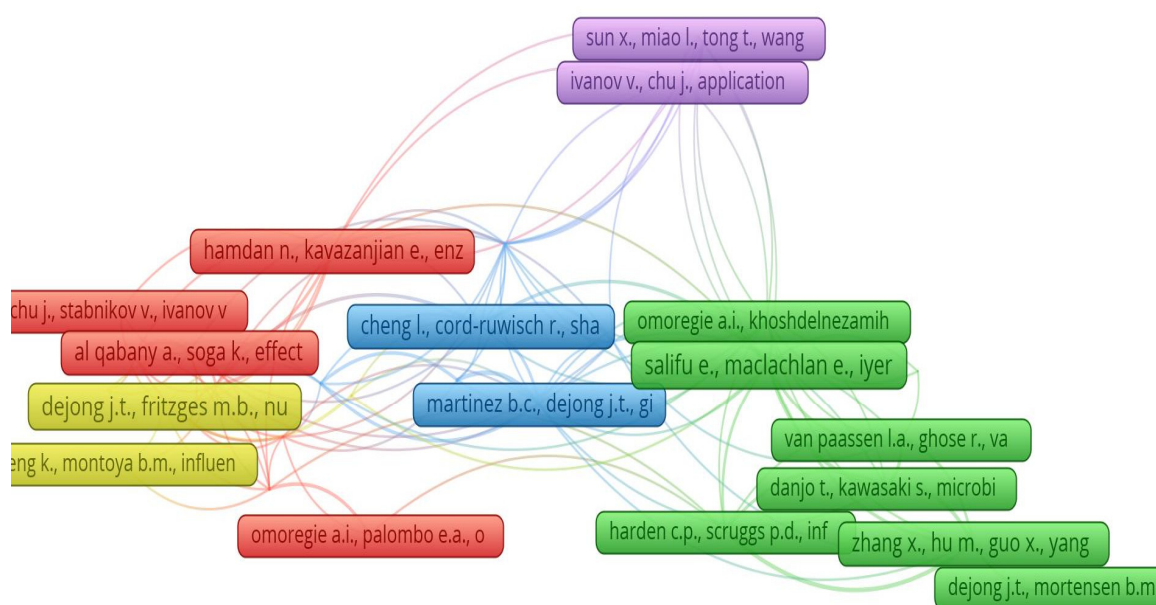


Figure 9. Visualization mapping of co-citation analysis of cited references. The online map is available online at <https://bit.ly/49ladxS> (accessed on 20 March 2024).

In Cluster 3 (Blue), Cheng et al. [51] explored the potential of MICP as a soil stabilization method in geotechnical engineering. This innovative technique utilizes bacteria to form calcite precipitation within the soil matrix, enhancing soil strength and stiffness. The results highlight the potential of MICP as a viable alternative for soil improvement in various geotechnical applications. Martínez et al. [103] focus on upscaling the MICP process for field applications. Whiffin et al. [104] conducted a study to evaluate the load-bearing capacity of soil treated with microbial carbonate precipitation over a five-meter sand column. Their results demonstrate a significant improvement in strength and stiffness without compromising soil permeability. Cheng et al. [105] investigated the environmental factors affecting the growth of *Sporosarcina pasteurii* and CaCO_3 precipitation induced by this bacterium, which is crucial for implementing MICP in situ. Montoya et al. [88] explored the potential of MICP to mitigate liquefaction-prone soils through geotechnical centrifuge tests. The study emphasizes the need to balance improving liquefaction resistance with minimizing undesirable surface accelerations when designing soil improvement strategies. Mortensen et al. [106] studied the environmental factors affecting the growth of *Sporosarcina pasteurii*, a bacterium used in MICP for soil improvement. They aimed to understand the bacterium's metabolism and CaCO_3 precipitation to optimize the MICP process in the field.

Cluster 4 (Yellow) highlights the diversity of current methods and the need for exploring new possibilities of soil improvement due to the increasing scarcity of suitable land for development. DeJong et al. [107] demonstrate the use of natural microbial biological processes to engineer a cemented soil matrix within initially loose, collapsible sand. They achieve MICP using *Sporosarcina pasteurii*, which results in a non-collapse strain softening shear behavior with higher initial shear stiffness and ultimate shear capacity than untreated loose specimens. This method shows potential for improving the mechanical properties of sand, similar to gypsum cemented specimens. He et al. [108] introduced a biogas method to reduce the liquefaction potential of saturated sand by making it slightly unsaturated. A denitrifying bacterium was used to generate tiny, inert nitrogen gas bubbles in the sand, effectively reducing pore water pressure and mitigating liquefaction hazards. This approach offers a cost-effective solution for large-scale liquefaction mitigation. Berli M. and Or D. [109] challenged the conventional constitutive models for unsaturated soils, suggesting that the identification of soil/water suction with the capillary component of the matrix potential may be inaccurate. Feng X. and Redfern S. A. T. [110] investigated the mechanical response of MICP cemented sand under different cementation levels and effective confining pressures. They found that stiffness, peak shear strength, and dilation increase with an increase in calcite content at a given confining pressure, while dilation is suppressed with higher confining pressures.

