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The global research trend on microbially induced carbonate precipitation during 2001–2021: a bibliometric review

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ABSTRACT

Microbially induced carbonate precipitation (MICP) is a remarkable method that creates sustainable cementitious binding material for use in geotechnical/structural engineering and environmental engineering. This is due to the increasing demand for alternative environmentally friendly technologies and materials that result in minimal or zero carbon footprint. In contrast to the previously published literature, through bibliometric analysis, this review paper focuses on the current prospects and future research trends of MICP technology via the Scopus database and VOSviewer analysis. The objective of the study was to determine the annual publications and citations trend, most contributing countries, the leading journals, prolific authors, productive institutions, funding sponsors, trending author keywords, and research directions of MICP. From 2001 to 2021, there were a total of 1,058 articles published in the field of MICP. The result demonstrated that the volume of publications is increasing. China, Construction and Building Materials, Satoru Kawasaki, Nanyang Technological University, and the National Natural Science Foundation of China are the leading country, journal, author, institution, and funding sponsor in terms of total publications. Through the co-occurrence analysis of the author keywords, MICP was revealed to be the most frequently used author keyword with 121 occurrences, a total link strength of 213, and 152 links to other author keywords. Furthermore, co-occurrence analysis of text data revealed that researchers are concentrating on four important research areas: precipitation, MICP, compressive strength, and biomineralization. This review can provide information to researchers that can lead to novel ideas and research collaboration or engagement on MICP technology.

Keywords: Biomineralization; Bibliometric analysis; Carbonate precipitates; Sustainable material.

1. Introduction

Scholars have paid close attention to climate change issues in recent decades since it is expected to cost the global economy $2-4 billion per year by 2030 (World Health Organization 2021; Islam et al. 2022). People living in the vicinity of a cement plant are exposed to nitrogen oxides ~~(NO_x)~~, carbon dioxide ~~(CO_2)~~, sulphur dioxide ~~(SO_2)~~ and particulate matter emissions (Raffetti et al. 2019). Moreover, the cement manufacturing industry is linked to cement dust emissions, solid waste pollution, respiratory illnesses, and malignant disorders (Lakreb et al. 2022) (Falkner 2016). ~~Furthermore, the cement manufacturing industry is associated with cement dust emissions, solid waste pollution, respiratory ailments, and~~ cancer (Falkner 2016). This has driven the demand for alternative technologies ~~ical advance~~ and enhanced manufacturing processes to create environmentally friendly materials ~~and goods~~. Because of its feasibility in producing cementitious material, microbially induced carbonate precipitation (MICP) has attracted ~~piqued~~ the curiosity of scholars from several disciplines during the last few decades. Furthermore, MICP necessitates a low operating cost, personnel, and ambient temperature to produce calcium carbonate ($CaCO_3$) biomineral (Stabnikov et al. 2015). The MICP approach is a feasible alternative to traditional cement binder procedures (Gowthaman et al. 2021). This is because MICP requires less mechanical energy and has a low or zero carbon footprint, both of which contribute to a more cost-effective process with environmental benefits (Muhammed et al. 2021).

MICP is a biomineralization mechanism that relies on microbial metabolic activity to precipitate carbonate crystals (Meng et al. 2021a; Moradi et al. 2021). The MICP process presently has five modes: denitrification, ammonification, ferric reduction, sulphate reduction, and urea hydrolysis (ureolysis) (Wang et al. 2022). The ureolysis procedure, on the other hand, is the most common MICP pathway used by researchers since it requires a simple mechanism, quick reaction, and precipitation process. Microbial urease (EC 3.5.1.5, urea amidohydrolase), which is nickel-dependent, can accelerate urea hydrolysis up to 10^{14} times faster than the typical urea hydrolysis process~~.~~ (Singh et al. 2017). Urease is one of the important enzymes secreted by microorganisms in the soil, but can also be produced through microbial fermentation (Khan et al. 2019).

It is critical to understand that the urease enzyme (EC 3.5.1.5) hydrolyzes/breaks down urea into one mole of ammonia and carbamate ions (Eqn. 1). This leads to the creation of ammonium and hydroxide ions (Eqn. 2-3) (Stocks-Fischer et al. 1999). However, after carbamate acid is spontaneously transformed into ammonia and carbonic acid, it is carbonic anhydrase (EC 4.2.1.1) rather than the urease enzyme that causes carbonic acid to be turned into bicarbonate ion (Eqn. 4-5) (Castro-Alonso et al. 2019). As indicated in Eqn. 6, the subsequent synthesis of ammonium and hydroxide ions raises the pH of the solution, which favours/allows carbonate precipitation in the presence of calcium ions (i.e., calcium chloride) (Medina Ferrer et al. 2020). The reactions create a shift in bicarbonate equilibrium, resulting in carbonate ions formation, which reacts with $CaCl_2$ in the microenvironment to produce 1 mol of $CaCO_3$ (Omoregie et al. 2022).

$$CO(NH_2)_2 + H_2O \longrightarrow NH_3 + NH_2COOH \quad (1)$$

$$NH_2COOH + H_2O \longrightarrow NH_3 + H_2CO_3 \quad (2)$$

$$2NH_3 + 2H_2O \longleftrightarrow 2NH^+ + 2OH^- \quad (3)$$

$$H_2CO_3 \longleftrightarrow HCO_3 + H^+ \quad (4)$$

$$HCO_3^- + H^+ + 2OH^- \longleftrightarrow CO_3^{-2} + 2NH_4 + 2H_2O \quad (5)$$

$$Ca^{+2} + CO_3^{-2} + cells \longrightarrow cells\text{-}CaCO_3 \quad (6)$$

The MICP activity requires active urease-producing microorganisms (i.e., *Sporosarcina pasteurii* and *Lysinibacillus sphaericus*) to mediate/facilitate the carbonate precipitation (Li et al. 2021). Scholars from around the world have also demonstrated that MICP technology can be utilised to improve soils in surface/subsurface zones (Mahawish et al. 2018). MICP has been successfully deployed at the field scale for soil embankments/reinforcement, in addition to laboratory-scale testing (Landa-Marbán et al. 2021). MICP technology can also be used for other engineering practises such as remediation/sequestration of heavy metals (Lyu et al. 2022); ~~surface~~ concrete crack repairs (Meng et al. 2021b); wastewater treatment (Zhao et al. 2019); erosion and groundwater control (Wang et al. 2021c); ornament restoration/recovery (Daskalakis et al. 2013); and mitigation of soil liquefaction (Sharma and Satyam 2021).

Su et al. (2020), demonstrated simultaneous groundwater remediation for the removal of fluoride, calcium, and nitrate with *Acinetobacter* sp. via the MICP process. It was further discovered by Wang et al. (2021b), that *Pseudomonas* sp. proved to be effective at removing both fluoride and nickel ions up to 98.24%. Several academics ~~in the literature~~ have validated the coupling of the biocementation process during MICP with the efficient treatment of wastewater, heavy metal, and radionuclide-contaminated groundwater utilizing diverse strains of fungal and bacteria species (Wu et al. 2021b). The literature also revealed that MICP technology may be applied for other practical engineering applications such as slope stabilisation (including cold regions) and stand-alone stabilising technology with MICP cement-stabilized road base materials (Gowthaman et al. 2022a; Yang et al. 2022).

Despite its enormous promise, MICP technology has significant drawbacks. A key disadvantage of MICP is the obstruction of treatment fluid flow, particularly from the pressure injection part during treatment due to clogging, as well as the uneven distribution of $CaCO_3$ precipitation along the treated soil matrix. This is because the homogeneity of $CaCO_3$ precipitates has a major influence on the treated soil sample, unconfined compressive strength, and treatment stability (Omoregie et al. 2017). To remedy this problem, several studies proposed reducing the pH of the cementation solution, varying the concentration of the cementation solution, and utilising a lower saline solution (Gomez et al. 2020). Also, modifying the injection pattern such as using multiple stages of injection treatment could be useful in limiting the formation of clogging at the injection wells/point (Muhammed et al. 2021). Another limitation affecting MICP implementation is the typical dependence on costly analytical-grade growth media for bacterial cultivation and MICP treatment. Researchers are now adopting alternative nutrient sources such as steep corn liquor, whey, commercial yeast extract, and soy flour (Kahani et al. 2020; Yang et al. 2020) Furthermore, the unwanted production of NH_4 ions as a by-product during MICP is a major drawback affecting this technology. When a substantial amount of ammonium concentration is unexpectedly emitted, the ecosystem suffers from soil acidification (Gowthaman et al. 2021).

Some of the most well-known scientific databases and search engines are Scopus, Dimensions, Web of Science (also known as Web of Knowledge), and PubMed. However, the Scopus database was chosen for this review to extract all possible MICP-related documents. Scopus is the world's biggest curated bibliographic abstract and citation database, containing a diverse range of scientific documents (such as journals, conference proceedings, and books) (Sweileh et al. 2016). These papers are typically obtained from scientific publishers of many disciplines (e.g., Taylor & Francis, Elsevier, Springer Nature, Frontiers and Emerald). It offers a variety of functionalities that make it suitable for bibliometric analysis, such as document types, journal names, citation numbers, and the *h*-index (Wu et al. 2021a). Scopus is regularly updated and examines existing and newly added journals to its database for the quality assurance (Baas et al. 2020). Using its conventional and enhanced features, the database may retrieve documents from several searchable fields.

Bibliometric analysis is particularly useful in supporting researchers in studying, interpreting, and extracting indicators on the evolution and trajectory of scientific knowledge in a discipline (Usman and Ho 2021).

This is accomplished by reviewing the extant literature on a specific issue to discover possible study topics for future efforts. There is an increasing number of MICP review papers that cover a wide range of topics (for example, historical background, $CaCO_3$ mechanisms, microbial species, metabolic processes, testing methodologies, kinetic parameters, problems impacting the MICP, and interesting applications). These reviews of the literature are frequently utilised as a subjective way to evaluate the contents and topic areas published in the field. However, detailed assessments of global research trends based on bibliometric analysis have been rare in this subject (Ahenkorah et al. 2021; Pacheco et al. 2021).

Currently, bibliometric analysis enables the formation of networks based on the relationships between countries, institutions, authors, journals, and keywords important to the research topic (Irfan et al. 2021). To the best of our knowledge, no bibliometric studies on MICP from 2001 to 2021 have been conducted utilising the Scopus database and VOSviewer. As a result, employing Scopus as a source of data mining on MICP-related articles would aid in determining the global research trend in the specific topic of interest. To address the knowledge gaps identified in past studies, the objectives of this bibliometric review were: (1) to analyze the annual article publications and citations trend of MICP from 2001 to 2021; (2) to discuss the leading countries, journals, authors, institutions, funding sponsors in the field of MICP; (3) to identify collaborations/network among authors and countries through VOSviewer analysis; and (4) to highlight the most popular author keywords and research terms used in each journal. Nonetheless, this bibliometric review study will provide many academics with quantitative and qualitative scientific insights into the current research trend and future direction of the MICP process.

2. Methodology

2.1. Data mining and search strategy

The search strategy was used to retrieve documents from the Scopus database on 09 October 2021. Twelves keywords (microbially induced carbonate precipitation, microbially induce calcite precipitation, microbiological precipitation of $CaCO_3$, biocalcifying bacteria, biocalcification, calcifying microorganism, biomediated calcite precipitation, bioprecipitation of calcium carbonate, microbial carbonate precipitation, microbially induce calcium carbonate precipitation, bacterially induced carbonate mineralization, microorganisms induce calcium carbonate precipitation) were used to search from the title, abstract and keyword sections of the Scopus database. The data collection period covered publications between 2001 and 2021. Article documents, ~~publishing~~, written in English language, published in journals, and at the final stage of publication were selected ~~the only document formats allowed~~.

2.2. Data extraction and analysis

The retrieved documents (2,942) from the Scopus database based on the selected keywords were classified into 11 different document types. **Fig. 1** illustrates the strategy used in selecting the query strings from the Scopus database for this bibliometric review, while **Supplementary information, Table 01** lists the corresponding query strings utilized in each subsequent phase. ~~The~~ Articles had the largest proportion (2,473), accounting for 84.1% of the total document types. This was followed by conference papers (272) and review articles (103). Articles are often the preferred document type by authors due to their high reliability and acceptance in the scientific community (Saravanan et al. 2022). The remaining proportion (3%) were book chapters (40), conference reviews (32), notes (10), erratum (6), editorial (3), book (1), short survey, (1), and retracted (1). The publications extracted from the Scopus database were further grouped into six different source types consisting of Journal (2589), Conference Proceeding (215), Book Series (109), Book (26), Trade Journal (2), and Undefined (1). Of the 14 different languages, 2,811 documents (95%) were written in ~~the~~ English language. The remaining 5% of the documents were written in other languages comprising of Chinese (105), Spanish (10), French (4), Hungarian (3), Portuguese (3), Polish (2), Czech (1), Estonian (1), Japanese (1), Persian (1), Russian (1), Turkish (1), and Undefined (1). For this study, only documents (1,058 articles) ~~only~~ written in English were selected and extracted for bibliometric analysis. The exported citations in comma-separated values ~~format~~ files were reviewed when moved to a Microsoft Excel spreadsheet (version 16.54, Microsoft Corporation, Redmond, WA, USA), for data ~~reliability and~~ data analysis. These files were then used to analyze the publication output trend, most prolific authors, countries, journals, institutions, funding sponsors, subject areas, and keywords.

