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MICP-Based Biocementation for Slope and Embankment Stabilization: A Bibliometric Review and Thematic Synthesis for Hydro-Mechanical Assessment and Field-Scale Implementation

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biocementation; slope stability; embankment stabilization; MICP; calcium carbonate precipitation

Abstract

Microbially induced calcite precipitation (MICP) based biocementation is a fast developing ground improvement method in geotechnical engineering. Nonetheless, utilization of MICP to slope and embankment stabilization is still spread across diverse investigations that consider enhancing soil mechanical characteristics, precipitation of calcium carbonate, erosion resistance, reducing liquefaction, and engineering applications and the constraints. This paper presents a bibliometric review and thematic synthesis of biocementation using MICP in slope and embankment stabilization. Using the search query ("slope stability" OR "slope stabilization" OR embankment OR landslide) AND (MICP OR biocementation OR "microbially induced calcite precipitation") as of 2016 up to July 4, 2026, the literature corpus was retrieved in ScienceDirect. Following the metadata-based filtering of records based on the publication period and document type, 265 records were selected to be subject to bibliometric analysis and mapped in VOSviewer version 1.6.20 by co-occurrence of terms. Among the identified terms 7,838, 159 met the minimum occurrence threshold, and 87 terms were included in the final mapping following a manual cleaning of the terms, the network generated consisted of four major clusters, 2,766 links, and a link strength of 8,416 in total. The four main themes were found during the analysis, and they were soil stabilization and shear strength, calcium carbonate precipitation and erosion resistance, biocementation and liquefaction resistance, and implementation and limitations at the field scale. The results suggest that the reviewed literature is still largely concentrated on laboratory-level research, microstructural characterization, and the mechanism of calcium carbonate precipitation, whereas field validation, the impact of rainfall infiltration, cementation durability, spatial variability, and numerical modeling of biocemented slopes are not well studied. The review offers an inclusive knowledge architecture that connects the biogeochemical processes, geotechnical performance, and engineering implementation issue to enable sustainable slope and embankment stabilization.

1. INTRODUCTION

The stability of slopes and embankments is the core issue in geotechnical engineering as it has a direct correlation with the infrastructure safety, sustainable land use, and risk reduction in geohazards (X. Wang et al., 2019). There are many factors that can lead to slope failure, which include the reduction of the shear strength of the soil, high pore water pressure, infiltration of rainfall, surface erosion, and dynamic load, a change in the slope geometry, and the loss of soil properties under the environmental conditions (Sidle & Bogaard, 2016). This issue is more acute in tropical areas and regions with a high intensity of rainfall since the rainfall infiltration may reduce the matric suction in unsaturated soils, destabilize the soil aggregate structure, promote erosion, and cause shallow landslides and embankment failures (Rangarajan et al., 2024). Slope stabilization therefore entails improvement of the parameters of soil strength and resistance to water, erosion and different environmental conditions.

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Geotechnical engineering is characterized by traditional techniques of stabilizing the soil like cement stabilization, lime stabilization, geosynthetics, soil nailing, retaining structures and other mechanical methods of soil stabilization. Nevertheless, most of these methods are associated with high cost of construction, high carbon emission by cementitious materials, environmental issues and reliance on heavy machinery. They are also incapable of application in places with inaccessibility or complicated slope geometry (Jiang et al., 2023). These have aided in the creation of more natural processes that can be used in soil stabilization that is more environmental friendly and flexible. Microbially-induced calcite precipitation (MICP) and biocementation are technologies that have been gaining momentum in this field, as other ground-improvement techniques to enhance slope and embankment stability(Fu et al., 2023).

MICP is a biogeochemical process, whereby, the microbial activity, particularly urease-producing bacteria, is employed to break urea down into carbonate ions. This calcium carbonate ($CaCO_3$) is then precipitated by these ions in the presence of calcium ions. The crystals of $CaCO_3$ formed can fill the pores of the soil, strengthen the interaction of particles, increase the apparent cohesion, and increase the soil stiffness, and reduce the ability to break the particle contacts (Naveed et al., 2020). Shear strength, unconfined compressive strength, erosion resistance, and stability of granular soil and parts of fine-grained soil can be enhanced by geotechnical MICP-induced interparticle bonding. Recent studies have also shown that MICP and enzyme-induced calcite precipitation (EICP) can strengthen the slope surfaces, decrease the propensity to be eroded by precipitation and mitigate the harm to the surface by runoff (D. Liu et al., 2025). The sequential mechanism of attachment, urea hydrolysis, precipitation of calcium carbonate, interparticle cementation and the resulting geotechnical impacts of the process are Figure 1 schematically illustrated.

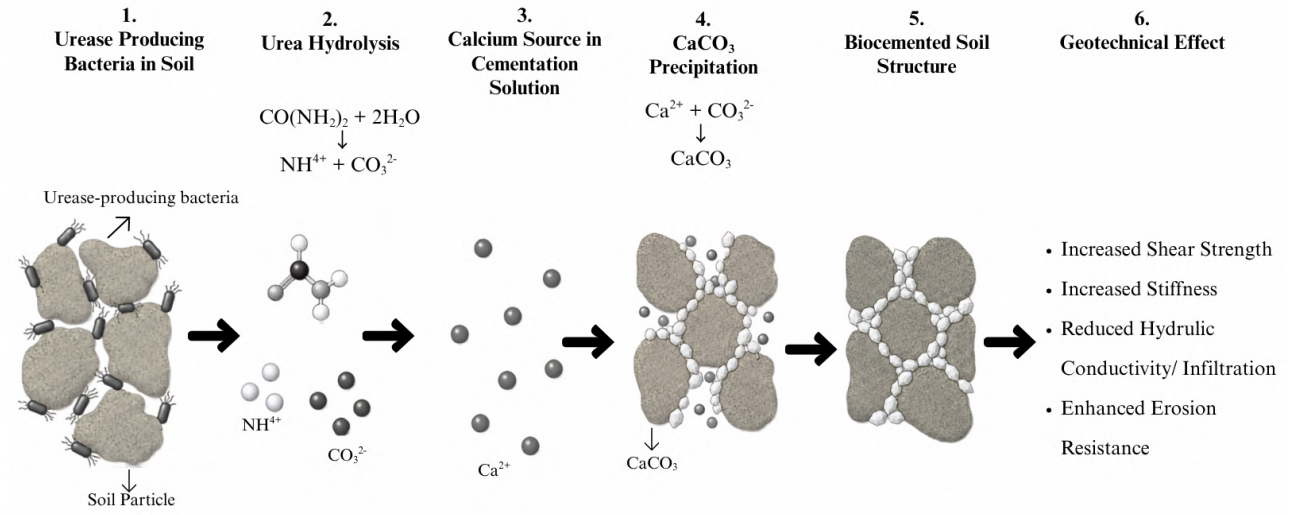


Figure 1. Schematic mechanism of MICP-based biocementation and $CaCO_3$ precipitation in soil. Adopted from Jiang et al. (2023), Naveed et al. (2020), Pan et al. (2023), and Jiang and Soga (2019).

The scope of MICP to slope and embankment stabilization is very crucial as slope failure is usually a product of interaction between mechanical properties of soils and hydrological processes. Biocementation has the potential to improve shear resistance on possible slip surfaces, and the precipation of CaCO3 on both the soil surface and within the pore spaces can reduce the particle detachment and increase the resistance to erosion and surface runoff due to rainfall(Jiang & Soga, 2019; Pan et al., 2023). Experimental studies have shown that microbial biocementation can improve the pysico-mechanical properties of sandy soils through bacterial and cementation-solution treatment penetration, and reliable performance at the field scale remains challenging (Sharaky et al., 2018).

Along with the performance of the MICP based biocementation against the performance of the static and rainfall related, MICP based biocementation can also be applied in the dynamic stability of saturated granular soils. It can also increase the rigidity of the soil and interparticles bond by rendering calcium carbonate

as the precipitate between the interparticles, and modify the cyclic behavior of the treated soils (X. Zhang et al., 2020). The experimental and numerical studies have indicated that MICP treatment has the capability of reducing the deformation and settlement of liquefaction, however, the response of the MICP treatment is determined by the degree and spatial homogeneity of cementation, soil density, design of treatment, saturation, and nature of seismic loading (Alam & Motamed, 2026). This is particularly true of the sandy embankment, saturated slope, reclaimed soil as well as other granular geotechnical systems located in an earthquake prone area. Therefore, the potential application of MICP-based biocementation in slopes and embankment stabilization needs to be addressed under both the conditions of the static and dynamic load. Although the research of MICP and biocementation has made progress recently, integrated studies, which take into account MICP-based biocementation, regarding slope stability, slope stabilization, embankments, and landslides are still few. Most of the MICP studies are confined to laboratory experiments, improvement of the mechanical properties of soils, manurement of bacteria or enzymes, cementation solution solution levels, content of $CaCO_3$ and microstructure analysis. Nevertheless, these results are still disjointed when it comes to slope and embankment stability, especially within subtopics like shear strength enhancement, erosion resistance, slope surface treatment, liquefaction reaction in sandy soils, and limitations to application at the field scale. More recent surveys of MICP have also pointed to its potential as a low-carbon ground improvement method and have also found that there are still systematic issues of scale effects of the technique to apply in field, control of precipitation distribution, injection efficiency, environment and validation of the technique in a field.