Finally, Cluster 5 (Purple) focuses on microbial geotechnology and sand solidification technology, highlighting their significance in geotechnical engineering. Ivanov et al. [111] discussed the applications of bioclogging and biocementation to reduce soil porosity and hydraulic conductivity or increase shear strength. Sun et al. [112] presented experimental methods for analyzing the effect of adding urea to a culture medium for sand solidification. Their study provides valuable insights into the optimal use of urea for sand solidification, with implications for various sand particle sizes. Ulusay R. and Erguler Z. A. [113] critique existing constitutive models for unsaturated soils, particularly the identification of soil/water suction with the capillary component of the matrix potential, neglecting the contribution of adsorption. They suggest that considering adsorption potential and a double porosity model is essential for interpreting unsaturated soil behavior accurately.

Bibliographic coupling analysis of documents in the field was conducted using VOSviewer, which identified three distinct cluster groups, as shown in Figure 10. Identifying the bibliographic coupling of documents in a field is relevant for several reasons. It

helps uncover the intellectual structure of a research field by revealing the relationships between different works based on their shared citations. In Figure 10, three different cluster groups were identified. In Cluster 1 (Red), Montoya et al. [114] conducted experiments to investigate the efficacy of MICP on coal ash materials. Kou et al. [115] quantitatively investigated the erosion resistance of biocemented sandy slopes under waves using bench-scale flume erosion tests. Gao et al. [116] conducted triaxial and K0 consolidation tests on sands with varying biocement treatment passes and relative densities. They found that even slight biocement treatment on sand could improve strength and deformation control, with 2-pass treatment sufficient for achieving shear strength similar to untreated dense sand for loose sand and 1-pass treatment sufficient for medium dense sand. Hamdan et al. [117] evaluated the potential of inducing carbonate precipitation in soil via bacterial denitrification using *Pseudomonas denitrificans*.

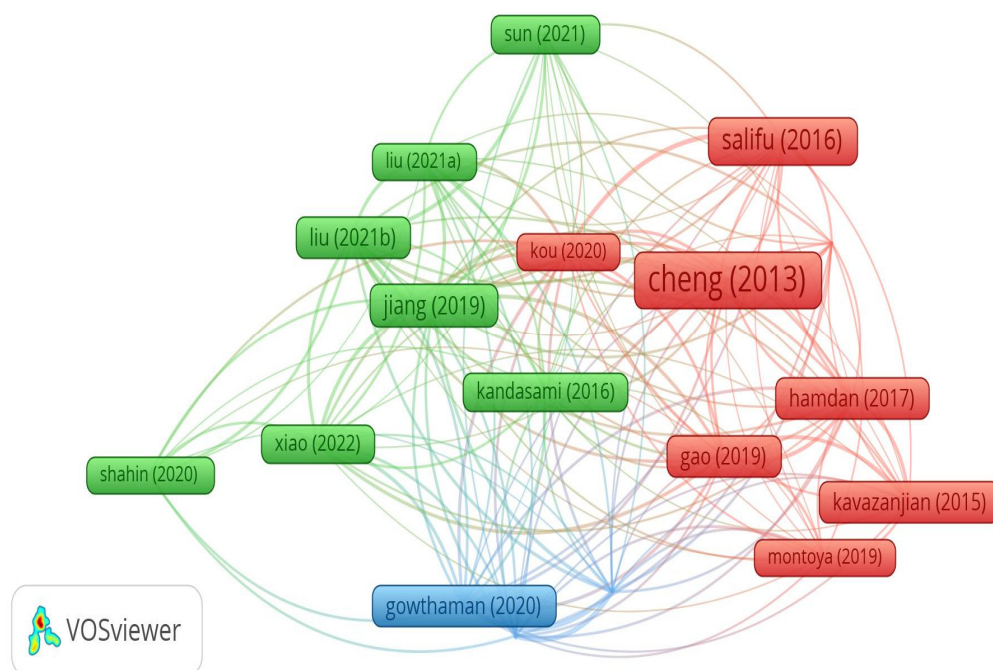


Figure 10. VOSviewer analysis of bibliographic coupling of documents in the field. The map is available online at <https://bit.ly/3vjOmJb> (accessed on 20 March 2024).

Kavazanjian E. and Hamdan N. [118] discussed EICP as a ground improvement technique using urease to precipitate CaCO_3 . They found that EICP columns of soil could be created by infusing a cementation solution through a perforated tube or pipe or by mix-and-compact methods, offering the potential for ground improvement in various geotechnical applications. Sharaky et al. [119] focused on studying the stabilization of loose soils via a biocementation process using bacteria named *Sporosarcina pasteurii*. Salifu et al. [98] developed laboratory microcosms to simulate tidal cycles and examined the effectiveness of MICP in mitigating erosion and stabilizing sandy foreshore slopes. They found that MICP-treated slopes showed significantly improved stability and negligible sediment erosion, indicating promise for protecting foreshore slope sites. Cluster 2 comprises studies that investigate various bio-mediated techniques for soil stabilization and erosion control, focusing on different environmental conditions and applications. Liu et al. [24] proposed the use of MICP to control surface erosion of clayey soils, while Sun et al. [120] explored the use of EICP technology for dust control, adding polyvinyl acetate to improve erosion resistance. Additionally, Liu et al. [28] compared the effectiveness of MICP and EICP in mitigating dune erosion under wave attack. Cluster 3 of the studies focuses on the

application of MICP for slope soil stabilization, particularly in cold subarctic regions in Japan. Gowthaman et al. [23] described the challenges of using MICP in cold climates due to reduced bacterial enzymatic activity and proposed the use of bacteria that could adapt to cold conditions. In a different study, Gowthaman et al. [121] investigated the durability and shear responses of MICP-treated slope soil, including freeze/thaw (FT) resistance and shear strength, and reported that MICP improves soil stability and cohesion, especially against FT cycles, with treated specimens showing mass losses ranging from 0.53% to 1.14% after 10 cycles.