2.3. Bibliometric mapping

The Java-based scientometrics research application is a highly efficient software tool for constructing bibliometric maps (Van Eck and Waltman 2010). The VOSviewer program (version 1.6.18 was adopted since it emphasises the graphical display of bibliometric maps (Afgan and Bing 2021). The number of co-authored documents is used in co-authorship analysis to determine the similarity of items. In contrast, co-occurrence analysis depicts the relationship between objects based on the number of times they are cited together and the number of works completed jointly (Leydesdorff et al. 2013). In network graphs created using the VOSviewer, the size of each node (i.e., circle) represents the weight of the link strength for various parameters (i.e., countries, authors, journals, or keywords). The nodes are assigned depending on several taxonomies or occurrences (Cen et al. 2020). The lines represent the connections between these characteristics, the thickness of the links denotes their relatedness/connection, and the different colours represent the clusters into which they are sorted. The estimated centrality of each parameter determines the node sizes (Cen et al. 2020). As a result, nodes with larger diameters imply higher levels of centrality. As a result, in visualisation maps, the total link strength can be employed to identify or characterise the items in various parameters leading to the groupings. Clusters are produced by VOSviewer analysis to express the collection of nodes that correspond to related subjects.

To determine the co-authorship network of authors on MICP research, visual mapping aided by the VOSviewer program was used. Out of the total of 2,944 authors, 703 met the thresholds. The minimum number of published documents by an author was kept at 2, ~~concerning~~ and the number of citations by an author was 0 ~~citations~~. Maintaining the criteria, some of the 703 authors in the network were not connected, thus the analysis focused on the largest set of connected items (442 authors) with connections. For VOSviewer analysis of co-authorship relating to countries, of the total 76 countries, 73 met the thresholds (the minimum number of documents of a country was 1, while the minimum number of citations of a country was 0). Using this criterion, only 69 items were connected and used to determine the overlay visualization of countries/regions on MICP research. The letters of each country in the thesaurus file used for bibliometric mapping were capitalized. Keywords analysis is a vital process to identify the current hot topics. The effectiveness of publications search and their accessibilities can be greatly influenced by author keywords and index keywords because they provide vital information that can be linked to the published papers in scientific databases. Co-occurrence analysis of author keywords is an effective tool in the VOSviewer program that can be used in the knowledge mining (Wang et al. 2021a). According to the analysis by VOSviewer, this study obtained a total of 2,456 author keywords, with a threshold of 899 (the minimum number of occurrences of an author keyword is 2). The VOSviewer program was can be used to detect how to research topics related to a field that changes/progresses through time (Jiang and Yanbin 2018). To identify the major research trend, co-occurrence analysis based on text data from titles and abstract fields was used. Of the total of 24,790 terms that were obtained, 275 met the threshold (the minimum number of occurrences of a term is 20, based on binary count). The analysis resulted in 158 terms that were used for the co-occurrence network visualization map of research topics.

3.3. Results and discussion

3.1. Annual publications and citations

Over the past two decades, 1,058 articles on the topic of MICP have been successfully published. The retrieved data was sorted and chronologically presented to find patterns and annual growth rates of publications from 2001 to 2021 ~~are shown in~~ (**Fig. 2**). The earliest publications on MICP-related research found in the Scopus database appeared in 1972 (Hathaway and Nelson 1972) and 1974 (Lie and Selvig 1974). The global publication trend has continuously increased over time. The fewest articles (4) were published in 2002, while the most articles (170) were published in 2021. According to the figure, there were only 4 to 9 papers published between 2001 and 2005, excluding 2003. However, scientific interest grew after 2005. Between 2006 and 2018, annual publications ranged from 10 to 94 papers. Surprisingly, research output in this sector has recently gained significant attention, with annual publications increasing to triple digits (154 to 170) between 2019 and 2021. This accounted for 45% (475 articles) of the total publications recorded within the years 2001 to 2021 from the Scopus database. This can be referred to as the blossom period which is when there is a rapid/significant increase in the annual publications (Ding and Yang 2020). Furthermore, as shown in **Fig. 2**, the continuous non-linear increase in the cumulative number of publications shows that the research inclination for annual publications will continue to rise in the future. According to the data gathered from the Scopus database, the MICP study is quickly becoming a prominent research subject to focus on, particularly in recent years. This could be attributed to better laboratory conditions, innovations and procedures, research collaboration, scientific impact, and societal/environmental advantages (Okaiyeto et al. 2020). Moreover, the fluctuation in total publications in the early 2000s is understandable because there were new scholars in the subject and global research interest was still in its infancy.

Fig. 3 depicts the total citations and normalised citations per article on MICP research from 2001 to 2021. These publications received a total of 25,996 citations. The chart demonstrated an unstable growth tendency, with numerous increases and dips in annual citations across the year. The year with the most total citations (2,342) was 2012, while the year with the fewest citations (215) was 2021. It was expected that articles published a decade ago would be more referenced than those published recently. This is understandable given that articles take longer to be mentioned after they are published. According to **Table 1**, the entire citations (25,996) were attributed to 922 articles. This meant that 87% of all MICP papers have been cited. The total number of citations could be used as a measure of academic accomplishment (Wu et al. 2021a). This is because it provides a measure of the scientific impact, visibility, and readability of a particular study to other scholars in a field (Shuaib et al. 2015). On the other hand, the years with the most normalised citations per article (119) were 2003 and 2006, while the years with the lowest normalised citations per paper (1) was 2021. The findings also revealed that there is no relationship between the total annual number of publications and the total annual number of citations. For example, the year 2021 had the most overall publications (170), but only 215 total citations. However, 2012 had the highest number of total citations (2,342) with only 39 total publications. This may have indicated that the work (such as improving sustainable bricks, biosoil consolidation/enhancement for in-situ application, on MICP during these periods was critical in regards to the emerging research interest (Dhami et al. 2012; Filet et al. 2012; Soon 2013). Like total citations, the *h*-index is the dominant metric often used to quantify or evaluate scholarly output (Engqvist and Frommen 2008). According to the Scopus database, the *h*-index of the retrieved articles was 78. This means that out of the 1058 articles that were considered for the *h*-index, 78 have been cited at least 78 times, and this value might increase with time (Sweileh et al. 2016). In addition, 2019 recorded the highest value for the *h*-index (25), while 2001 had the lowest number for the *h*-index (4).

3.2. Top contributing countries

Table 2 shows the top ten most productive countries in terms of the number of publications, while **Fig~~ure~~ 4** shows the global distribution of publications in this discipline. According to the graphic, research activity was conducted in 77 countries/territories between 2001 and 2021, with the majority coming from Asia (31 publications) and Europe (27 publications). China had the most publications in Asia (290), South Africa had the most in Africa (12), the United Kingdom had the most in Europe (76), the United States had the most in North America (229), Brazil had the most in South America (31), and Australia had the most in Oceania (67 publications). These six countries accounted for 45% of all publications worldwide. Among the 77 countries/territories, China had the most overall publications. Even though 1,058 articles on this topic came from 77 different nations, most publications came from just a few.

The United States, India, the United Kingdom, Australia, Japan, Germany, South Korea, Iran, and Spain had a total of 1000 publications, 23535 citations, and a combined *h*-index of 233. On the other hand, China was the most productive country, with 290 total publications and a single-country publishing proportion of 28%. This suggests that more MICP papers were written by Chinese authors than by authors from any other country. The United States quickly followed with 229 publications. It might be argued that publications from the United States were more accessible/of interest to researchers based on the *h*-index value and total citations because this country obtained the highest *h*-index (45) and total citations (8,180). Furthermore, the publication (DeJong et al. 2006) which originated in the United States was ranked as the most cited article (833 citations) in this field. This was followed by publications (Rodriguez-Navarro et al. 2003; Qabany et al. 2012) originating from Spain (346 citations) and the United Kingdom (327 citations). Interestingly, five of the top 10 most productive countries on MICP are among the six largest (China, United States, United Kingdom, India, Japan, and the Russian Federation) emitters of greenhouse gas (GHG) (Olivier and Peters 2019, 2020). While these six largest emitters of GHG account for 62% of the global carbon footprint, China (26%), and the United States (13%) lead the entire world as the largest emitters (Olivier and Peters 2020). The vital urgency to achieve carbon neutrality and reduce carbon intensity has shifted the need for more environmentally friendly manufacturing processes/methods that will result in zero or minimal carbon footprint (Omoregie et al. 2021). This may be the reason MICP has recently gained lots of interest in the scientific community.

The contributions from other countries around the world were low when compared to China and the United States. Out of the 77 countries, 54 published between 1 to 10 articles. The publication percentage of a single country during the period of study is heterogeneous. Among the 10 most productive countries, China and the United States have the highest publication percentage of a single country. The remaining eight countries have a percentage below 10% (4 to 7%). The disparities between co-authors from different countries have no bearing on the quality of the research or publication. It does, however, provide information on how countries and research institutes can network and collaborate to generate a paper. Besides, various factors such as the desire to expand research areas, evolving funding patterns and increasing human resources, and the difficulty of certain experiments that require specialised equipment have all contributed to international collaborative research participation from all over the world. (Melkers and Kiopa 2010; Loh et al. 2022).

By analyzing the evolution of article publication over the years from the scientific database it is possible to know the most performing countries that have occupied 1st to 3rd positions (Chang et al. 2020). In general, the magnitude of publications by some countries, such as China and the United States, stands out. However, while looking at country publications by year. It is worth noting that the United Kingdom was not among the top three countries from 2001 to 2008. In 2009, the United Kingdom was only one of the top three most productive countries. During these times, only the United States occupied the top three rankings (except for 2003, 2004, and 2007). China was the first country listed in 2005, reappeared in 2010, and will remain on this list (as one of the top three productive countries) until 2021. Only in 2013 and 2017 was the country listed. From 2009 to 2021, the

United States remained among the top three most productive countries. The top three countries in terms of overall rankings were only present in 2013, and 2017. The following countries were also named among the top three most prolific from 2001 to 2021: Australia (2002); Argentina (2002); Switzerland (2003); Italy (2004, 2005, and 2007); Austria (2004); Canada (2004, 2007, and 2015); France (2006, and 2011); India (2007, 2016, 2020, and 2021); Spain (2008); South Korea (2014); and Japan (2018 and 2019). All of these countries are also economically developed countries.

Fig. 5 shows a network visualisation map created using the VOSviewer application based on co-authorship and nation analysis. Network visualisation has proven to be a useful technique for assessing a wide range of bibliometric networks (i.e., networks of co-authorship relationships between scholars, and networks of co-occurrence of author keywords)) (Loh et al. 2022). The bibliometric mapping revealed a total of 69 elements (countries) divided into 6 clusters, with a total of 268 links and a total link strength of 615. The red cluster represented Asia, the green cluster represented Africa, the blue cluster represented North America, the alge-colour cluster represented South America, the purple cluster represented Europe, and the cyan cluster represented Oceania. The density of the publications is represented by the size of the nodes (items), while the strength of the collaboration is revealed by the thickness of the links. The bibliometric map revealed that the United States has the most total link strengths (179), with 39 ties to other countries. This was followed by China, which has the most total link strength (151), with 35 linkages to other countries. Surprisingly, these two countries (China and the United States) have the strongest association in this subject, with a link strength of 52. This is followed by China and Singapore, which have a link strength of 21, the United States and Singapore, and the United States and the United Kingdom, all of which have a link strength of 16. The total link strength displays co-authorship linkages with other nations/authors in a co-authorship analysis, whereas the link strength between countries and writers reveals the total number of publications co-authored by two related countries and authors (Loh et al. 2022).

Finally, 89.6% of the countries that participated in MICP research had an international collaboration that resulted in publications. This demonstrates that scholars from around the world are exchanging knowledge/ideas and engaging in research/resource engagement to increase scientific output on the use of the MICP process for sustainable environmental applications. The VOSviewer examination of co-authorship for countries revealed that countries had strong international partnerships. Indeed, the requirement for research financing, information exchange, access to facilities, and co-authorship of publications would all have an impact on the research collaboration (Bezak et al. 2021). Because the United States and China were the two major countries in the field of MICP, the co-authorship of articles demonstrated that these two countries have a strong transnational cooperation/connection (52 links). The majority of the 13 separate clusters had four to five countries.

3.3. Top productive journals

The Scopus database data was evaluated to discover the most relevant journals on this topic. **Table 3** summarised the most productive journals on MICP, as well as their total articles, total citations, and other relevant data (such as most-cited articles, publisher names, CiteScore, and quartile ranking). The top ten most productive journals in MICP were credited to five unique academic publishers: Elsevier Ltd, Taylor & Francis Ltd., American Society of Civil Engineers, Springer Nature, and Wiley-Blackwell Publishing Ltd. Elsevier Ltd. had the most journals of any of these publishers (4 journals). Taylor & Francis Ltd. (1 journal), the American Society of Civil Engineers (2 journals), Springer Nature (2 journals), and Wiley-Blackwell Publishing Ltd. published the remaining publications (1 journal). These top ten most prolific journals published 261 papers and garnered 10,056 citations. These publications are from the United Kingdom, the United States, the Netherlands, and Germany. These are developed nations. This proved that one of the G8 countries is leading the scientific world (Jiang and Yanbin 2018).

Construction and Building Materials held the top position in terms of overall publications, with 55 total publications. This was followed by *Geomicrobiology Journal*, and *Journal of Geotechnical and Geoenvironmental Engineering*, with 38 and 36 total publications, respectively. *The Journal of Geotechnical and Geoenvironmental Engineering*, on the other hand, had the most overall citations (2,541). This indicated that academics chose to publish their studies in *Construction and Building Materials*, while papers published in *Journal of Geotechnical and Geoenvironmental Engineering* were more likely to be cited. Publications in the later journal may be more accessible to readers/scholars. Furthermore, the American Society of Civil Engineers publishes the *Journal of Geotechnical and Geoenvironmental Engineering*, which primarily attracts academics interested in employing MICP to generate sustainable construction materials for diverse engineering applications.