Previous reviews have established important foundations for understanding MICP, but these are not the same areas that were examined in this study, which is slope- and embankment-based synthesis. Fu et al. (2023) thoroughly reviewed MICP as a method of strengthening soil, including the mechanisms, experimental data, and the challenges of its geotechnical implementation, whereas L. Jiang et al. (2023) and Y. Wang et al. (2023) synthesized the basic principles, engineering properties, and the overall civil-engineering use of microbially induced carbonate precipitation. Other reviews have been more precise like $CaCO_3$ cementation patterns and crystal polymorphs (Xu et al., 2021), erosion mitigation in different Erosive situations(Payan et al., 2024), and recent developments in treatment methods, engineering properties, and field applications of MICP-treated soils(Zhang et al., 2025). Combinations of these reviews provide a wealth of insight in to MICP mechanisms, soil property enhancement and engineering use; however, they do not provide the explicit synthesis of slope- and embankment-specific performance through the synergistic combination of mechanical strengthening, rainfall-related hydraulic response, erosion resistance, liquefaction behavior, spatial treatment variability and field-scale application within a bibliometrically-constructed thematic framework. This unanswered integration is the certain gap of analysis that is discussed in the present research.

Based on these conditions, this bibliometric review and thematic synthesis were conducted to map research trends in MICP-based biocementation for the stabilization of slopes and embankments. Rather than predefining thematic categories, the study used term co-occurrence analysis to identify the thematic structure that emerged from the analyzed literature. The resulting bibliometric clusters were subsequently interpreted by linking them to the underlying biocementation mechanisms, geotechnical performance, environmental loading, and field-scale implementation of MICP-treated soils.

Based on this research gap, the study was designed to address four research questions: (1) how did the publication landscape of research on MICP-based biocementation for slope and embankment stabilization evolvethese from 2016 to July 4, 2026; (2) what major thematic clusters and temporal patterns were identified through term co-occurrence, overlay, and density analyses using VOSviewer; (3) how do the identified themes explain the relationships among calcium carbonate precipitation, soil microstructure, mechanical strength, erosion resistance, liquefaction resistance, and the engineering performance of slopes and embankments performance; and (4) what research limitations and priority research directions remain for hydro-mechanical modeling, spatially variable treatment, long-term performance, probabilistic assessment, and field-scale implementation? These research questions guided the descriptive analysis, bibliometric mapping, thematic interpretation, development of the conceptual framework, and identification of future research priorities.

Accordingly, this study aims to characterize publication trends; identify and interpret the dominant thematic structure; synthesize interrelationships between biogeochemical mechanisms and geotechnical performance within the four identified clusters; and identify priority research directions for the design and field-scale implementation of MICP treatment for slopes and embankments.

This review contributes by integrating evidence on slope and embankment performance rather than reiterating the well-established benefits of MICP for soil improvement. By combining bibliometric mapping with cross-study thematic synthesis and quantitative evidence counts, this study develops a mechanism–performance–application framework that connects three analytical levels. At the mechanism level, $CaCO_3$ precipitation and microstructural modification provide the material basis of biocementation. At the performance level, these mechanisms are linked to mechanical strengthening, hydraulic modification, erosion resistance, and cyclic or liquefaction response. At the application level, the synthesis identifies treatment depth, spatial uniformity, treatment geometry, long-term durability, hydro-mechanical coupling, and field-scale validation as key factors determining whether material-scale improvements can be translated into reliable slope and embankment performance. Overall, this framework provides a cross-scale interpretation of well-established knowledge and highlights areas where the transition from material characterization to engineering design remains underdeveloped.

2. METHODS

This study used a bibliometric review combined with thematic synthesis to map research developments on microbially induced calcite precipitation (MICP)-based biocementation for slope and embankment stabilization. Bibliometric analysis was used to examine publication trends, relationships among terms, thematic structures, temporal developments, and topic density within the selected corpus of literature. Thematic synthesis was subsequently used to interpret the geotechnical relevance of the thematic clusters identified using VOSviewer and to link the resulting themes to slope and embankment performance, engineering limitations, and future research directions. Accordingly, the study was designed as a bibliometric mapping and interpretive synthesis of the selected literature rather than as a full-text systematic review.

The literature search was conducted using ScienceDirect as the literature source. ScienceDirect was selected because it provides extensive of peer-reviewed studies on geotechnical engineering, engineering geology, ground improvement, soil science, and construction materials, which can be directly applied to the MICP-based biocementation research. The search strategy, metadata framework and RIS export process also was similar throughout the bibliometric analysis as only one literature platform was utilized. According to this, the research was to be an article-limited bibliometric review of the literature that was available to us in the ScienceDirect as opposed to a systematic search of the sources published by different bibliographic databases and publishers. ScienceDirect was treated as the literature-retrieval platform rather than as a criterion for publisher ownership. To verify the retrieval provenance of the corpus, the source URL field in the exported RIS metadata was examined for all retained records. All records contained ScienceDirect URLs, although several journals represented in the corpus are published or co-published by organizations other than Elsevier. Therefore, publisher ownership was not used as an inclusion or exclusion criterion; inclusion was determined by retrieval through the ScienceDirect platform and the specified metadata filters. The search string used was: ("slope stability" OR "slope stabilization" OR embankment OR landslide) AND (MICP OR biocementation OR "microbially induced calcite precipitation"). This was a compound search query which consisted of two concept groups. The former group pertained to geotechnical situations, such as slope stability, slope stabilization, embankments, and landslides. The second group was the biocementation technology that included MICP, biocementation and microbially induced calcite precipitation. The OR operator was used to broaden the search to find records that contained alternative terms in each conceptual group, and AND operator was used to find records that contained slope- or embankment-related contexts and MICP-based biocementation. The publication period was limited to records published trough July4, 2026, corresponding to the literature available at the time of data collection. The type of research articles and review articles were the

only types used in the documents. The filtering phase based on metadata filtered out the records that were published after the period or were of a different type of documents, e.g. research articles and review articles.

Table 1. Metadata-Based Filters Used to Construct the Bibliometric Corpus

Filtering Aspect	Included Records	Excluded Record
Literature source	Records retrieved from ScienceDirect	Sources outside ScienceDirect were outside the retrieval scope.
Publication period	Articles published between 2016 and July 4, 2026	Articles published outside the 2016 – July 4, 2026 period
Document type	Research articles and review articles	Book chapters, encyclopedia entries, editorials, conference abstracts, short communications, and other non-journal-article document types.

The initial ScienceDirect search returned 431 records. Two metadata-level filters were subsequently applied: publication period (2016–July 4, 2026) and document type (research articles and review articles). These filters reduced the dataset to 265 records retained as the bibliometric corpus. No additional title-, abstract-, or full-text-based material-relevance screening was applied when constructing the bibliometric corpus. The bibliographic data were then exported in RIS format and analyzed using VOSviewer version 1.6.20. Bibliometric analysis was performed using term co-occurrence analysis through the "Create a map based on text data" option, with "Reference manager files" selected as the data source. VOSviewer identified 7,838 terms, of which 159 met the minimum occurrence threshold of 10. Based on relevance scores, 95 candidate terms were selected for verification. Manual term cleaning was applied conservatively and resulted in the exclusion of eight terms: "clay," "kPa," "presence," "challenge," "paper," "process," "work," and "range." "Clay" was excluded because it was semantically redundant with the retained term "clayey soil," while "kPa" represents a measurement unit rather than a substantive research concept. The remaining six terms were excluded because, in the context of the analyzed corpus, they were considered insufficiently specific to provide distinct thematic information. The cleaning procedure was intended to reduce selected lexical redundancy and contextually non-specific expressions rather than to eliminate all general terms from the corpus, and no term was excluded on the basis of its expected cluster membership. The thematic labels were assigned only after the final network had been generated, based on the dominant and strongly interconnected terms within each cluster. Thus, the number and composition of clusters were determined from the bibliometric network rather than defined a priori. The final term map comprised four clusters, 2,766 links, and a total link strength of 8,416.