4. Hydrological Implications of Biocementation Treatment Techniques

Applying biocementation techniques, such as MICP and EICP, has demonstrated significant potential in mitigating slope instabilities. While primarily recognized for their geotechnical benefits, these techniques also influence critical hydrological processes, including infiltration, runoff generation, pore water pressure regulation, and sediment control. These hydrological improvements make biocementation highly relevant for watershed management and erosion mitigation strategies.

In terms of erosion resistance and runoff dynamics, Kou et al. [115] reported a 60% reduction in erosion rate on MICP-treated sandy slopes during simulated wave action tests. The penetration resistance of these slopes increased from 0.14 MPa (untreated) to 2.04 MPa after four cycles of MICP treatment, significantly enhancing surface stability and reducing soil erodibility. Similarly, Li et al. [122] demonstrated that the permeability of biocemented slopes decreased from 1.5×10^{-4} m/s to 5.2×10^{-5} m/s, leading to a 40% increase in surface runoff during storm simulations. This reduction in permeability minimized sediment transport, which is crucial for maintaining downstream water quality and preventing sedimentation in aquatic ecosystems. Biocementation also plays a critical role in regulating infiltration and improving soil water retention. Sun et al. [66] found that biocemented foreshore slopes reduced infiltration rates by 35%, with a corresponding increase in surface runoff. The water retention capacity of the treated soil increased by 20%, enhancing the slope's resistance to internal erosion during heavy rainfall. Similarly, Huang et al. [70] observed a 50% reduction in infiltration rate in MICP-treated silty slopes, which limited the rise in pore water pressure during prolonged rainfall. This reduction in infiltration contributed to a 30% improvement in slope stability, effectively preventing shallow landslides.

The hydraulic conductivity of slopes is another crucial parameter affected by biocementation. Hang et al. [47] demonstrated that MICP reduced the hydraulic conductivity of silty sand slopes from 1.2×10^{-3} m/s to 3.8×10^{-5} m/s, significantly minimizing fine particle migration and improving resistance to suffusion, a common failure mechanism in slopes under sustained seepage. Ghalandarzadeh et al. [35] further noted that the critical hydraulic gradient increased from 0.4 (untreated) to 1.2 (treated), effectively preventing internal erosion under high hydraulic stress. Biocementation techniques have also been effective in controlling sediment runoff and improving water quality. Jiang et al. [123] reported a 70% reduction in sediment runoff from MICP-treated slopes during simulated rainfall events. This reduction was attributed to the formation of a protective CaCO_3 crust, which minimized soil detachment and reduced sediment transport into nearby water bodies. Wang et al. [68] highlighted that biocementation treatments reduced suspended sediment concentrations in runoff from 120 mg/L to 40 mg/L, significantly improving water clarity and reducing the risk of eutrophication in downstream ecosystems. The durability of biocemented slopes under fluctuating moisture conditions is another important consideration. Shao et al. [74] found that cyclic wetting and drying resulted in only a 5% reduction in shear strength for MICP-treated soils, compared to a 25% reduction in

untreated soils. This demonstrated the long-term stability and resilience of biocemented slopes, even under varying hydrological stresses such as seasonal wetting/drying cycles.

Beyond slope stabilization, biocementation offers a range of hydrological benefits, particularly in improving watershed functions and mitigating flood risks. Techniques such as MICP effectively regulate rainwater infiltration rates, a critical aspect of slope stability under varying precipitation intensities. For example, Pan et al. [29] demonstrated that MICP-treated soils reduced infiltration by over 80% across diverse soil types and slope angles. In addition, the formation of CaCO_3 crusts reduces fine particle migration, enhances sediment retention, and resists the impact of raindrops due to improved uniaxial compressive and flexural strength [25,86]. These hydrological and mechanical enhancements prevent rapid saturation and mitigate shallow landslide risks. The synergy between hydrological improvements and mechanical stabilization further enables the optimization of soil properties. Cheng et al. [124] highlighted that incorporating specific additives like magnesium and fibers strengthens the soil matrix and enhances thermal conductivity. These innovations not only improve soil water retention and pore pressure regulation but also support energy transfer efficiency in geotechnical applications, such as energy piles [125,126].

Additionally, biocementation techniques complement traditional erosion control measures like vegetation barriers. For example, integrating MICP-treated slopes with vegetative cover enhances both soil cohesion and water infiltration control. However, excessive calcite precipitation must be avoided, as it could impede root growth. Optimized treatment solutions, such as those incorporating phosphorus additives to balance calcite precipitation and promote vegetation health, can ensure the dual benefits of slope stabilization and ecological restoration [127,128]. Biocementation's potential extends to coastal environments, where techniques like MICP and EICP improve slope stability and reduce soil erodibility. Li et al. [36] showed that MICP-treated slopes developed a calcium carbonate crust, improving resistance to wave action and reducing erosion rates. These treatments not only enhance mechanical stability but also contribute to sustainable coastal ecosystem management by maintaining water quality and modifying terrain dynamics from erosional to depositional patterns [129,130]. By mitigating infiltration, reducing erosion, and enhancing soil resilience under dynamic conditions, biocementation contributes significantly to the stability of hydrological systems. Further interdisciplinary research and the integration of biocementation into hydrological models will ensure its efficacy in large-scale applications and its role in advancing sustainable land management practices.