According to the Scopus database's CiteScore 2020 metrics, there were 6 journals with CiteScores greater than 6. *Construction and Building Materials*, on the other hand, earned the highest CiteScore (8.8). *Acta Geotechnica* obtained the highest SJR (2.2) and SNIP scores (2.6). Furthermore, the top ten prolific journals on

MICP are all Q1-ranked journals. This means that the main journals in this subject are also top-tier publications with a scientific reputation. These top ten journals frequently attract high-quality manuscripts, which influences the journals' performance (Wu et al. 2021a). Future high-quality MICP publications are anticipated to be published in these top-performing journals. **Table 3** showed the most cited articles on MICP published by the top 10 most productive journals on MICP. The article (Whiffin et al. 2007) which was published in *Geomicrobiology Journal* received the highest number of citations (886). This was followed by articles (DeJong et al. 2006; Harkes et al. 2010a) that were published in the *Journal of Geotechnical and Geoenvironmental Engineering* (833), and *Ecological Engineering* (363). It was also observed that Scientific Reports received the lowest number of citations (287), and was the 9th-ranked journal with a total publication (18 articles) among all the top 10 journals. This journal also had the lowest cited article among this group despite having a high CiteScore value (7.1). The data however suggest that most articles on MICP do not receive many citations even though it is an open-access journal.

3.4. Top prolific authors

The Scopus database was used to extract the performance of the authors who were involved in the publication of pertinent MICP research. The top prolific authors in this subject were rated based on the number of publications they had received, as shown in **Table 4**. According to the analysis, the top 10 relevant writers published a total of 217 articles, accounting for 14% of the total publications (1,058) on MICP. However, from 2001 to 2021, these top authors each wrote between 13 and 38 publications. The top 10 most notable authors were discovered to be from six different countries. Three of the top ten authors were from China, with the other two from the United States and Japan. One was linked to Singapore, Australia, and India. **Table 4** showed that Satoru Kawasaki has the most publications (38). Jian Chu (31 publications) and Kazunori Nakashima came next (26 publications). Varenyam Achal, on the other hand, had the most citations (1510) and the highest h-index (18). Jian Chu was next, with a total of 1510 citations and an *h*-index of 15. Only three of the top ten most prolific authors (Abhijit Mukherjee, Robin Gerlach, and Mondem Sudhakara Reddy) had all of their works published between 2001 and 2021 referenced at least once. Abhijit Mukherjee had the earliest first publication on MICP within this group in 2009, while Kazunori Nakashima had the most current first publication in 2017. Among this group, Liang Cheng's publication (Cheng et al. 2013) received the most citations (303). This was followed by Jian Chu's publication (Chu et al. 2012) (215 citations). Varenyam Achal, Abhijit Mukherjee, and Mondem Sudhakara co-wrote the third most referenced article (168) among these highly prolific authors (Achal et al. 2009).

Satoru Kawasaki, a professor at Hokkaido University in Japan, was the most productive author. On MICP, the author authored a total of 38 articles. This author's most referenced article (Mwandira et al. 2017) was published in *Ecological Engineering* in 2017 and garnered a total of 47 citations. Satoru Kawasaki's article indicated that the ureolytic bacterium (*Pararhodobacter* sp) at 10^9 CFU/mL concentration was successfully employed to entirely remediate lead (1036 mg/L Pb^{2+}) using the MICP technique. According to the findings, MICP was able to convert lead ions in soil to a stable and bioprecicipitated form that afterwards crystallised with calcite/vaterite for sand enhancement. Jian Chu (31 articles) and Kazunori Nakashima (31 articles) were the next two most productive authors in terms of publication output (26 articles). These two authors are from Nanyang Technological University in Singapore and Hokkaido University in Japan (Japan).

Varenyam Achal, the researcher with the most total citations and the greatest h-index, is affiliated with the Guangdong Technion-Israel Institute of Technology (China). According to the Scopus database, the author has 25 articles of which had already been referenced. This author's most cited paper (168 citations) was published in the Journal of Industrial Microbiology and Biotechnology in 2009. This study showed that an optical density of 1.0 for ureolytic bacteria (*Sporosarcina pasteurii*) growing in a low-cost medium (lactose mother liquor) is comparable to that of a laboratory-grade yeast extract media (Achal et al. 2009). The bacterium's urease activity (366 U/mL and 412 U/mL) and calcite concentration (24 to 28% of total treated sand weight) were also equivalent in both mediums, according to the study. Varenyam Achal's research is significant in the field of MICP since it demonstrated that alternate cementation reagents (such as lactose mother liquor) might be employed for MICP in-situ applications.

Fig. 6 depicts an overlay visualization map of the author network for MICP collaboration from 2001 to 2021. From the VOSviewer map, it was revealed that a total of 442 authors were grouped into 29 different clusters, with total links of 1,711 and total link strength of 3,021. The bibliometric map showed that Satoru Kawasaki (identified as Kawasaki, S in the VOSviewer map) recorded the highest number of total link strengths (103), having 33 links with other authors. This was followed by Chu Jian (identified as Chu, J. in the VOSviewer map) (100 total link strength) and Yang Zhao (identified as Zhao, Y. in the VOSviewer map) (88 total link strength) having 38, and 47 links with other authors, respectively. The co-authorship study of authors revealed that, among all the scholars with whom Satoru Kawasaki, was associated, Kazunori Nakashima (identified as Nakashima, K.

in the VOSviewer map) had the most links (23 links). VOSviewer also reviewed that there were no research connections between Satoru Kawasaki, Chu Jian and Kazunori Nakashima.

3.5. Top productive institutions and funding sponsors

Table 5 summarises the top ten most prolific institutions in the field of MICP from 2001 to 2021. Six of the top ten institutions were in China or the United States. The four remaining institutions were located in Singapore, Australia, Japan, and Belgium. Nanyang Technological University and Hokkaido University were the leading institutions in terms of overall publications, with each having 39 publications. Southeast University followed suit (37 publications). Furthermore, the University of California, Davis had the most overall citations (2,082), followed by Nanyang Technological University (1,219 citations), and Curtin University (1,219 citations). Nanyang Technological University has the highest *h*-index rating (19), followed by the Chinese Academy of Sciences (17). Only Montana State University had all of its articles mentioned in the top ten most productive institutions. Five of the most prolific MICP researchers are linked with some of the most productive institutions (Nanyang Technological University, Hokkaido University, Montana State University, Curtin University, and Southeast University). Among this group, the highest cited article (DeJong et al. 2006) (833 citations) originated from the University of California, Davis. This was followed by publications (Chu et al. 2012; Cheng et al. 2013) originating from Curtin University (303 citations), and Nanyang Technological University (215 citations), respectively.

The top 10 most productive funding sponsors when it comes to the MICP scientific community include the National Natural Science Foundation of China (China); the National Science Foundation (United States); Japan Society for the Promotion of Science (Japan); Ministry of Education, Culture, Sports, Science, and Technology (Japan); National Key Research and Development Program of China (China); China Postdoctoral Science Foundation (China); Ministry of Science and Technology of the People's Republic of China (China); European Commission (Luxembourg); National Research Foundation of Korea (Korea); and Engineering and Physical Sciences Research Council (United Kingdom). The ranking shown in **Table 6** is based on the total number of publications. Four out of these top 10 funding sponsors originate from China, two are from Japan, and the remaining four were from the United States, Luxembourg, the Republic of Korea, and the United Kingdom. National Natural Science Foundation of China (China) had the highest total publication (188). This was followed by National Science Foundation (United States) (80), and the Japan Society for the Promotion of Science (Japan) (40). National Natural Science Foundation of China (China) also had the highest total citations (2,940), and *h*-index (30) among this group. This was followed by the National Science Foundation (United States) (total citations of 1,829, and a total *h*-index of 21). The table further indicated that only Engineering and Physical Sciences Research Council (United Kingdom) had all its publications cited. Among this group, the article (Bachmeier et al. 2002) which was sponsored by National Science Foundation (United States) had the highest total citations (290). This was followed by publications (Li et al. 2013; Kang et al. 2016) that were sponsored by the National Natural Science Foundation of China (China) (177), and the National Research Foundation of Korea (Korea) (118).

3.6. Most popular keywords

Author keywords have a significant impact on the impact of publishing searches and their accessibility since they provide crucial information that may be linked to published papers in scientific databases. These keywords serve as a vital link that distinguishes information sources from the enormous quantity of available publications (Saravanan et al. 2022). The overlay visualisation mapping of the co-occurrence of author keywords was shown in **Fig. 7**. The VOSviewer algorithm initially recognised a total of 2,456 author keywords. Keyword co-occurrence analysis is a powerful function in the VOSviewer application that can be utilised in knowledge mining (Wang et al. 2021a). After renaming the synonyms and phrases, 546 keywords met the threshold (the minimum number of occurrences is 2) and were grouped into 78 different clusters. The result showed that the term “MICP” was the most used author keyword with 121 occurrences, total link strength of 213, and 152 links to other author keywords. This keyword (MICP) also had an average publication year of 2018.26, and average citations of 30.32. "MICP" has a high association with "biocementation," "unconfined compressive strength," and "*sporosarcina pasteurii*" through 10, 9, and 8 link strength, respectively, among all the author keywords. Furthermore, "calcium carbonate content," "biomineralization," and "calcite precipitation" were among the top trending author keywords, with 84, 80, and 79 occurrences, respectively. The MICP technique increases soil strength and durability while decreasing permeability by combining calcium carbonate crystal fillings and extracellular polysaccharide bonding within soil particles. (Wang et al. 2022).

The VOSviewer analysis also indicated that the remaining top 10 most popular author keywords in this field consisted of “urease enzyme” (68 occurrences), “*sporosarcina pasteurii”* (66 occurrences), “biocementation” (62 occurrences), “calcium carbonate precipitation” (34 occurrences), “bioremediation” (28 occurrences), and “self-healing” (27 occurrences). These keywords were more popular than the remaining 536 author keywords used in publications. Biocementation is a biological method that uses biomineralization to improve the engineering qualities of granular soil and heal/repair concrete cracks (Xu et al. 2020). Heavy metal ions such as lead and copper can be sequestrated through the MICP process to make them stable and less toxic (Kang et al. 2016; Mwandira et al. 2017). MICP has been used in a variety of ways attributable to urease-producing bacteria like *Sporosarcina pasteurii*, which has been extensively explored.

There is a plethora of information that is available to scholars through the keywords (Loh et al. 2022). The correlation between author keywords from the Scopus database and VOSviewer analysis can assist researchers in detecting/identifying current study trends in the field of MICP. Only 28 of the 546 keywords were discovered to have occurrences ranging from 121 to 6, and so were chosen for further classification, as shown in **Fig. 8**. There were seven applications (bioremediation, biocementation, self-healing, bio-calcification, biogrouting, soil stabilisation, and wind erosion management), with keywords appearing 6 to 62 times. Furthermore, it was discovered that researchers in this sector primarily used calcite precipitation, unconfined compressive strength (UCS), strength and testing of materials, water permeability, and scanning electron microscopy for performance evaluation. The occurrences of these five approaches range from 9 to 79. There were 11 detected materials/sources referenced between 7 and 84 times in the author's keywords (calcium carbonate content, urease enzyme, *sporosarcina pasteurii*, urease-producing bacteria, microbialite, *bacillus* sp, stromatolites, *bacillus pasteurii*, clayey soil, cave, and microbial mat). Furthermore, the author's keywords related to the biological process included MICP, biomineralization, calcium carbonate precipitation, biofilm, and urea hydrolysis. Author keywords may have changed and may continue to change over time. For example, academics might begin employing terms related to environmental and human demands, such as resource management, waste control, and practical fields/applications. (Wang et al. 2021a).

3.7. Trending research terms

VOSviewer can be used to detect how to research topics related to a field that changes/progresses through time (Jiang and Yanbin 2018). Co-occurrence analysis based on text data from the title and abstract fields was utilised to identify the key research trend. Only 158 terms were chosen (the minimum number of occurrences of a term is 20, based on binary count) for the co-occurrence network visualisation map of study subjects shown in **Fig. 9**. The analysis yielded four distinct clusters with a total of 9,661 linkages and a total link strength of 65,466. The first cluster (red colour) had the most research items (75). This was followed by a second cluster (green colour) containing 64 research items in total. The third cluster (blue colour) contained a total of 10 research items, whereas the final cluster (alge colour) contained a total of 9 research items. The red cluster indicated that research trends were focused on "precipitation." This phrase has a total link strength of 8,516, 815 occurrences, and 157 connections to other research topics.

There are 220 publications in which the words "precipitation" and "soil" are linked. 327 studies link "precipitation" to "carbonate," 357 to "MICP," and 151 to "environment." Researchers are interested in the formation/origin of $CaCO_3$ precipitation, mineral deposition by microorganisms, and mineral deposition in sediment, according to more studies on the items in this cluster. The green-coloured cluster demonstrated that research items were concentrated on "MICP," with a total link strength of 4,749, 411 occurrences, and 153 links to other research items. "MICP" had 175 publications with links to "soil," 127 publications with links to "method," 135 publications with links to "test," and 86 publications with links to "property." Additional analysis of the items in this cluster revealed that researchers are concerned about the utility of MICP technology in improving the engineering properties of soil, developing various techniques to improve the shear strength and stiffness of soil specimens, and how to improve the performance of MICP treatment. The blue-coloured clustered research items were largely about "compressive strength," with a total link strength of 1,129, 107 occurrences, and 139 links with other research items. According to VOSviewer, "compressive strength" had 89 publications linked with "precipitation," 33 publications linked with "specimen," 46 publications linked with "MICP," and 40 publications linked with "carbonate."