To support the interpretation of underrepresented research areas, a supplementary quantitative evidence count was conducted across the 265-record bibliometric corpus using the research aspects and operational indicators listed in Table 2. Because a single record could address more than one research aspect, the categories were not mutually exclusive. The resulting frequencies and percentages were used to assess relative research coverage rather than treatment effectiveness.

Bibliometric visualization was presented in three forms: network, overlay, and density visualizations(van Eck & Waltman, 2010). Network visualization was used to examine term relationships and identify cluster structures. An overlay visualization was used to examine temporal trends in topic development, while a density visualization was used to assess the concentration of prominent terms across the bibliometric corpus. The sources were thematically sorted based on four clusters that were found in VOSviewer. The clusters were considered with regard to their research interests, methodologies, geotechnical parameters, soil improvement mechanisms, engineering applications, limitations and gaps in research. Figure 2 presents the research process which begins with data identification and screening of the articles up till data processing, analysis of VOSviewer and synthesizing the literature.

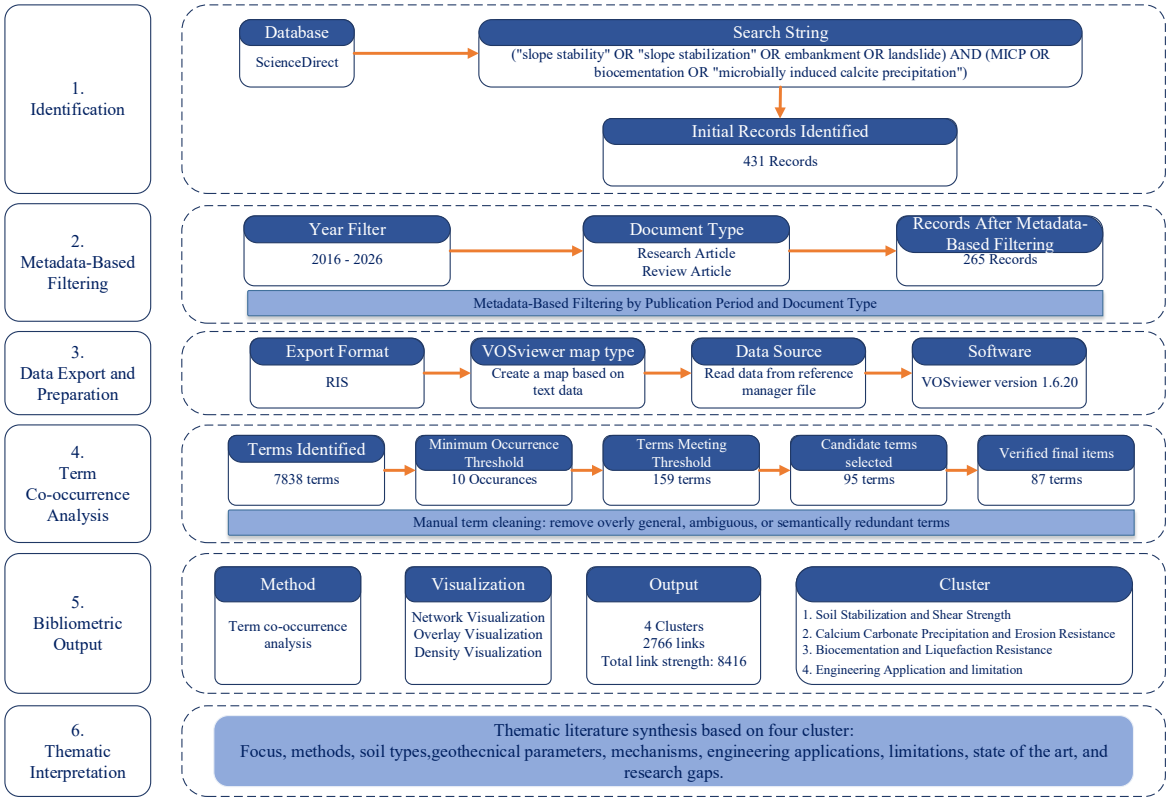


Figure 2. Bibliometric Review and Thematic Synthesis Workflow

3. RESULTS

3.1 Descriptive Analysis

As sustainable geotechnical engineering continues to gain attention, this study analyzed publication trends on microbially induced calcite precipitation (MICP)-based biocementation for slope and embankment stabilization and landslide mitigation. Descriptive analysis was conducted to assess annual publication trends and the distribution of journals covering slope stability, slope stabilization, embankment stabilization, landslides, MICP, and biocementation. Based on the search in the ScienceDirect search, 431 records were retrieved during the initial identification stage. Figure 3 shows the annual distribution of the 431 records initially retrieved.

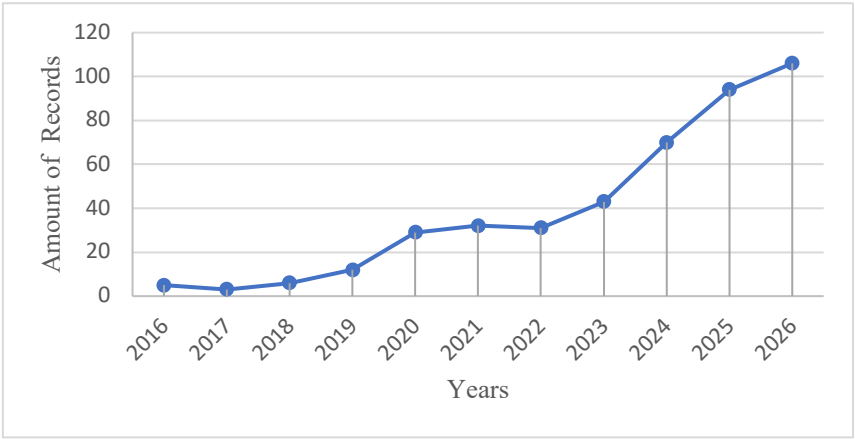


Figure 3. Annual Distribution of Retrieved Records

Compared to the past years, the number of records on MICP-based biocementation to stabilize the slope and embankment was relatively low in the last years with 5 records in 2016, 3 records in 2017, 6 records in 2018 and 12 records in 2019 (Figure 3). The annual record count then increased to 29 in 2020, 32 in 2021, and

31 in 2022. A further increase was observed in the most recent period, with 43 records in 2023, 70 in 2024, 94 in 2025, and 106 records as of July 4, 2026. This tendency indicates that the scientific attention to MICP-based biocementation in slope and embankment stabilization, as well as landslide protection have been on the rise within the past few years. The records preserved in the bibliometric corpus (265 records) were then broken down by the journal of publication in a bid to identify the major publications outlets. Figure 4 illustrates how many articles were published in each journal and Figure 5 illustrates the percentage distribution of articles.