5. Emerging Research Direction and Environmental Sustainability of Biocementation

This review explores emerging investigations in slope and landslide stabilization using biocementation, focusing on MICP and EICP techniques. Potential directions and advancements are highlighted to develop innovative solutions for various environmental applications. Pan et al. [29] proposed a controllable MICP method to manage rainwater infiltration in soil slopes. Their experiments showed it effectively prevented slope failure from rapid infiltration while allowing sufficient infiltration for plants and animals, preventing over 82.6%, 92.2%, and 84.4% of rainwater infiltration at a 15° slope and 50 mm/h rainfall intensity. Wang et al. [131] used MICP to protect granite residual soil slopes in Shantou against erosion. MICP treatment significantly reduced soil hydraulic conductivity and erosion rates, enhancing erosion resistance. After 7 days, calcite content increased to 4.3%, with a mean coating thickness of 4.2 mm, and unconfined compressive strength increased by 20.3%. Soil hydraulic conductivity and erosion rates were reduced by 90.9% and 95.2%. Phanvongsa et al. [34] used casein combined with EICP to mitigate shallow failures in cut

slopes. EICP treatment created an impermeable crust that prevented rainwater infiltration and slope subsidence. The treated slope remained stable after 113 mm/h of rain for 15 h and 39 min, while the untreated slope collapsed in 11 min and 30 s. Sun et al. [132] investigated MICP for foreshore slope erosion resistance, showing that biomineralization treatment significantly enhanced erosion resistance, especially at lower Mg^{2+}/Ca^{2+} ratios. Ratios of 0.2:0.8, 0.1:0.9, and 0:1.0 were effective for both slope stabilization and erosion mitigation.

Li et al. [133] explored cadmium mobility and speciation during microbial carbonate precipitation under simulated acid rain, showing MICP's potential for soil Cd remediation. Sustained urease activity confirmed the method's effectiveness in creating an impermeable, erosion-resistant layer. Zhang et al. [134] demonstrated that low-cost cementation media improved slope surface strength and erosion resistance through higher $CaCO_3$ content. Moqsud M. A. and Gochi T. [8] used native *Cytobacillus horneckiae* for biocementation, significantly enhancing slope stability after 21 days. Wang et al. [135] found that MICP effectively improved granite residual soil strength and cohesion. Hang et al. [47] showed the effectiveness of MICP in reducing suffusion and enhancing silty sand stability under seepage. Gowthaman et al. [19] used low-cost cementation media for slope preservation, significantly improving surface strength and $CaCO_3$ content, with a 97% reduction in material cost compared to analytical-grade media.

Emerging studies indicate significant advancements in biocementation and related technologies. Future research will likely focus on refining MICP processes to enhance rainwater infiltration management, slope failure prevention, and soil stability. Integrating biocementation with technologies like geosynthetics or soil nailing could improve overall slope stability. Biocementation has global applicability for addressing slope and landslide issues, benefiting regions like Southeast Asia, South America, Central Asia, Africa, Europe, and North America [9,136]. Countries with significant challenges, such as Indonesia, the Philippines, Malaysia, Ecuador, Colombia, Nepal, Bhutan, Kenya, Algeria, Nigeria, Rwanda, Poland, Portugal, and Italy, could particularly benefit from MICP applications [137,138]. Alzubaidi R. and Lafta S. H. [139] highlighted the lack of research on the effect of strain rate on stabilized soil properties. They investigated strain rate effects on the strength and deformation characteristics of soil/lime mixtures. Similarly, Maqsood et al. [140] studied the hardening characteristics and loading rate-dependent behavior of gypsum mixed sand. Future research in slope soil biocementation should include studies on strain rate effects to evaluate the strength and deformation characteristics of stabilized soils under transient conditions.

The sustainability, environmental impact, and cost-effectiveness of MICP and EICP approaches have been widely studied. Although these methods are more environmentally friendly than traditional ground improvement methods, they have some environmental impacts. Ammonium production during the MICP or EICP process is a significant issue, leading to soil acidification, adverse effects on humans and animals, and groundwater pollution. Omoregie et al. [141] demonstrated the environmental impact of ammonium leakage during an outdoor biocementation treatment, resulting in soil contamination and plant depletion. The ammoniacal nitrogen concentration in the effluent was measured at 1300 mg/L, exceeding the Occupational Safety and Health Administration's limit of 35 mg/m³. The ureolytic pathway for engineered MICP has poor sustainability due to the high carbon footprint and eutrophication potential of ammonium waste. Autotrophic pathways involving carbonic anhydrase bacteria and photosynthesis can reduce the carbon footprint by utilizing atmospheric carbon dioxide [142,143]. For example, $CaCO_3$ produced using carbonic anhydrase enzyme has a significantly lower carbon footprint compared to traditional methods [144]. However, MICP through ureolysis has a higher eutrophication potential due to ammonium gas production, reported to be 0.24 kg SO_4/kg

CaCO₃ [145]. Additionally, the energy required for MICP using laboratory-grade chemicals surpasses that of conventional methods. Porter et al. [144] also reported that MICP via ammonification or methane oxidation was the most expensive route, costing 138 USD/kg CaCO₃, while the most economical route was MICP via cyanobacteria, costing 62 USD/kg CaCO₃. Another study by Deng et al. [145] highlighted that carbon emissions from calcium sources accounted for 72.4% of total emissions, and energy consumption from calcium sources and urea accounted for 53.2% and 42.8% of total energy consumption, respectively. Alotaibi et al. [146] compared the environmental impact of EICP and Portland cement for soil enhancement. EICP resulted in a 3% reduction in global warming potential, with carbon dioxide being the highest contributor. Using Portland cement resulted in a total global warming potential of 255 tonnes of CO₂-eq, which was reduced to 247 kg CO₂-eq with the EICP application.