Further analysis of the items in this cluster suggested that researchers focused on concrete crack repair, mortar improvement, the productivity of self-healing concrete, and improving the durability and water absorption performance of the technology. The alge-coloured cluster showed that “Biomineralization” was the leading item, with a total link strength of 717, 69 occurrences, and 136 links. “Biomineralization” had 24 links with “formation”, 26 links with “MICP”, 32 links with “carbonate”, and 54 links with “precipitation. Further evaluation of the items in this cluster suggests scholars becoming interested in using biominerals from *Sporosarcina* sp for heavy metal remediation. Finally, based on a VOSviewer analysis of titles and abstract fields, it was noticed that the topic (precipitation) was predominantly popular from 2001 to 2018, however, the term “MICP” emerged as the hottest research topic of choice by scholars in 2019 to 2021.

3.8. Environmental impact of MICP technology

The literature has numerous reports on the potential of the MICP process through the precipitation of $CaCO_3$ minerals (**Fig. 10**). Unfortunately, MICP technology has a stringent environmental impact which has yet to be fully investigated (Anbu et al. 2016; Rajasekar et al. 2021). MICP pathways such as ureolysis, denitrification, and ammonification results in gaseous by-products. During the ureolysis-driven MICP process, high ammonium contents are produced due to urea hydrolysis. It is estimated that between 850 mg/L to 17,000 mg/L of ammonium is released into waterbodies (Lee et al. 2019; Mohsenzadeh et al. 2021). Other researchers discussed that if 1 m^3 of sand is cemented via the MICP process, it is projected to release 11.2 kg of ammonium, and if this is scaled up to a larger amount of soil, the produced ammonium ions may pollute 4.5 x 106 m^3 of drinking water due to the discharge of untreated biocementation effluent. Thus, this will have serious consequences for human health and regrettable environmental impact if not properly managed or prevented. If MICP is to be a sustainable economic construction technology, it must be treated or reused in a way that does not negatively affect other environmental considerations (Porter et al. 2021).

The majority of the literature has mostly ignored discussing their ammonium-rich effluent disposal or treatment process following the biocementation test. Furthermore, there is not a single publication in the literature that provides extensive information on the entire physicochemical or elemental compositions of biocementation effluents. This is significant because, in addition to ammonium, there may be other chemical substances that have not been detected and represent a severe environmental impact if not addressed. Knowing the specific features of the MICP effluent can assist scholars in deciding on the best wastewater treatment procedures to use. Nonetheless, few recently published have shown potential ways to mitigate ammonium discharge into the environment. Ion exchange and attaching zeolites to microbial cultures in the soils are two treatment methods proposed to help remove the ammonium effluents after soil biocementation (Keykha et al. 2018; Lee et al. 2019; Su et al. 2022). Furthermore, substituting carbonate ions with phosphate ions or magnesium ions through a process called Microbial-induced struvite precipitation is another alternative suggested option (Gowthaman et al. 2022b). All of the approaches mentioned above appear to have a promising potential to mitigate the environmental impact of MICP technology.

3.9. Limitations of the study

This study has some limitations, as have prior bibliometric investigations. Because all the data included in this bibliometric analysis came solely from the Scopus database, many MICP articles that are not indexed in the Scopus database were inevitably excluded. In addition, the selected keywords (microbially induced carbonate precipitation, microbially induce calcite precipitation, microbiological precipitation of $CaCO_3$, biocalcifying bacteria, biocalcification, calcifying microorganism, biomediated calcite precipitation, bioprecipitation of calcium carbonate, microbial carbonate precipitation, microbially induce calcium carbonate precipitation, bacterially induced carbonate mineralization, microorganisms induce calcium carbonate precipitation) may have not captured all the publications in this field. This is possible if authors mentioned different terminologies in the titles, abstracts, and keyword sections of their papers.

The data collection period covered publications published between 2001 and 2021. As a result, documents published before 2001 and after 2021 are excluded. Because the data mining and extraction were completed in October 2021, it was not possible to incorporate publications from 2022. As a result, documents published before 2001 and after 2022 are excluded. ~~Because the data mining and extraction were completed in October 2021, it was not possible to incorporate publications from 2022. As a result, future bibliometric analyses of MICP research trends should include publications from 2022.~~ Furthermore, the document types were restricted to article publishing, English language, journal publication, and publication at the final stage. This is due to our desire to focus solely on actual research documents. Nonetheless, the findings given in this bibliometric research provide a clear picture of the state and direction of the MICP publication trend. Furthermore, we expect that future researchers will be able to overcome these constraints and use unified scientific databases to further analyse the literature on this topic.

4. Conclusion

This bibliometric review was able to identify the annual publications and citations output on MICP from 2001 to 2021 in the Scopus database. MICP is an active research discipline that has attracted the attention of researchers around the world. Despite a few noticeable fluctuations, the growth in research output is expected to continue increasing with time. The United States and China are the leading contributors in this field. Satoru Kawasaki had the highest number of total publications, while Varenyam Achal had the most citations and h-index. The top 10 most prolific authors originated from Japan, Singapore, China, Australia, the United States, and India. Of the most influential academic journals, Construction and Building Materials was the most preferred journal by authors for publications on MICP. The Journal of Geotechnical and Geoenvironmental Engineering received the most citations among all academic journals. Of the 546 author keywords analyzed through VOSviewer, "MICP" was the leading keyword, with 121 occurrences.

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Ethical Approval

Not applicable.

Consent to Participate

Not applicable.

Consent to Publish

Not applicable.

Authors Contributions

A.I. Omoregie: conceptualization; data curation; methodology; software analysis; first to final draft writing. K. Muda: funding acquisition; administration; and review & editing. C. Y. Hong, F. M. Pauzi, N. S. B. Aftar Ali and O.O. Ojuri: data validation; review & editing; and software analysis. All authors contributed to the manuscript revision and read and approved the submitted version.

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Competing interests

The authors declare no competing interests.

Availability of data and materials

Please feel free to contact the corresponding author if you require the data.

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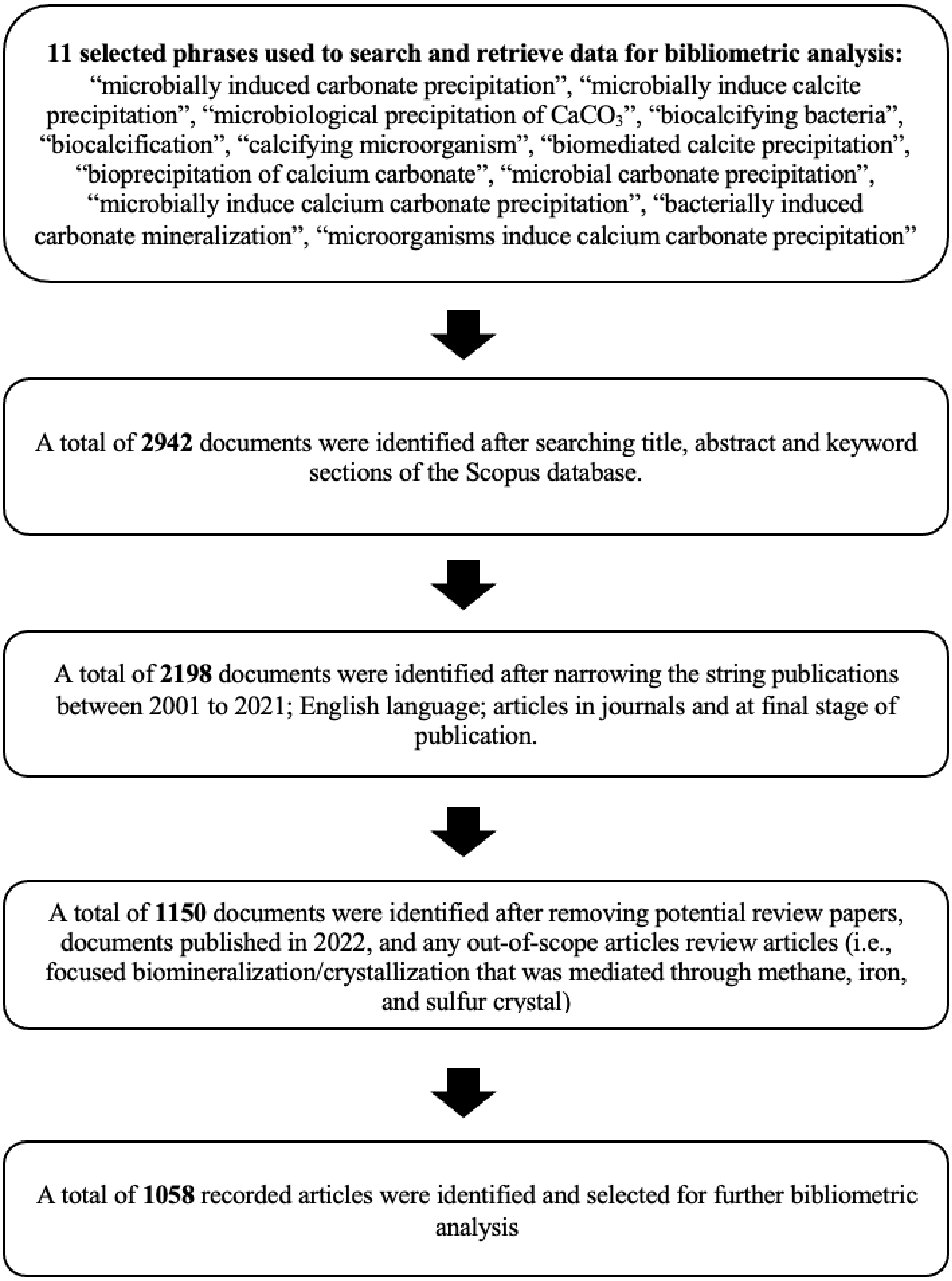


Fig. 1: Flow chart of the overall methodology used for data retrieval from the Scopus database.

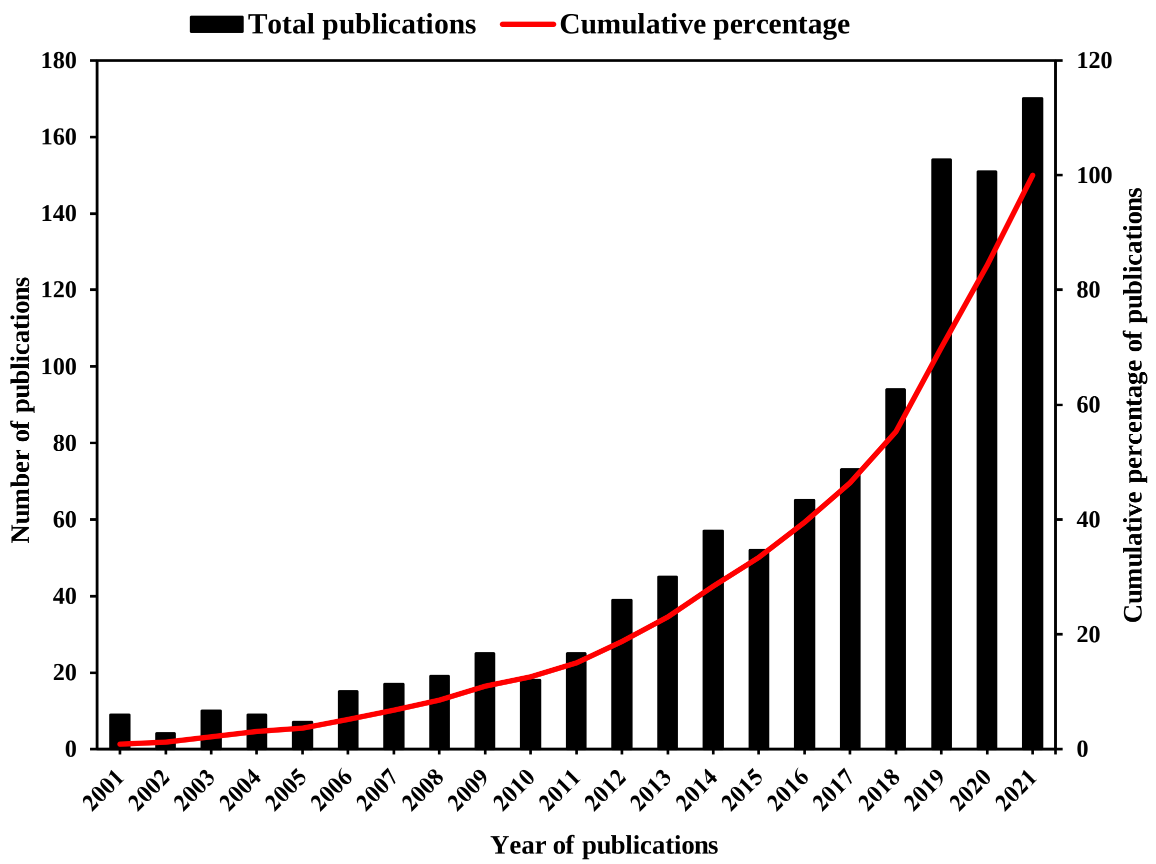
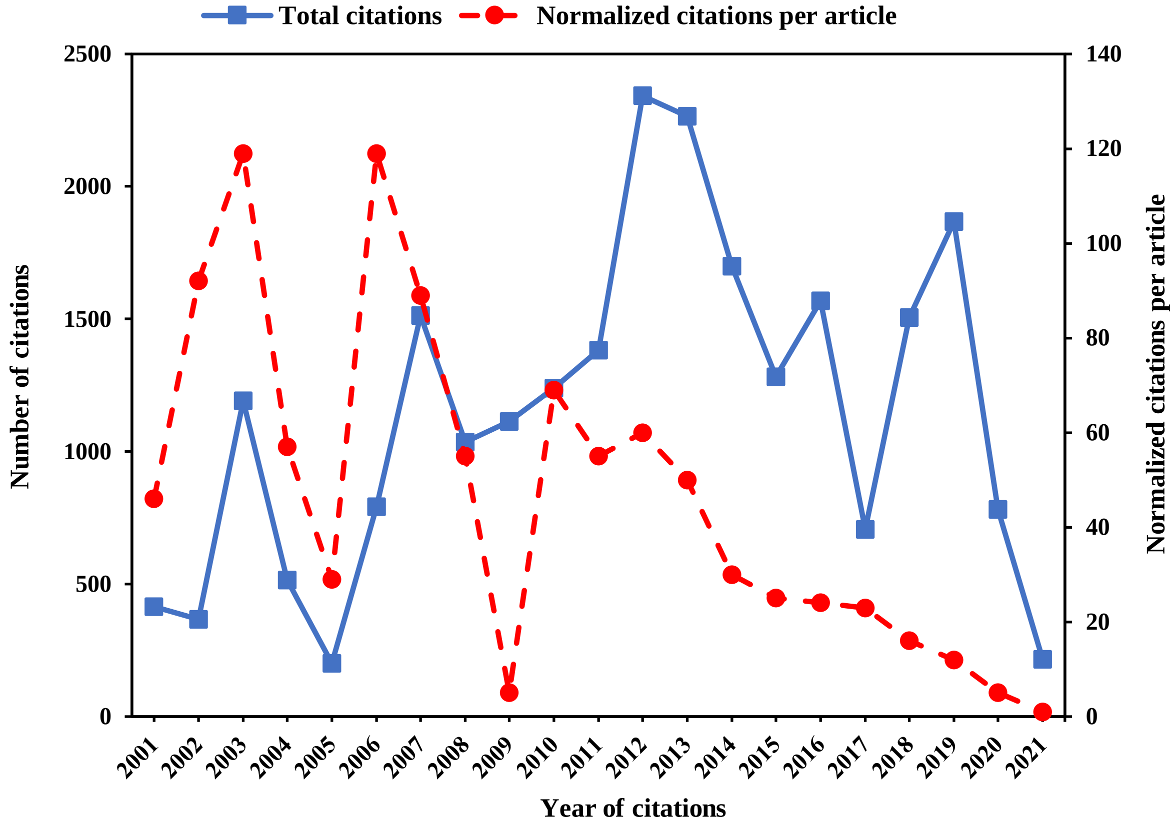