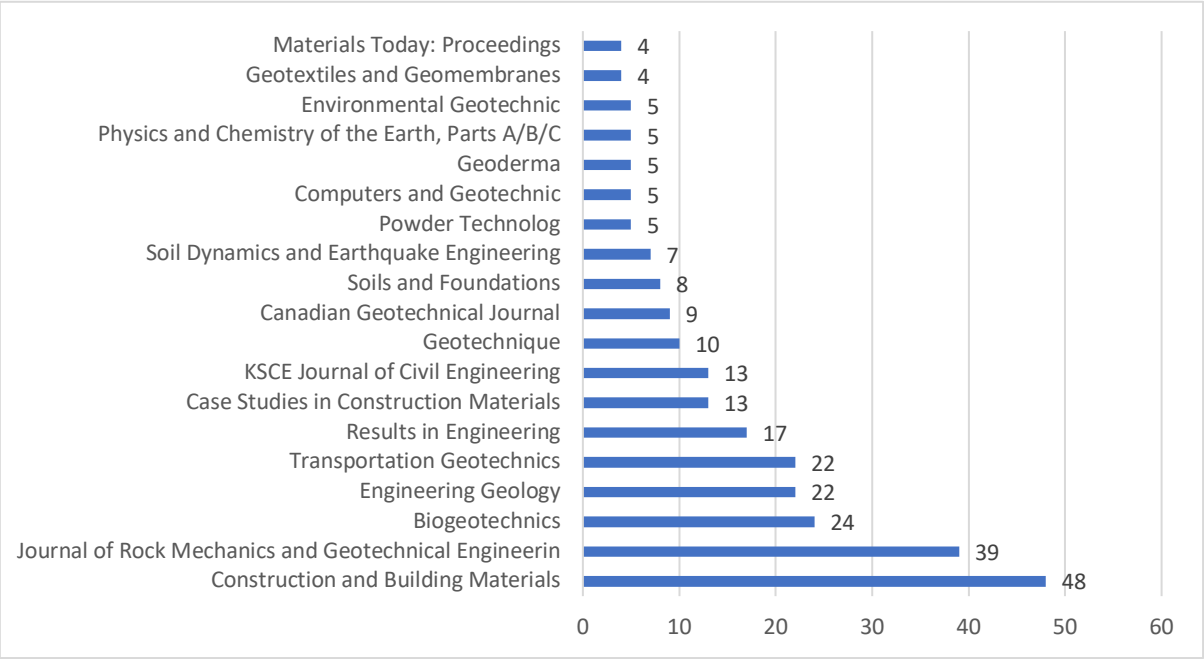


Figure 4. Distribution of Bibliometric Corpus Records across Journals

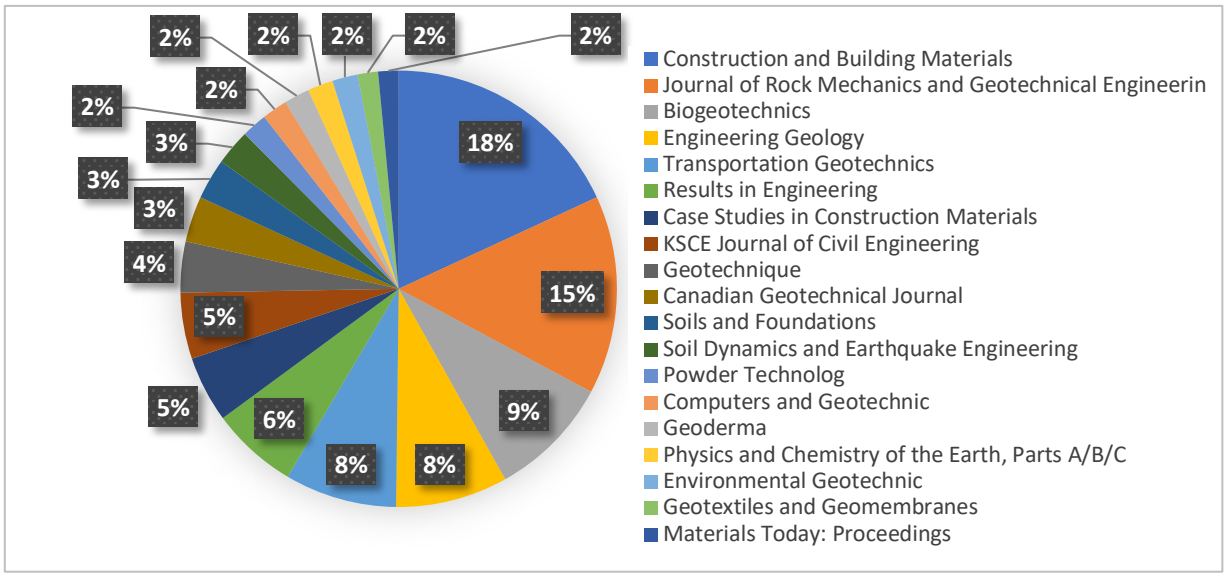


Figure 5. Percentage Distribution of Bibliometric Corpus Records across Journals

Figures 4 and 5 show that the 265 records in the bibliometric corpus were distributed across multiple journals. *Construction and Building Materials* had the largest share, with 48 records (18%), followed by the *Journal of Rock Mechanics and Geotechnical Engineering*, with 39 records (15%); *Biogeotechnics*, with 24 records (9%); *Engineering Geology*, with 22 records (8%); and *Transportation Geotechnics*, with 22 records (8%). Other publication outlets were *Results in Engineering*, with 17 records (6%); *Case Studies in Construction Materials* and the *KSCE Journal of Civil Engineering*, with 13 records each (5%); *Géotechnique*,

with 10 records (4%); the *Canadian Geotechnical Journal*, with 9 records (3%); *Soils and Foundations*, with 8 records (3%); and *Soil Dynamics and Earthquake Engineering*, with 7 records (3%). The remaining records were distributed among several other journals, each accounting for approximately 2% or less of the bibliometric corpus.

This distribution is due to the interdisciplinary character of studies on MICP-based biocementation to stabilize slopes and embankments. The subject has evolved not just in microbiology and materials science, but is also associated with geotechnical engineering, engineering geology, construction materials, soil dynamics, transportation geotechnics and environmental geotechnics. The coverage of the journals such as *Construction and Building Materials*, *Journal of Rock Mechanics and Geotechnical Engineering*, *Biogeotechnics*, *Engineering Geology*, and *Transportation Geotechnics* demonstrates that research on MICP-based biocementation is being pursued in the discipline of material, soil and engineering applications. This descriptive research confirms that MICP-based biocementation has become a rapidly expanding area of research that is becoming very popular to sustainable geotechnical engineering.

3.2 Bibliographic Analysis

VOSviewer version 1.6.20 was used to assess the bibliographic corpus to identify the most common themes of the studies on microbially induced calcite precipitation (MICP)-based biocementation to stabilize slope and embankments. To examine the relationship of terms that occurred in article titles, abstracts and keywords, the analysis was performed by term co-occurrence mapping. It was used to form conceptual relationships between the topics and key words, as well as the formation of thematic groups in the literatureThe term co-occurrence network mapping appears in figure 6.

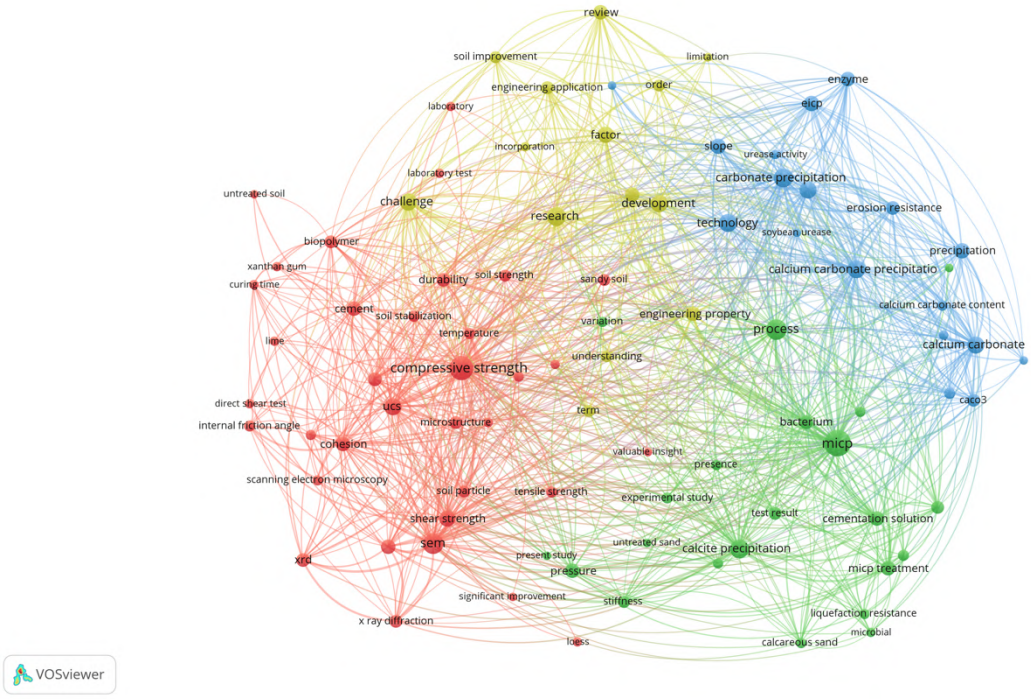


Figure 6. Term Co-occurrence Network of MICP-Based Biocementation for Slope and Embankment Stabilization

The bibliometric network that was represented in the form of the network indicates that 87 terms were related to one another. The resulting term map was made up of four big clusters, 2,766 links and the total strength of all the links was 8,416. The links degree is the links degree between the terms in the network and the total link strength is the sum of the strength of these co-occurrence relationships in the bibliometric corpus. These values reflect a very closely knit thematic framework of research on MICP-based biocementation of slope and embankment stabilization, and a well-knit knowledge base. A number of key words such as MICP,

biocementation, precipitation of calcium carbonate, soil stabilization, shear strength, erosion resistance, liquefaction resistance, slope and engineering application proved to be key nodes in the network.

The results of the visualization obtained show that the literature on MICP-based biocementation is not limited only to the study of the precipitation of calcium carbonate but also the analysis of geotechnical performance. The co-occurrence relationships show conceptual relationships between microbial activity, $CaCO_3$ precipitation, microstructural changes, enhancement of mechanical properties, erosion and resistance to liquefaction and use in soil stabilization and slope and embankment stabilization. As such, it is clear in this bibliometric map that MICP-based biocementation has turned into a transdisciplinary framework concerning biogeochemical pathways and geotechnical performance and engineering practices. The four clusters were obtained based on the co-occurrence network created in VOSviewer and these were not pre-determined prior to the bibliometric analysis. The labels of the clusters in Section 3.2.1-3.2.4 were post hoc based on the most common terms, their co-occurrence relationship and substantive relevance to geotechnical engineering.