6. Successful Biocementation Methods for Soil Stability and Erosion Resistance

Biocementation has emerged as a promising technique globally for enhancing slope stability. Figure 11 outlines the biocementation treatment process, beginning with preparation and site assessment to understand soil conditions. Techniques involve selecting urease biocatalysts, biocementation methods, and appropriate cementation solutions. Geotechnical analyses ensure treatment effectiveness, followed by continuous monitoring and optimization to achieve stable slopes. Numerous studies have explored various methodologies and microbial strains to optimize biocementation effectiveness. For example, Kou et al. [115] utilized *Sporosarcina pasteurii* in a spray application (spray rate of 0.5 mL/cm²/min) on sandy slopes, controlling saturation levels from top to bottom. They reported that biocementation reduced the erosion rate of sandy slopes by up to 50%. Treated slopes showed increased calcite content and penetration resistance, significantly enhancing strength. Calcite content in residual samples ranged from 10% to 30%, with higher content correlating to greater erosion resistance. Chen X. and Achal V. [147] investigated biocementation resilience under simulated acid rain, applying cementation solutions (100 mL) for 7 days. Gowthaman et al. [23] employed enriched bacterial cultures through injection to stabilize soil slopes over two weeks, demonstrating efficacy in both lab and field settings. The authors reported that biocementation increased unconfined compressive strength (UCS) more in finer sands than in coarser sands. Soil slope, with a well-graded mix of particle sizes, showed substantial improvement in UCS.

Different biocementation techniques have been explored, including injection and mixing methods by Sharaky et al. [119], where *Sporosarcina pasteurii* was used to precipitate calcite within sand columns. They demonstrated that treated sandy soil samples had significantly higher compressive strength and water stability. Injection with fixation yielded the highest compressive strength at 17.73 kg/cm². All treated samples displayed excellent stability in water, showing no collapse post-treatment. Liu et al. [24] treated clayey soils with multiple cycles of bacterial and cementation solutions, enhancing soil microstructure and erosion resistance. They observed that MICP-treated clayey soil exhibited significantly less soil loss in erosion tests. Treated samples formed a dense surface crust, reducing erosion and enhancing soil stability. Soil loss in treated samples was minimal compared to severe erosion in control samples. Huang et al. [70] utilized a sprinkler system for MICP treatment on sandy slopes, optimizing surface coverage and application efficiency. The treated slope showed minimal surface damage and slowed slope creep after failure.