Fig. 2: Number of publications on MICP from 2001 to 2021 indexed in the Scopus database.



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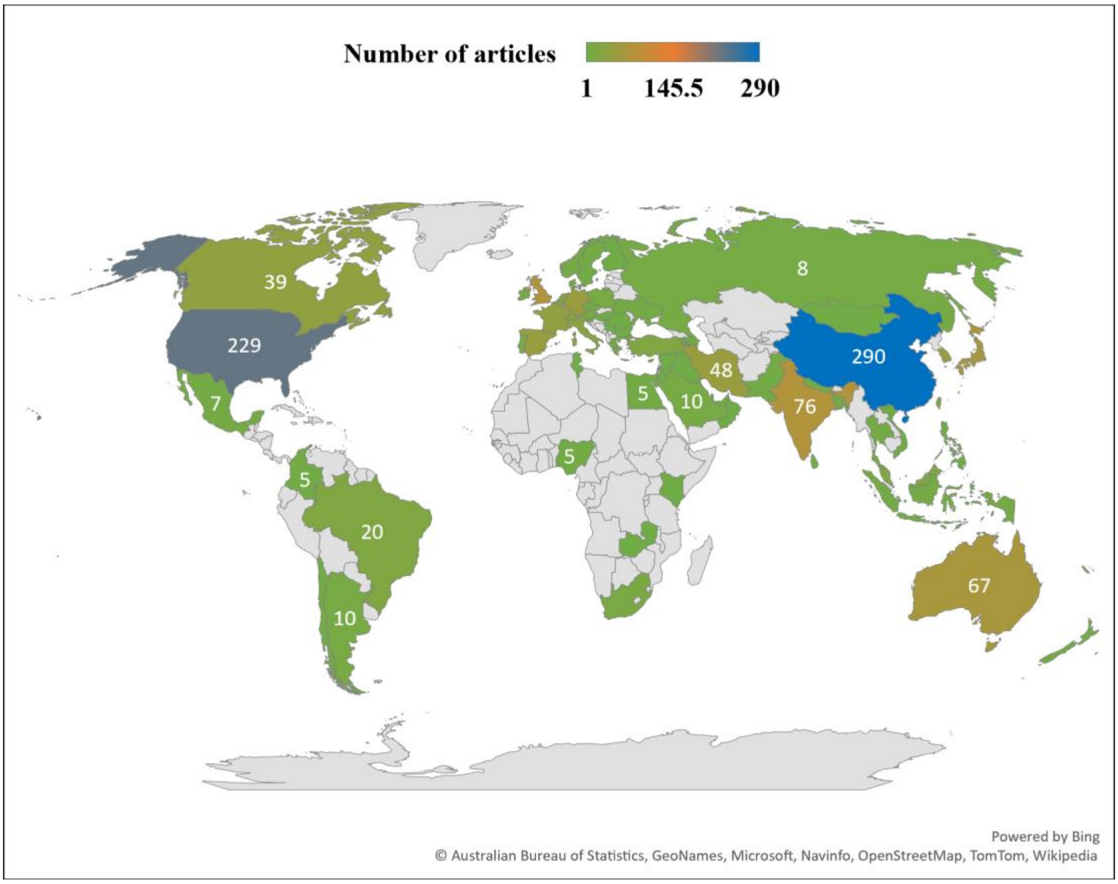

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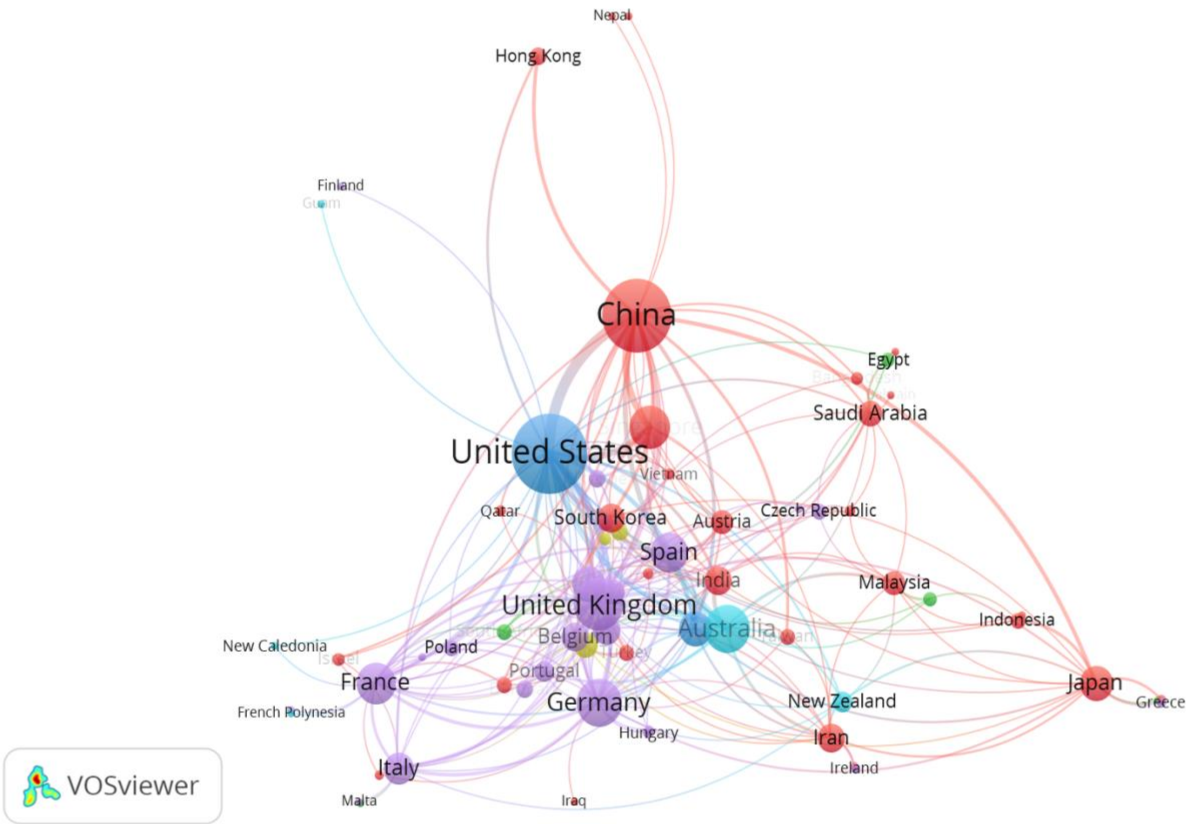

Fig. 5: Network visualization of the bibliometric map based on co-authorship analysis of countries. The online map is available at https://bit.ly/3o6ZWjv

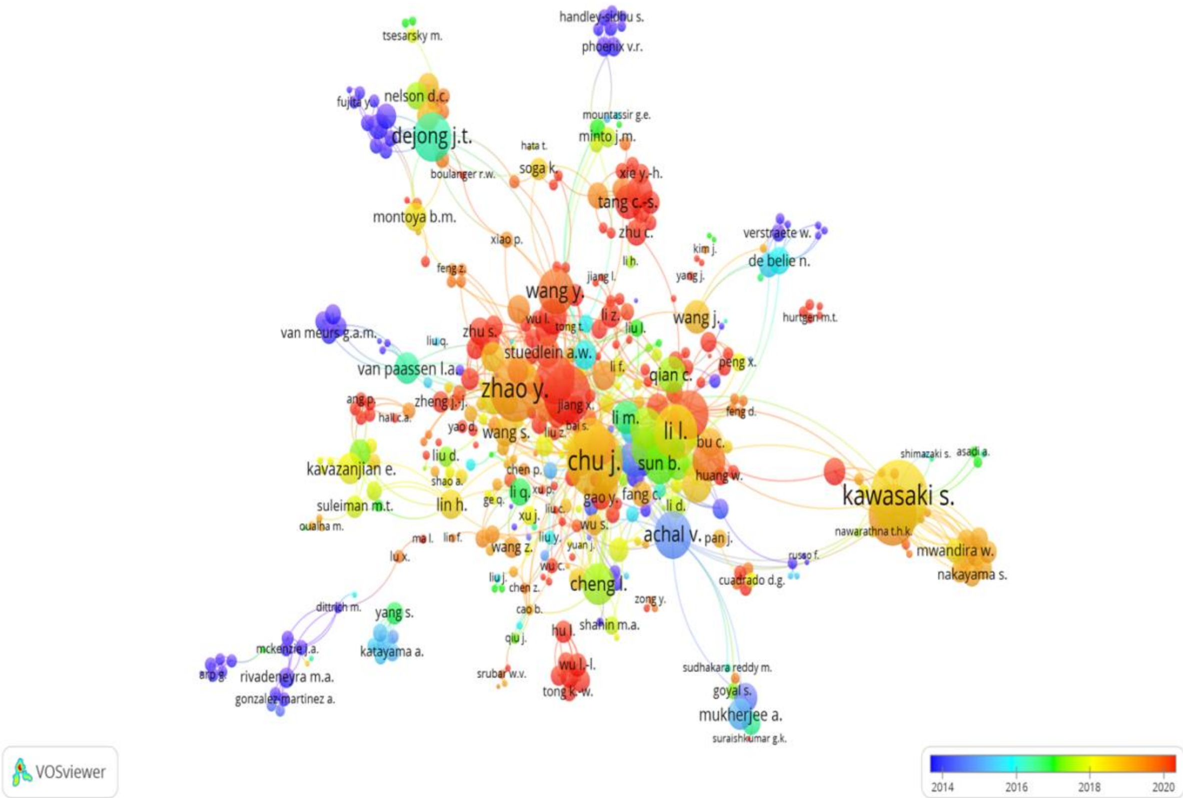

Fig. 6: Overlay visualization of the bibliometric map based on co-authorship analysis of authors. The online map is available at https://bit.ly/3uRCcn4

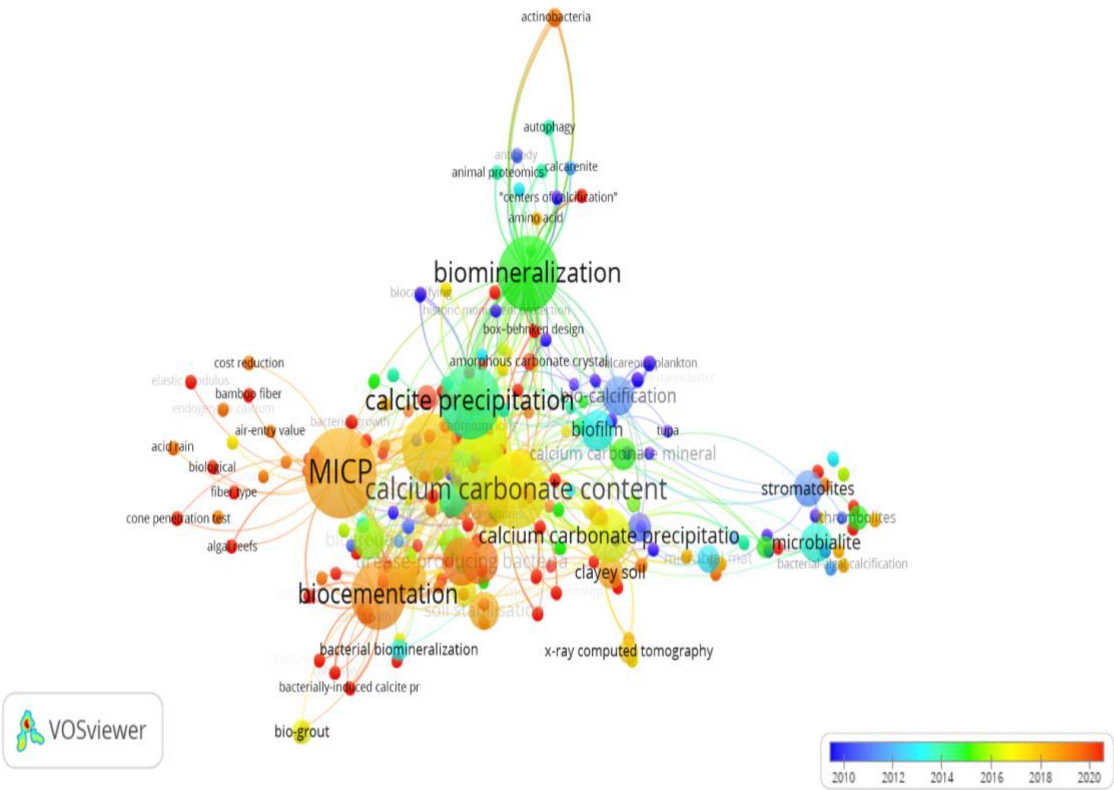

Fig. 7: Overlay visualization of co-occurrence for author keywords. The online map is available at https://bit.ly/3IGdH2b