3.2.1 Cluster 1: Soil Stabilization and Shear Strength

The previous group is related to soil stabilization and shear strength. The literature provided in this cluster demonstrates that the soil stabilization is related to increased mechanical properties, in particular, shear strength, cohesion, internal friction angle, unconfined compressive strength, tensile strength, and durability. These are key parameters applied in assessing the performance of ground improvement techniques on the sandy soils, clay soils, loess and untreated soils.

In the context of biocementation using MICP, interparticle cementation bonding formed as a result of the precipitation of CaCO3 is largely credited with the enhancement of the shear strength. These bonds do not just enhance the interparticle bonding but also occupy pore spaces to some degree ensuring that the soil becomes hard. The names shear strength, UCS, cohesion, internal friction angle, microstructure, scanning electron microscopy (SEM) and X-ray diffraction (XRD) are hints that the stabilization of soil is described at the macroscopic level by determining the mechanical tests, the microscopic level by describing the alterations of the particles in terms of their sizes and the cementation products of $CaCO_3$ Therefore, this cluster shows that geotechnical performance of MICP-based biocementation is strongly related with enhancing soil mechanical properties. One of the primary properties of slope and embankment applications is higher shear strength as it directly influences the mass stability of soils, the resistance to deformation of soils and their ability to withstand driving shear stresses that can cause slope failures.

3.2.2 Cluster 2: Calcium Carbonate Precipitation and Erosion Resistance

The other category revolves around the calcium carbonate precipitation and erosion resistance. This is the theme of $CaCO_3$ precipitation as the most important cementation process of MICP and EICP because of the microbial or enzymatic hydrolysis of urea. The resultant $CaCO_3$ precipitates provide interparticle bonds, strengthening of particle contacts, and strengthening of the integrity of the soil surface. Cluster can be particularly used in terms of slope and embankment stabilization (Yuan et al., 2026), since the surface of slopes and embankments may be eroded, the process can eventually result in erosion of surfaces. Rainfall and surface runoff could assist in soil particle detachment and surface erosion and infiltration of rainfall could modify the hydraulic and mechanical environment of the near-surface soil and cause the surface to become less stable. The contact formation between particles of $CaCO_3$ can reduce particle detachment sensitivity, enhance surfaces, and resistance to erosive impact (N.-J. Jiang & Soga, 2019). This group suggests that MICP-based biocementation can be used to increase the soil properties and erosion resistance of the slope and embankment surfaces. The correlation of the erosion resistance and precipitation of calcium carbonate determines the potential of biocementation in eroding the surface through the precipitation and runoff.

3.2.3 Cluster 3: Biocementation and Liquefaction Resistance

The third group deals with biocementation and liquefaction resistance. The sources in this cluster suggest that biocementation has been more and more used to enhance cyclic and dynamic loading resistance of granular soils, in sand and calcareous sand, in liquefaction-prone conditions (Alam & Motamed, 2026). The ureolytic bacterial activity and cementation solutions would increase the CaCO3 precipitation at the interparticle contacts in the MICP process to a more firmly bonded and rigid soil structure. The enhanced stiffness as a result of biocementation is important to reduce cyclic deformation and reduce the decline in strength of soil under cyclic loading. Excessive pore water pressure can be held by the sand that possesses stronger interparticle bond and allow it to provide effective stress during the cyclic loading. Therefore, biocementation via MICP can be implemented to the sphere of static stabilization, and it can be potentially promising in terms of liquefaction reduction. This cluster plays an important role in slope and embankment works because most geotechnical systems composed of granular materials are saturated and can be unstable during an earthquake. Therefore, biocementation has the capability to associate microstructural ground-ameliorating exercises to augmented cyclic and liquefaction obstinacy at the engineering dimension.

3.2.4 Cluster 4: Engineering Applications and Limitations

The fourth cluster is concerned with engineering applications and limitations relating to the same. This cluster shows that the creation of the research on MICP-based biocementation is evaluated in terms of the laboratory performance evaluation and the possibilities to be applied to the geotechnical engineering practice. Some of the applications in this cluster include slope stabilization, embankment stabilization, ground improvement, erosion control and enhancement of soil engineering properties. Though biocementation using MICP has significant potential as bio-based ground improvement method, its application continues to be limited by a number of factors. The most notable problems are the spatial nonuniformity of precipitation of $CaCO_3$ microbial or enzyme control, efficiency of injection of cementation solutions, reaction time requirements, sensitivity to environmental parameters, permeability change, and transfer of laboratory-scale results to field slope and embankment. Based on this cluster, the successful engineering application of MICP-based biocementation in geotechnical engineering appears to be based on the integration of the enhancement of soil properties, as well as an adequate technical consideration. It is suggested that future research should be devoted to the field scale validation, hydro-mechanical modeling, control of $CaCO_3$ distribution, and the long-term durability test that will help to make the transition between the laboratory scale treatment to the stable field-scale application to slope and embankment stabilization.

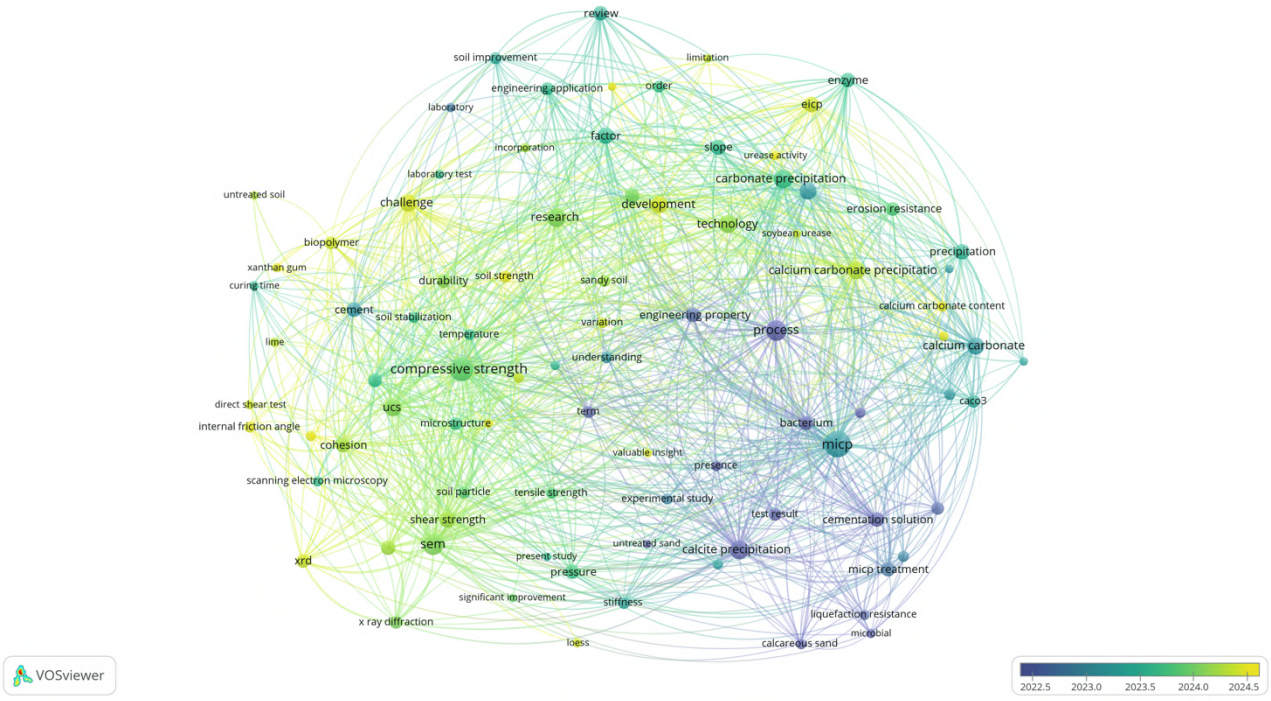


Figure 7. Overlay Visualization of MICP-Based Biocementation Research for Slope and Embankment Stabilization

The temporal changes in the research terms related to MICP-based biocementation to stabilize slopes and embankments are presented in figure 7 through the overlay visualization. The color curve used in this visualization shows the distribution of the terms over time as an average of the year of publication. Blue to purple reflect the terms that were more common to the earlier publications, green reflects the terms that were used in the intermediate period and yellow reflects the terms that were used in the recent publications. The blue and purple terms are usually related to the basic biocementation processes and material description, such as MICP, cementation solution, calcite precaution, calcareous sand, calcium carbonate crystal, and liquefaction resistance. The popularity of these words in the past suggests that the literature was initially interested in the $CaCO_3$ precipitation, granular soil properties and the soil reaction to biocementation treatment. The change in the color gradient to green implies the change of the focus to the evaluation of the soil engineering properties and geotechnical performance, such as calcium carbonate, carbonate precipitation, compressive strength, durability, soil stabilization, and development. The trend itself is a sign of a shift in the literature on the processes of calcite formation to the analysis of their impact on the soil strength, soil structure, and stabilization behavior. The terms that are marked in yellow refer to more recent articles, such as soil improvement, reviews, slope stability, erosion resistance, enzymes, EICP, soybean urease, SEM, XRD, direct shear testing, internal friction angle. The terms become more commonly used in later articles, which could suggest a more interest in research in specific applications, in particular in erosion resistance, enzyme-based processes and the more detailed description of soil mechanical properties and microstructure.