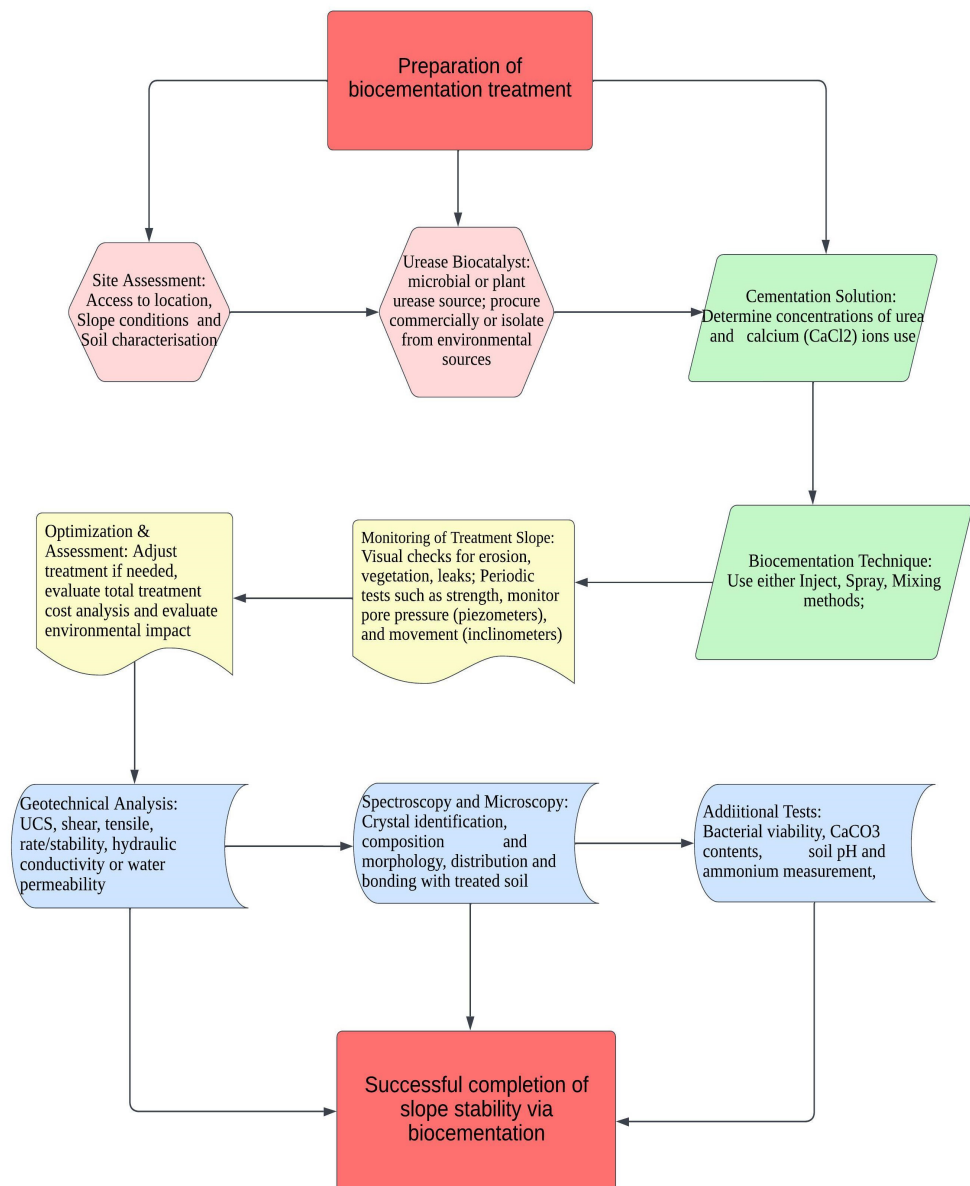


Figure 11. Flowchart of the biocementation treatment process for slope stability.

Studies like those by Wang et al. [135] and Li et al. [122] further investigated grouting methods and erosion resistance improvements using MICP treatments. These methods significantly enhanced soil stability, demonstrating increased tensile and compressive strengths across different soil types. Wang et al. [135] reported a significant improvement in the strength and stability of granite residual soil. Peristaltic pump grouting enhanced shear strength by over 55% and unconfined compressive strength by 513.65%, demonstrating significant improvements in soil stability. Li et al. [122] found that MICP treatment improved erosion and penetration resistance of sandy slopes. Treated slopes showed a maximum penetration resistance of 2.04 MPa, compared to 0.14 MPa in untreated slopes. Calcium carbonate crystals bridged gaps between sand particles, enhancing wave resistance and slope stability. Shen et al. [148] combined bio-enzymatic and chemical methods, integrating basalt fibers for enhanced soil matrix reinforcement and erosion control. They revealed that treatments with higher basalt fiber content led to greater surface strength and erosion control. Erosion was significantly delayed, and cumulative soil loss was reduced during dry/wet cycles. These studies demonstrate that biocementation techniques, particularly MICP, significantly enhance soil stability and erosion resistance. Konstantinou et al. [149]

investigated the tensile strength of biocemented sands using MICP. Fine and coarse sands were subjected to a two-stage MICP treatment, and it was found that the tensile strength of biocemented sands increased significantly, with fine sand's tensile strength rising from 50 kPa to 700 kPa and coarse sand from 25 kPa to 500 kPa.

7. Limitation and Future Direction of Biocementation for Slope Stability

Biocementation techniques offer promising solutions for slope stabilization, but several challenges must be addressed for real-world effectiveness. Laboratory studies often do not accurately represent real-world conditions, which are more complex and larger in scale. The long-term durability of biocementation under varying temperatures, moisture levels, and natural bacterial communities requires further investigation. Short-term studies provide insights, but longer-term research is needed to understand stability under prolonged exposure to environmental factors such as acid rain [133]. Bacterial strains used in biocementation may have reduced effectiveness under certain conditions, with some bacteria producing urease more efficiently at specific temperatures and pH levels, limiting their applicability in varying climates [150–152]. Emerging studies suggest identifying bacterial strains with wider environmental tolerance or engineering urease-producing microbes to adapt to site-specific conditions.

The long-term stability of CaCO_3 precipitation under various environmental conditions remains uncertain, although they can be expected to be stable for over 50 years, provided alkaline conditions persist. Research on the dissolution rates of calcite under acidic and fluctuating conditions will help refine predictions of durability and maintenance needs [153,154]. Understanding the impact of biocementation on different soil types and its potential for ecological restoration is essential. The effectiveness of MICP or EICP beyond clayey soils needs evaluation, as treatments are often concentrated in shallow soil layers, requiring additional rounds or alternative methods for deeper reinforcement [155]. Scaling up laboratory models to real-world slopes presents practical challenges, and the environmental impact of materials like urea and calcium chloride needs a thorough assessment. Recent findings indicate that bio-based alternatives to these chemicals, such as agricultural by-products or biopolymers, could mitigate ecological concerns without compromising efficacy [14,156].

Several successful case studies illustrate the potential of biocementation in practical settings. Stefaniak et al. [157] demonstrated the efficacy of MICP in enhancing the shear strength of soils in Poland by employing *Sporosarcina pasteurii*. The site work was carried out in Głuchów and Poznań, Poland. This approach not only increased soil bearing capacity by up to 50% but also provided a sustainable alternative to traditional hydraulic mixtures, significantly reducing CO_2 emissions. Furthermore, the innovative use of bio-waste and secondary raw materials for bacterial nutrients underscores the cost-effectiveness and environmental benefits of the method. Similarly, Gao et al. [158] showcased the use of soybean crude extract in EICP to combat wind erosion in the Ulan Buh Desert, China. The treatment improved sandy soil surface strength to 306.2 kPa and effectively mitigated wind erosion over a year, particularly in sheltered topographic areas. These findings highlight the feasibility of biocementation for desertification control and sandstorm mitigation.