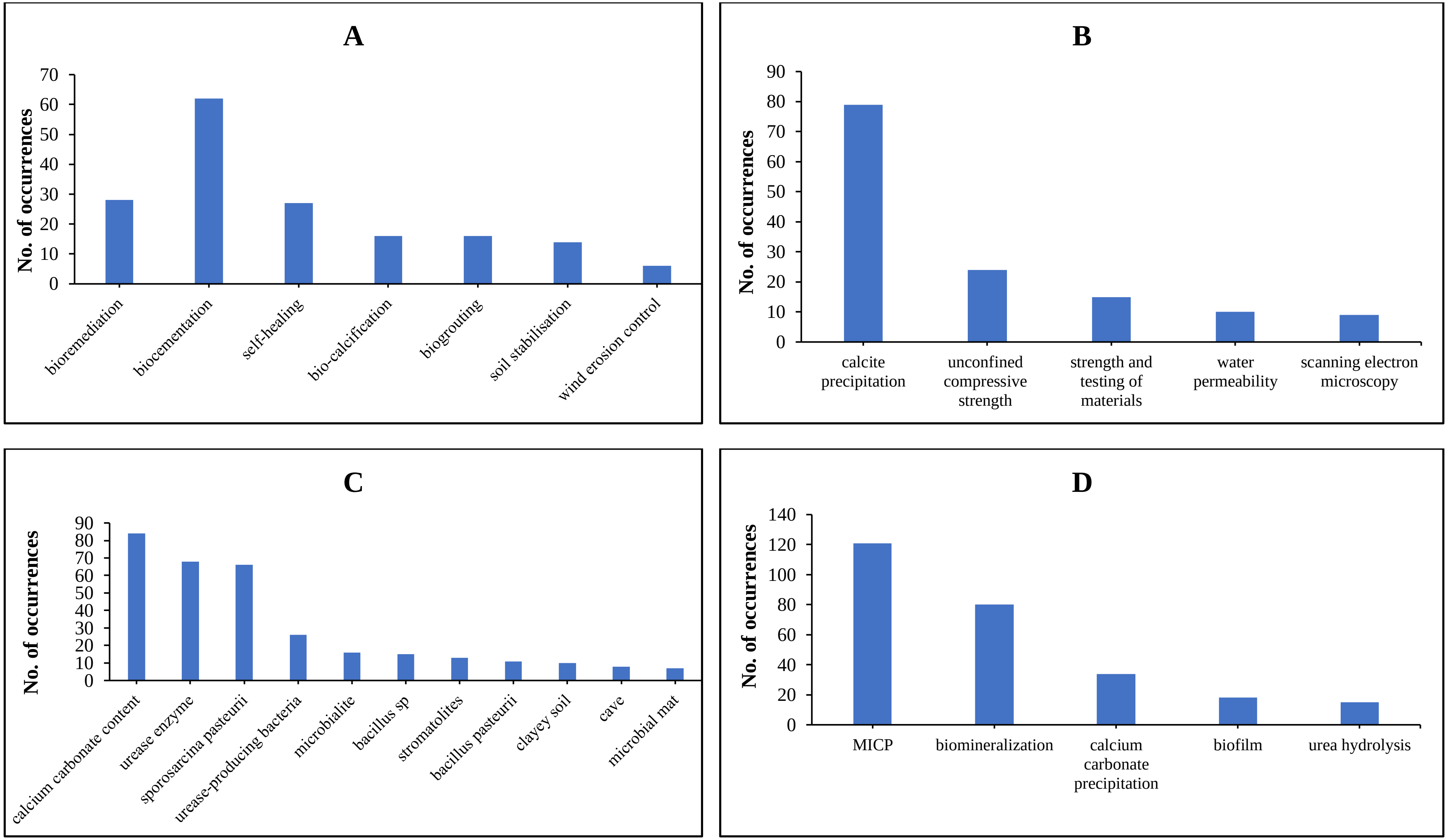

Fig. 8: The author keywords grouped into various parts: (A) application; (B) performance evaluation methods; (C) materials; and (D) process.

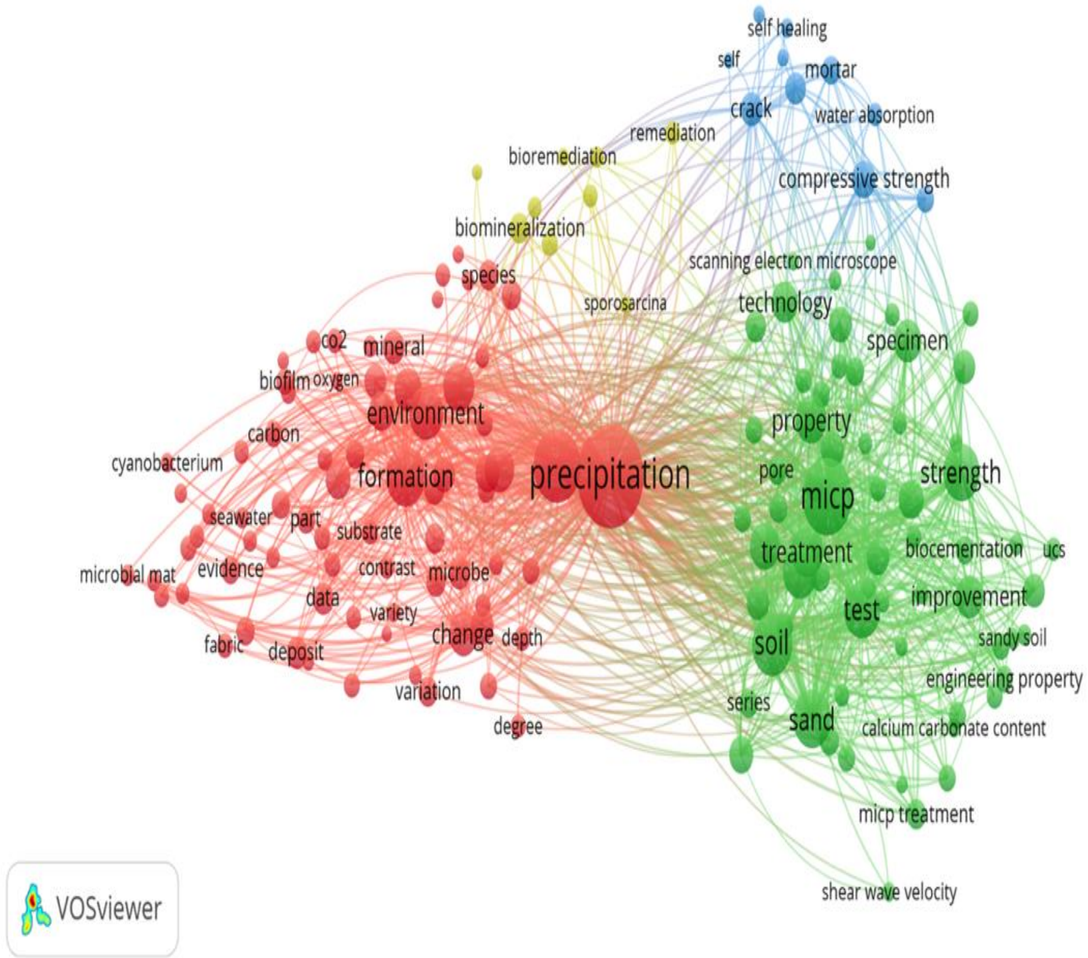

Fig. 9: Network visualization map of the high-frequency terms in the field of MICP. The online map is available at https://bit.ly/3IFp4r7

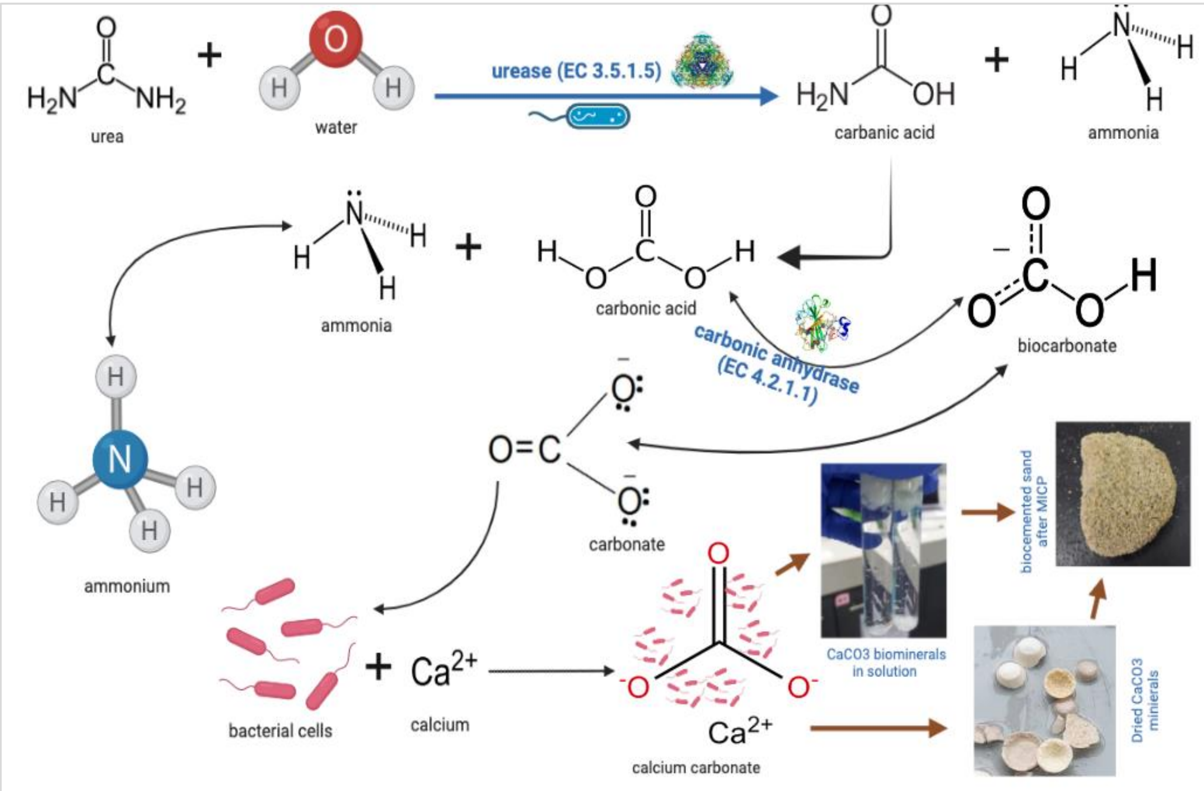

Fig. 10: A illustration of the MICP mechanism that enables $CaCO_3$ precipitation in solution and soil.

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Table 1: Total publications and citations on MICP research from the Scopus database.

Year	**Total publications**	**Total citations**	***h*-index**	**Articles cited (%)**
2021	170	215	7	46
2020	151	781	13	85
2019	154	1867	25	96
2018	94	1505	24	98
2017	73	1706	24	96
2016	65	1568	23	95
2015	52	1283	22	96
2014	57	1700	24	98
2013	45	2265	22	98
2012	39	2342	23	97
2011	25	1383	17	100
2010	18	1238	16	100
2009	25	1113	17	100
2008	19	1036	16	100
2007	17	1514	13	94
2006	15	1792	13	100
2005	7	201	7	100
2004	9	516	8	100
2003	10	1191	9	100
2002	4	366	4	100
2001	9	414	7	78

Table 2: List of top 10 most contributing countries in the field of MICP from 2001 to 2021

List	Countries	Total publications	Total citations	*h*-index	Publication of single country (%)	Normalized citations per article
1	China	290	4555	36	28	16
2	United States	229	8180	45	22	36
3	India	76	1577	20	7	21
4	United Kingdom	76	2463	27	7	32
5	Australia	67	2025	24	6	30
6	Japan	66	760	17	6	12
7	Germany	51	1068	16	5	21
8	South Korea	50	764	13	5	15
9	Iran	48	485	12	5	10
10	Spain	47	1658	23	4	35

Table 3: The top 10 most productive journals on MICP from 2001 to 2021 and their most cited articles

List	**Journal**	**TP**	**TC**	**NCPA**	**PCA**	**CiteScore (2020)**	**SJR (2020)**	**SNIP (2020)**	**Quartiles**	**HCA**	**CHCA**	**Publisher**
1	*Construction and Building Materials*	55	1352	25	95	8.8	1.7	2.5	Q1	Biogenic treatment improves the durability and remediates the cracks of concrete structures (Achal et al. 2013)	152	Elsevier Ltd.
2	*Geomicrobiology Journal*	38	1784	47	87	3.9	0.6	0.8	Q1	Microbial carbonate precipitation as a soil improvement technique (Whiffin et al. 2007)	886	Taylor & Francis Ltd.
3	*Journal of Geotechnical and Geoenvironmental Engineering*	36	2541	12	81	5.9	2.0	2.3	Q1	Microbially induced cementation to control sand response to undrained shear (DeJong et al. 2006)	833	American Society of Civil Engineers

4	*Journal of Materials in Civil Engineering*	24	426	20	75	4.7	1.1	1.4	Q1	Factors affecting improvement of engineering properties of MICP-treated soil catalyzed by bacteria and urease (Zhao et al. 2014)	158	American Society of Civil Engineers
5	*Sedimentary Geology*	20	481	24	90	5.3	1.2	1.4	Q1	Optimization of calcium-based bioclogging and biocementation of sand (Chu et al. 2014)	131	Elsevier Ltd.
6	*Acta Geotechnica*	20	528	26	100	6.4	2.2	2.6	Q1	Plausible mechanisms for the boring on carbonates by microbial phototrophs (Garcia-Pichel 2006)	89	Springer Nature
7	*Ecological Engineering*	19	1498	79	100	7.8	1.1	1.4	Q1	Fixation and distribution of bacterial activity in sand to induce carbonate precipitation for ground reinforcement (Harkes et al. 2010b)	363	Elsevier Ltd.
8	*Scientific Reports*	18	287	16	94	7.1	1.2	1.4	Q1	Red coral extinction risk enhanced by ocean acidification (Cerrano et al. 2013)	55	Springer Nature

9	*Sedimentology*	17	629	37	100	6.2	1.5	1.5	Q1	Microbially induced cementation of carbonate sands: Are micritic meniscus cements good indicators of vadose diagenesis? (Hillgärtner et al. 2001)	93	Wiley-Blackwell Publishing Ltd
10	*Chemical Geology*	14	530	38	100	6.4	1.5	1.4	Q1	Experimental and numerical modeling of bacterially induced pH increase and calcite precipitation in saline aquifers (Dupraz et al. 2009)	110	Elsevier Ltd.