Overall, the overlay visualization shows that the interest of the research has shifted to more specific engineering applications and less on fundamental research on the mechanism of biocementation. The conceptual development of this development involves the calcium carbonate precipitation and characterization of granular soil, the improvement of soil mechanical properties and resilience, and improvement of the ground, slope stability, erosion resistance, and development of MICP- and EICP-based technology. Future research directions include further incorporation of MICP and EICP in slope and embankment stabilization particularly with regard to the effects of rain, erosion resistant properties, field level testing, and creation of more efficient and sustainable bio-based ground improvement methods.

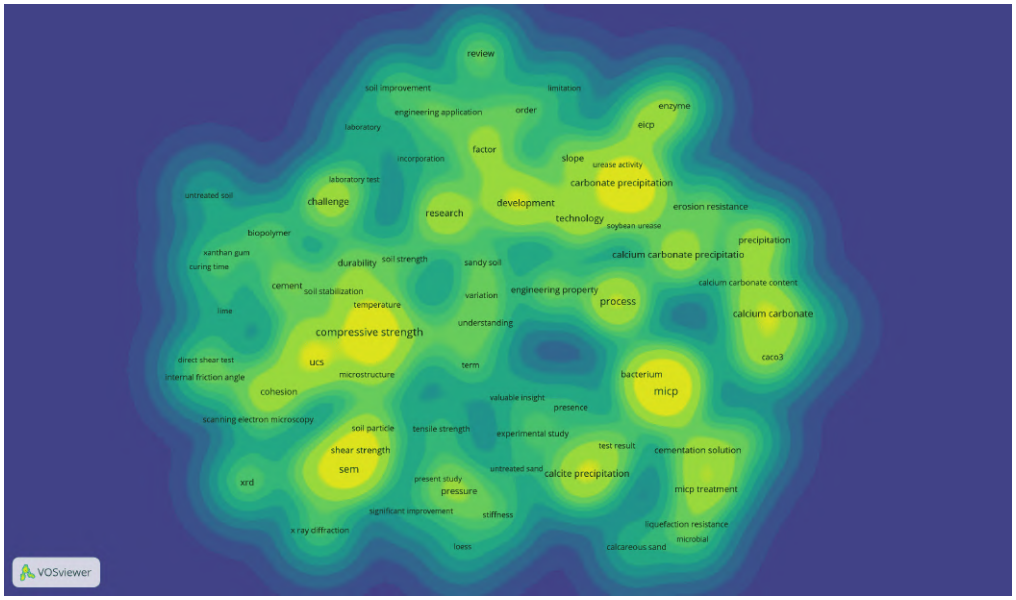


Figure 8. Density Visualization of MICP-Based Biocementation Research for Slope and Embankment Stabilization

In Figure 8, the density visualization indicates the meaning of density in the literature on MICP-based biocementation in slope and embankment stabilization. In the visualization of the VOSviewer, the yellow color shows the terms with high frequency of occurrence and with high degree of linkage with the rest of terms, whereas the green to dark blue color shows the terms with lower frequencies of occurrence. Therefore, this visualization was used to establish those issues that are more common in the literature and those that are not fully represented in research. Figure 8 shows that the highest density terms are calcium carbonate precipitation, calcium carbonate, MICP, compressive strength, shear strength, SEM, XRD, enzyme, EICP, and erosion resistance. The terms are most common, meaning that the research in MICP-based biocementation field is still centered on the fundamentals of the biocementation process, in particular, the precipitation of $CaCO_3$, the modification of the mechanical behavior of soils, and the enhancement of microstructures. This finding implies that compressive and shear strength behaviour, microstructure, and development of the interparticle bond is often employed in the analysis of the performance of MICP-based biocementation. In addition, the fact that such terms as enzyme, EICP, soybean urease, and erosion resistance are mentioned implies that enzyme-based biocementation and erosion control find their echo in literature too. It is particularly significant in slope stabilization where surface runoff, surface erosion and soil particle detachment can augment slope and embankment erosion process. The application of engineering, limitation, liquefaction resistance, calcareous sand and MICP treatment are, however, located at a relatively less dense. Their low densities indicate that engineering functionalities, workability limitations, dynamic geotechnical behaviour, and treatment effectiveness to more complex geotechnical conditions but are unclear as research priorities of eminence.

Therefore, the density visualization shows that the studies of the MICP-based biocementation are still focused on the calcium carbonate precipitation, microstructural characterization, and enhancement of the soil mechanical properties improvement. However, there is a dearth of studies on the direct slope, embankment application, influence of rainfall infiltration, long-term stability, spatial uniformity of $CaCO_3$ distribution, dynamic soil actions, and field level scale examination. Future research should therefore integrate laboratory experiments, computerized modeling, hydrological, and field experiments to ascertain the effectiveness of MICP-based biocementation under a more geotechnical realistic environment.

4. DISCUSSION

This study came up with a conceptual framework to incorporate the relationships of the four core clusters and how they can be applied to geotechnical engineering based on the visualization of the network, overlay and density. There are four major themes that this framework was founded on: Soil Stabilization and Shear

Strength; Calcium Carbonate Precipitation and Erosion Resistance; Biocementation and Liquefaction Resistance; and Engineering Applications and Limitations. These four groups indicate that MICP-based biocementation incorporates the $CaCO_3$ precipitation process with ground-improvement processes, which enhance shear strength, erosion resistance, cyclic and liquefaction resistance, and slope and embankment applications.

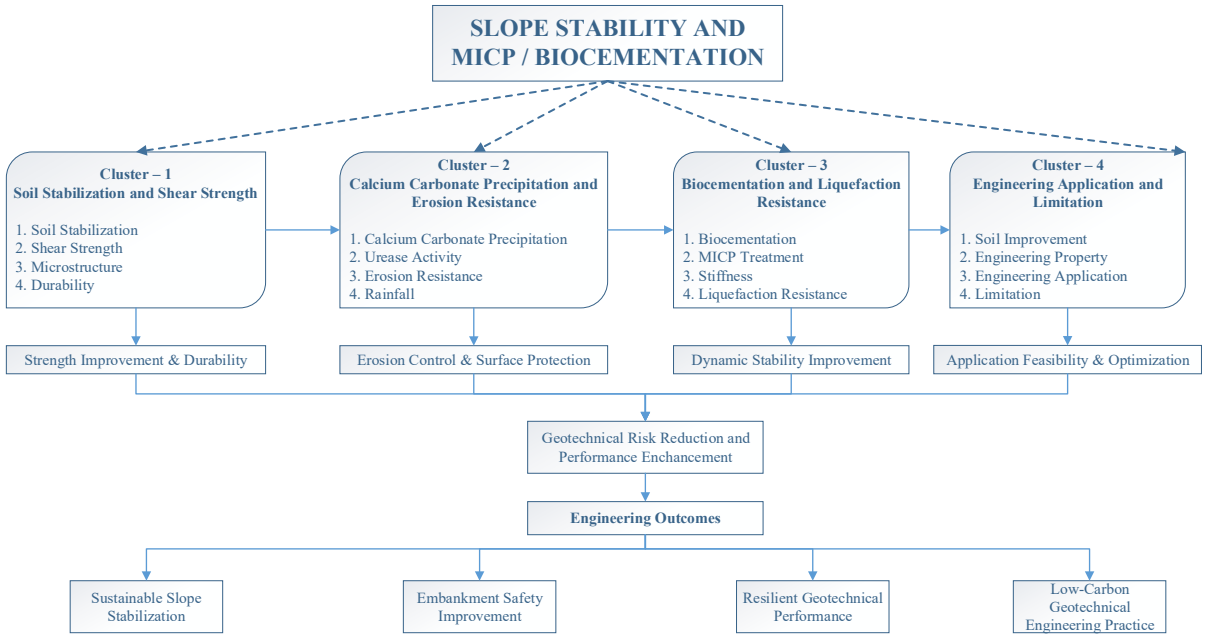


Figure 9. Conceptual Framework Linking MICP-Based Biocementation Mechanisms to Slope and Embankment Stabilization

The thematic structure that was derived by using the bibliometric network was condensed into a conceptual framework that is shown in Figure 9 and is not repeated when describing the four distinct clusters. The themes in the analyzed corpus are related: $CaCO_3$ precipitation and microstructural changes are the mechanistic basis of the changes in soil strength, stiffness, hydraulic response, erosion resistance, and cyclic behavior, and the engineering performance of these themes is determined by the configuration of the treatment, the loading of the environment, and the scale of application. The discussion below thus compares evidence of the past research to determine the uniformity of results, conditional reactions, and unsolved concerns in the extrapolation of material-scale biocementation impacts into slope- and embankment-scale performance.