In Japan, Gowthaman et al. [19] successfully implemented MICP using low-grade chemicals for slope stabilization on the Hokkaido Expressway. *Lysinibacillus sphaericus* (previously *Bacillus sphaericus*) was utilized to promote the use of indigenous bacteria instead of exogenous species, considering biological reliability, bio-safety, and legal acceptance. By replacing analytical-grade chemicals with fertilizer-grade urea, snow-melting agents, and beer yeast, the researchers reduced material costs by 97% while achieving comparable improvements in surface strength and CaCO_3 content. This field-scale experiment

demonstrates the potential for cost-effective and scalable MICP applications. However, the study by Zeng et al. [48] highlighted the challenges of applying MICP in heterogeneous soils. Despite inconclusive cone penetration tests, numerical modeling revealed that uneven flow distribution limited treatment effectiveness to 5% of the soil volume. These findings underscore the need for improved injection techniques and strategies to address soil heterogeneity in field applications.

Treatments with additional EICP cycles can result in crust formation that hinders solution infiltration. Scaling treatments uniformly on large slopes is more complex than in laboratory settings. Experiments using specific sand types may not generalize to other sands with different properties [159]. Standard silica sands would serve as better reference geomaterials for laboratory experiments. Focusing on tensile strength without considering other mechanical properties like compressive and shear strength limits the understanding of overall soil behavior. Laboratory tests on disturbed soil samples may not fully represent in situ conditions, necessitating field tests with undisturbed samples [19,46]. In particular, long-term field trials are essential to assess the effects of biocementation on groundwater systems, vegetation growth, and soil/water interactions over multiple seasonal cycles. Long-term performance under factors like freezing/thawing cycles and sustained pressure needs evaluation. Using local bacterial strains could improve environmental compatibility and long-term effectiveness. Further optimization of grouting methods, cement solution concentrations, and other variables is required. The above case studies provide critical insights into both the successes and challenges of biocementation technologies. They highlight the importance of site-specific approaches, cost-effective materials, and the need to overcome limitations such as uneven treatment distribution and long-term durability concerns. By learning from these examples, researchers can refine techniques and address key barriers to widespread adoption.

To enhance the effectiveness and applicability of biocementation, several future directions should be explored. Moving beyond laboratory settings to large-scale field trials is crucial. These trials should encompass diverse environments with varying climates, soil types, and stress conditions. Field validation and real-world testing will provide valuable insights into practical challenges and pave the way for practical implementation [15,160]. Coupling biocementation with predictive modeling techniques, such as finite element analysis, can provide additional insights into the distribution and long-term performance of calcite precipitation in field applications. Comprehensive long-term durability studies are needed to assess how biocemented products endure harsh weather conditions like freeze/thaw cycles, acid rain, and sustained loads over extended periods. This will help determine the longevity and maintenance needs of biocemented slopes, ensuring they remain stable and effective over time [132]. Techniques like genetic engineering and adaptation studies can create more robust strains suitable for diverse environments and broader applicability of biocementation [161]. Advanced injection systems utilizing drones or automated ground robots could enable precise and uniform application of cementation solutions across large and inaccessible slopes. Implementing real-time monitoring and control systems during MICP or EICP treatments can significantly improve biocementation effectiveness [162].

Thorough environmental impact assessments are essential to understand and mitigate the potential negative impacts of biocementation components like urea and calcium chloride on the surrounding ecosystem [163–165]. Investigations into biocompatible stabilizers or the use of locally available materials could significantly enhance sustainability. Exploring hybrid approaches that combine biocementation with other slope stabilization techniques like geosynthetics or traditional chemical grouting can offer synergistic benefits [166–168]. This could address specific limitations inherent to each method, leading to more robust and

reliable slope stabilization solutions. Detailed economic analyses are needed to understand the cost/benefit ratio of biocementation compared to traditional methods [169–171]. Identifying and implementing cost-reduction strategies, such as optimizing material usage and improving process efficiency, will make biocementation a more competitive and attractive option. For example, there is an increasing interest in substituting the calcium source for crystallization with alternatives like kitchen waste and pig bones [172]. Expensive purified plant-derived urease is being replaced with locally produced crude urease from sources like soybeans [173]. Additionally, industrial wastes, such as palm oil mill effluent, are being considered as economical nutrient alternatives [174], and animal urine, such as cow urine, is being used to replace traditional urea sources [163]. The process of ureolysis results in the release of undesirable ammonium by-products, and their removal from the system is another remaining context for future work [175–177]. If the reactions could be controlled at low pH levels, it may help to inhibit the release of toxic ammonia gas. The ammonium ions can be possibly eliminated by extracting and treating the drained solutions, which could help to avoid any contaminations with groundwater [141]. By addressing these technical, environmental, and economic challenges, researchers can unlock the full potential of biocementation as a sustainable and scalable solution for slope stabilization.