Note: TP = Total publications; TC = Total citations; NCPA = Normalized citations per articles; PCA = Percentage of cited articles; SJR = Scimago journal ranking; SNIP = source normalized impact per paper; HCA = Highest cited article; CHCA = Citation of highest cited article

1109 **Table 4:** The top 10 most prolific authors on MICP from 2001 to 2021.

List	Author	TP	TC	PCA	*h*-index	YFP	Scopus author ID	Country	HCA	HCAC	Journal
1	Satoru Kawasaki	38	482	97	13	2013	54782723900	Japan	Bioremediation of lead-contaminated mine waste by *Pararhodobacter* sp. based on the microbially induced calcium carbonate precipitation technique and its effects on strength of coarse and fine grained sand (Mwandira et al. 2017)	47	*Ecological Engineering*
2	Jian Chu	31	993	90	15	2012	25026007400	Singapore	Microbially induced calcium carbonate precipitation on surface or in the bulk of soil (Chu et al. 2012)	215	*Geomicrobiology Journal*
3	Kazunori Nakashima	26	269	92	9	2017	7401504351	Japan	Bioremediation of lead-contaminated mine waste by	47	*Ecological Engineering*

									Pararhodobacter sp. based on the microbially induced calcium carbonate precipitation technique and its effects on strength of coarse and fine grained sand (Mwandira et al. 2017)		
4	Varenyam Achal	25	1510	96	18	2009	15076974200	China	Lactose mother liquor as an alternative nutrient source for microbial concrete production by *Sporosarcina pasteurii* (Achal et al. 2009)	168	*Journal of Industrial Microbiology and Biotechnology*
5	Liang Cheng	19	990	95	4	2010	55474102700	China	Cementation of sand soil by microbially induced calcite precipitation at various degrees of saturation (Cheng et al. 2013)	303	*Canadian Geotechnical Journal*

6	Chunxiang Qian	18	138	83	7	2010	7202310696	China	Loose sand particles cemented by different bio-phosphate and carbonate composite cement (Yu et al. 2016)	26	*Construction and Building Materials*
7	Abhijit Mukherjee	17	772	100	14	2009	56863660200	Australia	Lactose mother liquor as an alternative nutrient source for microbial concrete production by *Sporosarcina pasteurii* (Cheng et al. 2013)	168	*Journal of Industrial Microbiology and Biotechnology*
8	Robin Gerlach	16	459	100	10	2012	57189020312	United States	Potential CO_2 leakage reduction through biofilm-induced calcium carbonate precipitation (Phillips et al. 2013)	116	*Environmental Science and Technology*

9	Mondem Sudhakara Reddy	14	709	100	13	2009	19036075100	India	Lactose mother liquor as an alternative nutrient source for microbial concrete production by *Sporosarcina pasteurii* (Cheng et al. 2013)	168	*Journal of Industrial Microbiology and Biotechnology*
10	Lin Li	13	308	85	6	2014	55570965800	United States	Factors affecting improvement of engineering properties of MICP-treated soil catalyzed by bacteria and urease (Zhao et al. 2014)	156	*Journal of Materials in Civil Engineering*

Note: TP = Total publications; TC = Total citations; PCA = Percentage of cited articles; YFP = Year of first publication; HCA = Highest cited article; CHCA = Citation of highest cited article

1119 **Table 5:** The top 10 productive institutions on MICP research from 2001 to 2021.

List	Institution	Location (city and country)	TP	TC	*h*-index	PAC	HCA	HCAC	Journal
1	Nanyang Technological University	Singapore City, Singapore	39	1219	19	92	Microbially induced calcium carbonate precipitation on surface or in the bulk of soil (Chu et al. 2012)	215	*Geomicrobiology Journal*
2	Hokkaido University	Hokkaido, Japan	39	520	14	95	Bioremediation of lead-contaminated mine waste by *Pararhodobacter* sp. based on the microbially induced calcium carbonate precipitation technique and its effects on strength of coarse and fine grained sand (Mwandira et al. 2017)	47	*Ecological Engineering*
3	Southeast University	Jiangsu, China	37	363	11	81	Microbial induced carbonate precipitation for immobilizing Pb contaminants: Toxic effects	46	*Science of the Total Environment*

							on bacterial activity and immobilization efficiency (Jiang et al. 2019)		
4	Chinese Academy of Sciences	Beijing, China	37	1136	17	84	Biomineralization based remediation of As(III) contaminated soil by *Sporosarcina ginsengisoli* (Achal et al. 2012)	150	*Journal of Hazardous Materials*
5	Ministry of Education China	Beijing, China	26	491	12	88	Self-healing of concrete cracks by use of bacteria-containing low alkali cementitious material (Xu and Wang 2018)	78	*Construction and Building Materials*
6	University of California, Davis	California, United States of America	25	2082	16	96	Microbially induced cementation to control sand response to undrained shear (DeJong et al. 2006)	833	*Journal of Geotechnical and Geoenvironmental Engineering*
7	Curtin University	Perth, Australia	25	1211	16	92	Cementation of sand soil by microbially induced calcite	303	*Canadian Geotechnical Journal*

							precipitation at various degrees of saturation (Cheng et al. 2013)		
8	Montana State University	Montana, United States of America	21	572	13	100	Potential CO_2 leakage reduction through biofilm-induced calcium carbonate precipitation (Phillips et al. 2013)	116	*Environmental Science and Technology*
9	Arizona State University	Arizona, United States of America	19	478	11	89	Mechanical behavior of sands treated by microbially induced carbonate precipitation (Lin et al. 2016)	123	*Journal of Geotechnical and Geoenvironmental Engineering*
10	Universiteit Gent	Ghent, Belgium	19	810	11	79	Diatomaceous earth as a protective vehicle for bacteria applied for self-healing concrete (Mondal et al. 2020)	201	*Journal of Industrial Microbiology and Biotechnology*

Note: TP = Total publications; TC = Total citations; PCA = Percentage of cited article; HCA = Highest cited article; CHCA = Citation of highest cited article

Table 6: The top 10 funding sponsors for MICP research from 2001 to 2021

List	Funding sponsors	Country	TP	TC	*h*-index	PAC	HCA	HCAC	Journal
1	National Natural Science Foundation of China	China	186	2940	30	80	Heavy metal removal by biomineralization of urease producing bacteria isolated from soil (Li et al. 2013)	177	*International Biodeterioration and Biodegradation*
2	National Science Foundation	United States of America	80	1829	21	88	Urease activity in microbiologically-induced calcite precipitation (Bachmeier et al. 2002)	290	*Journal of Biotechnology*
3	Japan Society for the Promotion of Science	Japan	40	432	12	93	Bioremediation of lead-contaminated mine waste by *Pararhodobacter* sp. based on the microbially induced calcium carbonate precipitation technique and its effects on strength of coarse and fine grained sand (Mwandira et al. 2017)	47	*Ecological Engineering*

4	Ministry of Education, Culture, Sports, Science and Technology	Japan	33	347	12	94	Whole-cell evaluation of urease activity of *Pararhodobacter* sp. isolated from peripheral beachrock (Fujita et al. 2017)	30	*Biochemical Engineering Journal*
5	National Key Research and Development Program of China	China	30	374	9	77	Influence of cementation level on the strength behaviour of bio-cemented sand (Cui et al. 2017)	100	*Acta Geotechnica*
6	China Postdoctoral Science Foundation	China	29	383	9	86	Influence of cementation level on the strength behaviour of bio-cemented sand (Cui et al. 2017)	100	*Acta Geotechnica*
7	Ministry of Science and Technology of the People's Republic of China	China	25	473	12	92	Influence of cementation level on the strength behaviour of bio-cemented sand (Cui et al. 2017)	100	*Acta Geotechnica*
8	European Commission	Luxembourg	24	594	16	96	Application of microbially induced calcite precipitation in erosion mitigation and stabilisation of sandy soil	101	*Engineering Geology*

							foreshore slopes: A preliminary investigation (Salifu et al. 2016)		
9	National Research Foundation of Korea	Republic of Korea	22	334	8	77	Bioremediation of heavy metals by using bacterial mixtures (Kang et al. 2016)	118	*Ecological Engineering*
10	Engineering and Physical Sciences Research Council	United Kingdom	19	795	12	100	Factors affecting efficiency of microbially induced calcite precipitation (Qabany et al. 2012)	27	*Journal of Geotechnical and Geoenvironmental Engineering*

Note: TP = Total publications; TC = Total citations; PCA = Percentage of cited articles; HCA = Highest cited article; CHCA = Citation of highest cited article

Supplementary information

Table 01: Summary of query strings used to search for bibliometric data from Scopus

Retrieval strategy	**Query string**	**Document results**
General search	(TITLE-ABS-KEY (microbially AND induced AND carbonate AND precipitation*) OR TITLE-ABS-KEY (microbially AND induced AND calcite AND precipitation*) OR TITLE-ABS-KEY (microbiological AND precipitation AND of AND caco3*) OR TITLE-ABS-KEY (microbially AND induce AND calcium AND carbonate AND precipitation*) OR TITLE-ABS-KEY (biocalcification*) OR TITLE-ABS-KEY (bacterially AND induced AND carbonate AND mineralization*) OR TITLE-ABS-KEY (biomediated AND calcite AND precipitation*) OR TITLE-ABS-KEY (calcifying AND microorganism*) OR TITLE-ABS-KEY (biocalcifying AND bacteria*) OR TITLE-ABS-KEY (microorganisms AND induce AND calcium AND carbonate AND precipitation*) OR TITLE-ABS-KEY (microbial AND carbonate AND precipitation) OR TITLE-ABS-KEY (bioprecipitation AND of AND calcium AND carbonate))	2942
Narrowing	(TITLE-ABS-KEY (microbially AND induced AND carbonate AND precipitation*) OR TITLE-ABS-KEY (microbially AND induced AND calcite AND precipitation*) OR TITLE-ABS-KEY (microbiological AND precipitation AND of AND caco3*) OR TITLE-ABS-KEY (microbially AND induce AND calcium AND carbonate AND precipitation*) OR TITLE-ABS-	2198

	KEY (biocalcification*) OR TITLE-ABS-KEY (bacterially AND induced AND carbonate AND mineralization*) OR TITLE-ABS-KEY (biomediated AND calcite AND precipitation*) OR TITLE-ABS-KEY (calcifying AND microorganism*) OR TITLE-ABS-KEY (biocalcifying AND bacteria*) OR TITLE-ABS-KEY (microorganisms AND induce AND calcium AND carbonate AND precipitation*) OR TITLE-ABS-KEY (microbial AND carbonate AND precipitation) OR TITLE-ABS-KEY (bioprecipitation AND of AND calcium AND carbonate)) AND (EXCLUDE (PUBYEAR , 2000) OR EXCLUDE (PUBYEAR , 1999) OR EXCLUDE (PUBYEAR , 1998) OR EXCLUDE (PUBYEAR , 1997) OR EXCLUDE (PUBYEAR , 1996) OR EXCLUDE (PUBYEAR , 1995) OR EXCLUDE (PUBYEAR , 1994) OR EXCLUDE (PUBYEAR , 1993) OR EXCLUDE (PUBYEAR , 1992) OR EXCLUDE (PUBYEAR , 1991) OR EXCLUDE (PUBYEAR , 1990) OR EXCLUDE (PUBYEAR , 1989) OR EXCLUDE (PUBYEAR , 1988) OR EXCLUDE (PUBYEAR , 1987) OR EXCLUDE (PUBYEAR , 1986) OR EXCLUDE (PUBYEAR , 1985) OR EXCLUDE (PUBYEAR , 1984) OR EXCLUDE (PUBYEAR , 1983) OR EXCLUDE (PUBYEAR , 1979) OR EXCLUDE (PUBYEAR , 1977) OR EXCLUDE (PUBYEAR , 1976) OR EXCLUDE (PUBYEAR , 1975) OR EXCLUDE (PUBYEAR , 1974) OR EXCLUDE (PUBYEAR , 1972)) AND (EXCLUDE (LANGUAGE , "Chinese") OR EXCLUDE (LANGUAGE , "Spanish") OR EXCLUDE (LANGUAGE , "Hungarian") OR EXCLUDE (LANGUAGE , "Portuguese") OR EXCLUDE (LANGUAGE , "French") OR EXCLUDE (LANGUAGE , "Polish") OR EXCLUDE (LANGUAGE , "Czech") OR EXCLUDE (LANGUAGE , "Estonian") OR EXCLUDE (LANGUAGE , "Japanese")) AND (EXCLUDE (LANGUAGE , "Persian") OR EXCLUDE (LANGUAGE , "Russian") OR EXCLUDE (LANGUAGE , "Turkish")) AND (EXCLUDE (DOCTYPE , "cp") OR EXCLUDE (DOCTYPE , "ch")	