At the material level, past researchers have always demonstrated that biocementation can be used to improve the mechanical behavior of granular soils, by improving the interparticle bonding through the use of carbonates. The improvement of strength, stiffness and microstructure of biocemented calcareous sand has been reported in the study by L. Liu et al. (2019) and physicomechanical properties of sandy soil, which have been enhanced following microbial biocementation, have also been reported by Sharaky et al. (2018) These findings always relate the bonding brought about by biocementation to the enhanced soil mechanical performance, but the extent of increase depends on the material properties and conditions. It is important to note that gains in strength or stiffness of scale of a specimen are not to be interpreted as system-scale gain in slope or embankment stability because system-scale performance depends on the depth of the treatment, spatial continuity, slope geometry, hydraulic conditions and the position of the potential failure surface. Hence, the increase in shear strength must be seen as a material-scale process that promotes the stability of slopes and embankments, and not necessarily as an indicator of an enhanced stability.

Research on hydraulic behavior and erosion also suggests that precipitation of carbonate might affect slope performance not by a mechanical strengthening process. N.-J. Jiang and Soga (2019) have mentioned that the treatment of MICP enhanced erosion resistance of gravel-sand mixtures by enhancing interparticle contacts and decreasing detachment of particles. Conversely, Pan et al. (2023) investigated slope-scale

biocementation and demonstrated that surface treatment decreased rainfall infiltration, which implies that biocementation can alter the surface protection and water intrusion in the soil. The reduction in hydraulic conductivity of silty sand following the enzyme-induced calcium carbonate precipitation also was reported by Shi et al. (2025) which is consistent with the general result that the calcium carbonate precipitation can have a significant effect on the hydraulic behavior of soils. These experiments are therefore not mutually exclusive, but may very well be directly incompatible as erosion resistance, control of rainfall infiltration, and decrease in hydraulic-conductivity are all various responses to carbonate-based treatment. Thus, the fact of an increase of erosion resistance, or the decrease of the permeability is not necessarily an indication that the overall slope stability has been improved, as the overall response also depends upon the depth of the treatment, the conditions of drainage, the nature of rainfall, as well as the location of the potential failure surface.

Dynamic-loading studies further indicate that the benefits of MICP-based biocementation depend on both material improvement and treatment configuration. X. Zhang et al. (2020) state that in shake-table experiments, MICP treatment increased the dynamic characteristics of the calcareous sandy ground by increasing soil stiffness and decreasing the deformation due to liquefaction. However, the behaviour of the treated ground under study could not be manipulated by the increase of the strength alone as the change of the stiffness also affected the transmission of the seismic loading through the soil system. Alam and Motamed (2026) also discovered the effectiveness of liquefaction mitigation is dependent on the extent and conception of MICP-treated zone, implying that the geometry of treatment is a key engineering variable to contemplate in addition to the degree of cementation. These results once again point to the possibility of biocementation to enhance cyclic resistance of granular soils, but also demonstrates that the performance of treatment can not be evaluated by material-scale stiffness or $CaCO_3$ content alone. In saturated slopes and embankments, now the dynamic performance can be considered according to the degree of cementation, the form of treatment, the conditions of saturation as well as the reaction of pore-water pressure, deformation and the seismic load combined.

At At the engineering level, the issue of whether biocementation can be used to promote the desired properties of the chosen soil ceases to be the biggest issue, but instead, the question is whether the changes caused by the treatment can be homogeneous across the treated field and can be maintained on a regular basis in the conditions of the real field. L. Jiang et al. (2023) treatment delivery, sensitivity of MICP to environmental conditions, and scale-up between laboratory and field still limit the application of MICP in civil engineering. These limits correspond to the slope-scale results that Pan et al. (2023), described in which the reliance on the configuration and intensity of biocementation during rainfall, and with the dynamic results reported by Alam and Motamed (2026), who found that the performance of the system at a system level was dependent on the size and shape of the treated area. Together these studies indicate that successful engineering application is not merely a matter of the amount of the amount of $CaCO_3$ produced or the resulting increase in strength but they also demand that treatment has been uniform, that the depth of treatment and spatial distribution is uniform, the hydraulic response is uniform, the environment to which the treatment is subjected is uniform, and the performance scale is measured. Therefore, the laboratory level of material enhancement transformation to constant slope and embankment stabilization requires performance requirements that are direct reflection of the spatial variability, field-level conditions, and the performance of the treatment in the long run.

A supplementary quantitative evidence count was conducted to further assess the representation of engineering issues identified through the thematic synthesis within the bibliometric corpus. Table 2 summarizes the number and proportion of records addressing selected material-scale, hydraulic, dynamic, and engineering-scale research aspects. This comparison provides a quantitative basis for distinguishing well-established research themes from those that remain underrepresented in the bibliometric corpus. For this evidence count, titles, abstracts, and available keywords of the 265 records were examined using the operational indicators listed in Table 2. Variations in capitalization, singular/plural forms, hyphenation, and commonly used abbreviations were treated as equivalent when they represented the same concept. Candidate matches were checked manually for contextual relevance to minimize false-positive classification. Each record

was counted once within a given research aspect, although the same record could be assigned to more than one aspect because the categories were not mutually exclusive.

Table 2. Quantitative Evidence of Research Coverage across Selected Engineering Aspects in the 265-Record Bibliometric Corpus

No.	Research aspect	Operational indicators in title/abstract/keywords	Records, n	Corpus, %
1	$CaCO_3$ precipitation and microstructure	calcium carbonate, $CaCO_3$, calcite, carbonate precipitation, microstructure, SEM, XRD	134	50.6
2	Mechanical strength and stiffness	shear strength, UCS, compressive strength, stiffness, cohesion, internal friction angle, tensile strength	68	25.7
3	Erosion resistance	erosion, erosion resistance, particle detachment, soil loss, erosion control	36	13.6
4	Long-term durability and environmental cycling	durability, wetting–drying, dry–wet, freeze–thaw, ageing, weathering, long-term performance	23	8.7
5	Rainfall and rainfall infiltration and seepage-related hydraulic response	rainfall, rainfall infiltration, infiltration, seepage, matric suction	22	8.3
6	Liquefaction and dynamic response	liquefaction, cyclic loading, dynamic response, shaking/shake-table testing, cyclic resistance	15	5.7
7	Spatial variability and treatment uniformity	spatial variability, spatial distribution, non-uniformity, treatment uniformity, homogeneity	15	5.7
8	Hydro-mechanical and numerical modeling	coupled multiphysics/BCHM modeling, numerical simulation, constitutive modeling, DEM, CFD–DEM, finite-element-based modeling	10	3.8
9	Field- and large-scale empirical validation	field tests/trials, outdoor cubic-meter-scale trials, large-scale experiments, mid-scale experiments	8	3.0
10	Treatment depth	explicit treatment depth, treated-zone depth	1	0.4
11	Preferential flow	preferential flow, preferential flow path	1	0.4
12	Spatial stochastic/random-field representation	random field, spatial stochastic representation	1	0.4
13	Explicit reliability assessment	reliability index, probability of failure, failure probability/Pf	0	0.0

Note: Frequencies were calculated at the record level from titles, abstracts, and available keywords. Each record was counted once within a given research aspect but could be assigned to more than one aspect when multiple topics were addressed. Therefore, the research aspects were not mutually exclusive, and the percentages are not intended to sum to 100%

The numerical data, which are collected in Table 2, show that the percentage of researches carried out in the analyzed bibliometric corpus is sharply uneven. The number of 134 records (50.6) that mentioned $CaCO_3$ precipitation and microstructural characterization and 68 records (25.7) that mentioned mechanical strength and stiffness indicates a strong material-scale emphasis of the literature. In comparison, the spatial variability and treatment uniformity, hydro-mechanical and numerical modeling, and field- or large-scale empirical validation were only represented by 15 records (5.7), 10 records (3.8), and 8 records (3.0) respectively. The more engineering-specific ones were even less represented: one record (0.4%) specifically covered treatment depth, one record (0.4%) specifically covered preferential flow and one record (0.4%) had a spatial stochastic or random-field representation. No report was specifically on reliability index or probability-of-fail. Such quantitative differences can be viewed as confirming the fact that the transition to material scale characterization to spatial variability, hydro-mechanical coupling, probabilistic assessment and field scale

validation remains largely under-represented when compared to the material scale characterization in the bibliometric corpus.