8. Ramifications for Practice, Policy, and Future Research in Biocementation

To further explore the broader implications of biocementation for slope stability, it is essential to consider its potential ramifications for practice, policy, and future field studies. Biocementation presents a sustainable and innovative solution for slope stabilization and hydrological management, offering a viable alternative to conventional methods that rely on synthetic materials and heavy infrastructure. As these techniques align with global sustainability objectives, such as the United Nations' SDGs (SDG 6: Clean Water and Sanitation, SDG 11: Sustainable Cities and Communities, and SDG 13: Climate Action), they provide a pathway toward more resilient and environmentally responsible infrastructure development. By reducing sediment transport, enhancing water retention, and mitigating soil erosion, biocementation contributes to sustainable water management and climate-resilient infrastructure. For instance, Liu et al. [178] demonstrated the use of MICP to reduce sediment transport and enhance water retention in sandy slopes, improving water quality and availability in line with SDG 6. Additionally, biocementation's eco-friendly nature supports the Sendai Framework for Disaster Risk Reduction (2015–2030), which emphasizes sustainable engineering solutions to prevent landslides and reduce disaster risks [179,180]. Phanvongsa et al. [34] showed that casein-combined EICP could create an impermeable crust on slopes, protecting infrastructure in landslide-prone areas, aligning with SDG 11. Similarly, Shilpi et al. [37] found that MICP can stabilize homogeneous slopes, reducing landslide risk even in varied soil conditions, aligning with SDG 13.

From a policy perspective, the integration of biocementation into national and international frameworks can significantly advance environmental and disaster resilience goals. Policymakers could leverage biocementation to meet environmental targets set within guidelines such as the United States Environmental Protection Agency's erosion control regulations. In Malaysia, the government's adoption of Environmental, Social, and Governance principles in major infrastructure projects, such as the Pan Borneo Highway, demonstrates a commitment to aligning with global sustainability objectives [181,182]. Similarly, Sarawak's post-COVID-19 development agenda promotes environmental conservation and sustainable development, further emphasizing the importance of biocementation in regional infrastructure planning [183,184]. Additionally, government support for a circular economy, including the use of industrial by-products like fly ash and slags in biocementation, provides economic and environmental incentives for scaling these technologies [185,186].

Furthermore, the wide adoption of biocementation technologies calls for continued field studies to refine these methods and assess their long-term effectiveness across diverse soil types, climates, and infrastructure needs. While laboratory studies have shown promising results, real-world applications are crucial for understanding the scalability and durability of these techniques. Ongoing research should focus on optimizing biocementation agents, improving cost-effectiveness, and developing comprehensive guidelines for their integration into large-scale infrastructure projects. The increasing number of publications from countries like China and the United States highlights the growing recognition of biocementation's potential, with government policies in these regions already supporting its use for slope stability. This global momentum suggests that further research and practical applications of biocementation can enhance the sustainability of infrastructure, reduce environmental impact, and contribute to achieving long-term climate and disaster resilience goals.

9. Conclusions

Biocementation is a promising technique for improving slope stability, enhancing soil strength, and reducing erosion. Studies have explored various methods and microbial strains, such as *Sporosarcina pasteurii* and *Bacillus pasteurii*, to optimize the process through calcite precipitation. Techniques like premixing, spraying, and injection have demonstrated significant improvements in soil stabilization. Our bibliometric analysis shows a steady growth in biocementation research over the past decade. Before 2010, fewer than 50 publications on the topic appeared annually. By 2018, this number exceeded 200 per year, with most studies originating from countries with advanced geotechnical research facilities, including the United States, China, and Australia. *Sporosarcina pasteurii* is the most commonly studied bacterial strain, highlighting its central role in this field.

This study makes several unique contributions to the field of biocementation. Firstly, the bibliometric analysis identifies actionable research gaps, such as the limited focus on hydrological resilience in slope stabilization. Secondly, the interdisciplinary clusters revealed by co-authorship and keyword co-occurrence analyses demonstrate the potential for integrating geotechnical innovations with hydrological engineering. By bridging these gaps, the study contributes to the advancement of sustainable practices and highlights the applicability of MICP and EICP in diverse engineering contexts.

Despite these advancements, several challenges remain. Laboratory studies often fail to reflect real-world conditions, emphasizing the need for comprehensive field trials. Key areas for future research include ensuring long-term durability under varying environmental conditions, improving bacterial strain adaptability across climates, and addressing the challenges of scaling laboratory findings to field applications. Optimizing the even distribution of bacteria and cementation solutions, particularly in deeper soil layers, is also a critical hurdle. Future work should prioritize large-scale field trials, the development of robust bacterial strains, and effective distribution methods. Real-time monitoring and control systems, environmental impact assessments, and hybrid approaches combining biocementation with other stabilization techniques could further enhance the process. Economic analyses will help evaluate the cost-effectiveness of biocementation compared to traditional methods, encouraging broader adoption.

By addressing these challenges and exploring new directions, biocementation can become a practical and sustainable solution for slope stabilization. Continued innovation and research will support safer infrastructure and more resilient slopes, benefiting both society and the environment. The growing volume of research and expanding geographic distribution underscore the increasing recognition of biocementation as a viable method for soil stabilization and slope management.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/hydrology12010014/s1>: Table S1. Search strategy used for retrieval of documents in Scopus database; Table S2. Additional information in the Scopus database about the leading authors in the field; Table S3. Performance metrics of the leading publishing spots in the field; Figure S1. An image showing riprap soil slope protection in Malaysia that disintegrated or failed; Figure S2. Top leading cited countries in the field from 2013 to 2023.

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