This evidence-based imbalance can also explain the added value of the mechanism-performance-application framework: instead of summarizing the existing well-known MICP mechanisms, the framework can be used to establish the key gap between the more fully-represented material-scale material evidence and the less-represented hydro-mechanical, spatial, probabilistic, and field-scale evidence that is pertinent to slope and embankment design.

Overall, the cross-study synthesis assists in concluding that MICP-based biocementation during the slope and embankment stabilization process and can be explained by a mechanism-performance-application. On the mechanism level, modifications of the interparticle contacts due to $CaCO_3$ precipitation and the subsequent change of the interparticle contacts are always associated with the modification of the microstructure of soils and their material-scale mechanical characteristics. At the performance level, the changes can improve strength, erosion resistance and cyclic resistance and change hydraulic response. Their size and engineering worth however varies with the kind of soil, treatment and loading environment conditions. At the application level, in order to scale these material-scale advantages into slope- and embankment-scale performance, a combination of other factors ought to be considered, including the depth of treatment, the spatial uniformity, the hydraulic conditions, the geometry of the treatment, and environmental loading, and the restrictions of field-scale application. Therefore the series in Figure 9 can be considered an integrative conceptual framework, rather than a deterministic cause-pathway. This synthesis demonstrates that further studies are needed to bridge material characterization on laboratory scale to hydro-mechanical analysis, long-term durability test, numerical modeling, and field-scale test under realistic slope and embankment geometry.

This study has a database-coverage limitation because the bibliometric corpus was derived solely from ScienceDirect. Consequently, relevant publications indexed in other bibliographic databases, such as Scopus and Web of Science, as well as studies available through publisher-specific platforms, including SpringerLink, Wiley Online Library, Taylor & Francis Online, and the ASCE Library, may not have been represented in the analyzed corpus. This source restriction may introduce coverage bias related to the selected publisher platform and excluded bibliographic databases, thereby limiting the generalizability of the publication trends and thematic structures identified in this study. Nevertheless, the ScienceDirect-derived corpus provides a focused representation of research across geotechnical engineering, engineering geology, ground improvement, and construction materials and is sufficient for examining thematic relationships within the predefined corpus. Future bibliometric studies should integrate multiple bibliographic databases and literature platforms, with appropriate deduplication procedures, to determine whether the thematic structure identified here remains stable across a broader literature base.

5. CONSIDERATIONS AND FUTURE RESEARCH DIRECTIONS

Based on the study findings, this research mapped the literature on MICP-based biocementation for slope and embankment stabilization into four main clusters: (1) Soil Stabilization and Shear Strength, (2) Calcium Carbonate Precipitation and Erosion Resistance, (3) Biocementation and Liquefaction Resistance, and (4) Engineering Applications and Limitations. These four clusters show that research on MICP-based biocementation in geotechnical engineering encompasses $CaCO_3$ precipitation, shear-strength enhancement, soil microstructural changes, erosion resistance, cyclic and liquefaction resistance, and engineering applications and their associated limitations.

Although the relationships among calcium carbonate precipitation, soil microstructure, shear strength enhancement, erosion resistance, and liquefaction resistance have been extensively investigated, their integration into reliable slope- and embankment-scale design procedures remains limited. To address the fourth research question, the limitations identified across the four clusters were translated into priority research directions. Therefore, future research should move beyond conventional material characterization and

prioritize multiscale modeling and spatial variability in soil stabilization and shear-strength enhancement; coupled rainfall infiltration, $CaCO_3$ distribution, erosion resistance, and long-term durability; cyclic loading and liquefaction resistance; and probabilistic assessment, field-scale quality control, and sustainable engineering applications.

Table 3. Recommendations for Future Research

No.	Research Theme	Recommendations for Future Research
1	Multiscale Constitutive Modeling and Long-Term Mechanical Performance	Future research should move beyond conventional assessments of calcium carbonate content, soil microstructure, and strength enhancement by developing quantitative multiscale relationships between carbonate-bond characteristics and the constitutive behavior of biocemented soils. Particular attention should be given to translating microstructural changes into engineering parameters, including stiffness, cohesion, internal friction angle, dilatancy, strain-softening behavior, and post-peak strength. The long-term variation in these parameters under wetting–drying cycles, cyclic loading, chemical exposure, and environmental ageing should also be assessed. Integrating laboratory observations with constitutive modeling, finite-element analysis, and probabilistic assessment could improve parameterization of materials to assess the stability and long-term performance of MICP-treated slopes and embankments.
2	Spatially Variable Biocementation under Coupled Rainfall Infiltration and Erosion Processes	Future research should focus on the effects of spatially nonuniform biocementation on the interaction of hydraulic and mechanical behavior of slopes and embankments that are subjected to rainfall infiltration and surface runoff. The degree of treatment, spatial heterogeneity of the $CaCO_3$ precipitation, hydraulic conductivity changes, preferential flow, crack propagation, evolution of pore-water pressure and progressive surface erosion during successive rainfall cycles are important. Minimum treatment uniformity, cementation depth and strength increment necessary to ascertain the quantifiable changes in slope stability must be determined by research and not the performance of the treatment which can be quantified by losses in soil. Rainfall simulation, seepage analysis, slope stability modeling, field monitoring, and long-term performance evaluation are required to combine laboratory scale erosion resistance into valid design criteria of slopes and embankments.
3	Biocementation, Stiffness, and Liquefaction Resistance of Biocemented Sand	Research should then be conducted on how biocementation can enhance the stiffness and liquefaction strength of sand, calcareous sand and other granular soils which are used in saturated slopes and embankments. Especially, there is a need to conduct research to monitor the relationship between MICP treatment, $CaCO_3$ precipitation, stiffening, change in the pore-water pressure response and the ability of treated soils to maintain effective stress in cyclic and seismic loading.
4	Engineering Applications and Treatment Limitations	Research should be followed by the next step of engineering applications and technical limitations of MICP-based biocementation in order to stabilize slope and embankment. The areas, which need further research, are the effectiveness of application techniques, regulation of biocementation processes, uniformity of treatment, sensitivity to environmental factors, curing time, economic viability, and difficulty in extrapolating laboratory-scale to field-scale use. These studies are critical in coming up with viable design requirements to facilitate the sound application of MICP-based biocementation as a ground improvement technique in the practice of geotechnology.

6. CONCLUSION

Based on the study findings, the current study could map the literature on MICP-based biocementation to stabilize slopes and embankments into four general clusters namely: (1) Soil Stabilization and Shear Strength, (2) Calcium Carbonate Precipitation and Erosion Resistance, (3) Biocementation and Liquefaction Resistance, and (4) Engineering Applications and Limitations. The existence of these clusters indicates that the following processes are involved in developing the MICP-based biocementation in geotechnical engineering; $CaCO_3$ precipitation, shear-strength enhancement, soil microstructural adjustment, erosion resistance, cyclic and liquefaction resistance and engineering applications with associated limitations. The findings also show that the literature discusses three larger areas that involve the processes of biocementation and $CaCO_3$ precipitation, enhancement of the soil geotechnical behaviour, and the engineering applications that are constrained in terms of scale restrictions of field-scale application. Biocementation can increase interparticle bonding, mechanical properties of soil, erosion and liquefaction resistance by the urease activity and $CaCO_3$ precipitation. Nevertheless, the literature is still mostly concentrated on laboratory-scale research.

Although it is apparent that the fundamental interactions among the $CaCO_3$ precipitation, soil microstructure, mechanical strength and erosion resistance had already been widely investigated, their use in sound prediction of slope- and embankment-scale performances is limited. The next step of research should then quantify the impact of spatially nonuniform cementation, hydro-mechanical alterations due to rainfall, mechanical degradation and uncertainty of the parameters of biocemented slopes and embankments on stability and reliability.

In order to improve the future studies, laboratory tests and the constitutive modeling, finite-element analysis, probabilistic analysis, repeat environmental loading, field monitoring and field-scale validation are to be included. This incorporation is required to come up with credible design requirements, treatment conditions and quality-control measures of MICP-based stabilization of slope and embankments. Overall, the paper follows the history of the literature and offers a conceptual framework of more adaptive, low-carbon and sustainable ground improvements strategies that might foster the safety of infrastructure and reduce geotechnical risk.

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