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Remove all potential 2022 publication.	(TITLE-ABS-KEY (microbially AND induced AND carbonate AND precipitation*) OR TITLE-ABS-KEY (microbially AND induced AND calcite AND precipitation*) OR TITLE-ABS-KEY (microbiological AND precipitation AND of AND caco3*) OR TITLE-ABS-KEY (microbially AND induce AND calcium AND carbonate AND precipitation*) OR TITLE-ABS-KEY (biocalcification*) OR TITLE-ABS-KEY (bacterially AND induced AND carbonate AND mineralization*) OR TITLE-ABS-KEY (biomediated AND calcite AND precipitation*) OR TITLE-ABS-KEY (calcifying AND microorganism*) OR TITLE-ABS-KEY (biocalcifying AND bacteria*) OR TITLE-ABS-KEY (microorganisms AND induce AND calcium AND carbonate AND precipitation*) OR TITLE-ABS-KEY (microbial AND carbonate AND precipitation) OR TITLE-ABS-KEY (bioprecipitation AND of AND calcium AND carbonate)) AND NOT EID (2-s2.0-9344256654) AND NOT EID (2-s2.0-70349307412) AND NOT EID (2-s2.0-74149091993) AND NOT EID (2-s2.0-23944443706) AND NOT EID (2-s2.0-4444274902) AND NOT EID (2-s2.0-84904874863) AND NOT EID (2-s2.0-10044230606) AND NOT EID (2-s2.0-85036480437) AND NOT EID (2-s2.0-84959264662) AND NOT EID (2-s2.0-84880011137) AND NOT EID (2-s2.0-67649880645) AND NOT EID (2-s2.0-84939955108) AND NOT EID (2-s2.0-79958148413) AND NOT EID (2-s2.0-	2106

	85019838157) AND NOT EID (2-s2.0-84955593660) AND NOT EID (2-s2.0-33747501039) AND NOT EID (2-s2.0-78650852367) AND NOT EID (2-s2.0-0041663572) AND NOT EID (2-s2.0-84960443515) AND NOT EID (2-s2.0-84960871885) AND NOT EID (2-s2.0-84989767537) AND NOT EID (2-s2.0-85029154829) AND NOT EID (2-s2.0-84929413140) AND NOT EID (2-s2.0-84904876263) AND NOT EID (2-s2.0-84871518046) AND NOT EID (2-s2.0-77954199412) AND NOT EID (2-s2.0-85042596806) AND NOT EID (2-s2.0-84977581036) AND NOT EID (2-s2.0-72449153869) AND NOT EID (2-s2.0-85090914272) AND NOT EID (2-s2.0-84983780708) AND NOT EID (2-s2.0-85026896337) AND NOT EID (2-s2.0-84879868481) AND NOT EID (2-s2.0-85065698556) AND NOT EID (2-s2.0-85069531897) AND NOT EID (2-s2.0-84875273879) AND NOT EID (2-s2.0-85080091873) AND NOT EID (2-s2.0-84945304051) AND NOT EID (2-s2.0-85069695839) AND NOT EID (2-s2.0-85039450097) AND NOT EID (2-s2.0-85057243899) AND NOT EID (2-s2.0-17644374135) AND NOT EID (2-s2.0-84899835461) AND NOT EID (2-s2.0-85061334535) AND NOT EID (2-s2.0-85055906842 AND 2-s2.0-30344461328) AND NOT EID (2-s2.0-85081656917) AND NOT EID (2-s2.0-85065720160) AND NOT EID (2-s2.0-85094979113) AND NOT EID (2-s2.0-85078656192) AND NOT EID (2-s2.0-85095789457) AND NOT EID (2-s2.0-85083403083) AND NOT EID (2-s2.0-85063369465) AND NOT EID (2-s2.0-63249121479) AND NOT EID (2-s2.0-85084958099) AND NOT EID (2-s2.0-85053527817) AND NOT EID (2-s2.0-85010754782) AND NOT EID (2-s2.0-85091107686) AND NOT EID (2-s2.0-85082797698) AND NOT EID (2-s2.0-85070333302) AND NOT EID (2-s2.0-85093892040) AND NOT EID (2-s2.0-85087684494) AND NOT EID (2-s2.0-85067872930) AND NOT EID (2-s2.0-85088642851) AND NOT EID (2-s2.0-84939505837) AND NOT EID (2-s2.0-85088835482) AND NOT EID (2-s2.0-85081282658) AND NOT EID (2-s2.0-85033364992) AND NOT EID (2-s2.0-85103969970) AND NOT EID (2-s2.0-85107762354) AND NOT EID (2-s2.0-	

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	NOT EID (*2-s2.0-85042596806*) AND NOT EID (*2-s2.0-84977581036*) AND NOT EID (*2-s2.0-72449153869*) AND NOT EID (*2-s2.0-85090914272*) AND NOT EID (*2-s2.0-84983780708*) AND NOT EID (*2-s2.0-85026896337*) AND NOT EID (*2-s2.0-84879868481*) AND NOT EID (*2-s2.0-85065698556*) AND NOT EID (*2-s2.0-85069531897*) AND NOT EID (*2-s2.0-84875273879*) AND NOT EID (*2-s2.0-85080091873*) AND NOT EID (*2-s2.0-84945304051*) AND NOT EID (*2-s2.0-85069695839*) AND NOT EID (*2-s2.0-85039450097*) AND NOT EID (*2-s2.0-85057243899*) AND NOT EID (*2-s2.0-17644374135*) AND NOT EID (*2-s2.0-84899835461*) AND NOT EID (*2-s2.0-85061334535*) AND NOT EID (*2-s2.0-85055906842* AND *2-s2.0-30344461328*) AND NOT EID (*2-s2.0-85081656917*) AND NOT EID (*2-s2.0-85065720160*) AND NOT EID (*2-s2.0-85094979113*) AND NOT EID (*2-s2.0-85078656192*) AND NOT EID (*2-s2.0-85095789457*) AND NOT EID (*2-s2.0-85083403083*) AND NOT EID (*2-s2.0-85063369465*) AND NOT EID (*2-s2.0-63249121479*) AND NOT EID (*2-s2.0-85084958099*) AND NOT EID (*2-s2.0-85053527817*) AND NOT EID (*2-s2.0-85010754782*) AND NOT EID (*2-s2.0-85091107686*) AND NOT EID (*2-s2.0-85082797698*) AND NOT EID (*2-s2.0-85070333302*) AND NOT EID (*2-s2.0-85093892040*) AND NOT EID (*2-s2.0-85087684494*) AND NOT EID (*2-s2.0-85067872930*) AND NOT EID (*2-s2.0-85088642851*) AND NOT EID (*2-s2.0-84939505837*) AND NOT EID (*2-s2.0-85088835482*) AND NOT EID (*2-s2.0-85081282658*) AND NOT EID (*2-s2.0-85033364992*) AND NOT EID (*2-s2.0-85103969970*) AND NOT EID (*2-s2.0-85107762354*) AND NOT EID (*2-s2.0-85088787764*) AND NOT EID (*2-s2.0-85109012219*) AND NOT EID (*2-s2.0-85105290941*) AND NOT EID (*2-s2.0-85111075936*) AND NOT EID (*2-s2.0-85106248904*) AND NOT EID (*2-s2.0-85098202097*) AND NOT EID (*2-s2.0-85098594961*) AND NOT EID (*2-s2.0-85078097807*) AND NOT EID (*2-s2.0-29544433319*) AND NOT EID (*2-s2.0-85115322102*) AND NOT EID (*2-s2.0-85114614533*) AND NOT EID (*2-s2.0-85114035314*) AND NOT EID (*2-s2.0-85109171942*) AND NOT EID (*2-s2.0-*	

	85111298808) AND NOT EID (2-s2.0-85108813421) AND NOT EID (2-s2.0-85108376819) AND NOT EID (2-s2.0-85105335454) AND NOT EID (2-s2.0-85109428396) AND NOT EID (2-s2.0-85100552760) AND NOT EID (2-s2.0-85055906842) AND NOT EID (2-s2.0-30344461328) AND NOT EID (2-s2.0-85109145028) AND NOT EID (2-s2.0-85108792484) AND NOT EID (2-s2.0-85104286443) AND NOT EID (2-s2.0-85089476071) AND NOT EID (2-s2.0-85079815345) AND NOT EID (2-s2.0-85077710074) AND NOT EID (2-s2.0-85017116349) AND NOT EID (2-s2.0-84991674455) AND NOT EID (2-s2.0-84957541927) AND NOT EID (2-s2.0-85042666061) AND NOT EID (2-s2.0-84907142114) AND NOT EID (2-s2.0-79951826157) AND NOT EID (2-s2.0-79955027044) AND NOT EID (2-s2.0-77952243417) AND NOT EID (2-s2.0-67349158614) AND NOT EID (2-s2.0-46749142616) AND NOT EID (2-s2.0-0344961678) AND NOT EID (2-s2.0-0141460749) AND NOT EID (2-s2.0-0038666002) AND NOT EID (2-s2.0-0034799674) AND NOT EID (2-s2.0-84912567983) AND NOT EID (2-s2.0-77956608553) AND NOT EID (2-s2.0-85027943519) AND NOT EID (2-s2.0-84969814747) AND NOT EID (2-s2.0-84876181933) AND NOT EID (2-s2.0-58149202327) AND NOT EID (2-s2.0-74149092972) AND NOT EID (2-s2.0-74149092972) AND NOT EID (2-s2.0-84907355788) AND NOT EID (2-s2.0-70349307412) AND NOT (methane*) AND NOT (sulfur*) AND NOT (iron*) AND NOT (sulphur*) AND NOT EID (2-s2.0-1542289624) AND NOT EID (2-s2.0-74149091659) AND NOT EID (2-s2.0-58149512789) AND NOT EID (2-s2.0-1342287541) AND NOT EID (2-s2.0-33646571600) AND NOT EID (2-s2.0-0036903708) AND NOT EID (2-s2.0-0034926098) AND NOT EID (2-s2.0-36849065807) AND NOT EID (2-s2.0-33645050414) AND NOT EID (2-s2.0-84894438505) AND NOT EID (2-s2.0-74949100157) AND NOT EID (2-s2.0 60949110770) AND NOT EID (2-s2.0-51149109798) AND NOT EID (2-s2.0-84957831081) AND NOT EID (2-s2.0-19944414704) AND NOT EID (2-s2.0-38949188610) AND NOT EID (2-s2.0-84856966005) AND	

	NOT EID (*2-s2.0-70350125582*) AND NOT EID (*2-s2.0-84982208063*) AND NOT EID (*2-s2.0-74549224540*) AND	
	NOT EID (*2-s2.0-84920381694*) AND NOT EID (*2-s2.0-52249097030*) AND NOT EID (*2-s2.0-0037438930*) AND	
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	NOT EID (*2-s2.0-80053937530*) AND NOT EID (*2-s2.0-84455171980*) AND NOT EID (*2-s2.0-80051581245*) AND	
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	NOT EID (*2-s2.0-84863797991*) AND NOT EID (*2-s2.0-0142137633*) AND NOT EID (*2-s2.0-534425967*) AND	
	NOT EID (*2-s2.0-77954014929*) AND NOT EID (*2-s2.0-84934880038*) AND NOT EID (*2-s2.0-84871118664*) AND	
	NOT EID (*2-s2.0-84884371876*) AND NOT EID (*2-s2.0-33645277822*) AND NOT EID (*2-s2.0-4243148638*) AND	
	NOT EID (*2-s2.0-4544239539*) AND NOT EID (*2-s2.0-84872672407*) AND NOT EID (*2-s2.0-84979834020*) AND	
	NOT EID (*2-s2.0-84902674931*) AND NOT EID (*2-s2.0-76049118701*) AND NOT EID (*2-s2.0-24944529003*) AND	
	NOT EID (*2-s2.0-84951193642*) AND NOT EID (*2-s2.0-84926431933*) AND NOT EID (*2-s2.0-84876497085*) AND	
	NOT EID (*2-s2.0-84876497085*) AND NOT EID (*2-s2.0-84924239362*) AND NOT EID (*2-s2.0-61349195135*) AND	
	NOT EID (*2-s2.0-85064262930*) AND NOT EID (*2-s2.0-84983387624*) AND NOT EID (*2-s2.0-84896727556*) AND	
	NOT EID (*2-s2.0-70349987110*) AND NOT EID (*2-s2.0-41149172498*) AND NOT EID (*2-s2.0-81555199303*) AND	
	NOT EID (*2-s2.0-36349021848*) AND NOT EID (*2-s2.0-0036800835*) AND NOT EID (*2-s2.0-85072013477*) AND	
	NOT EID (*2-s2.0-85059469578*) AND NOT EID (*2-s2.0-85044870065*) AND NOT EID (*2-s2.0-84975889691*) AND	

	NOT EID (*2-s2.0-84913549625*) AND NOT EID (*2-s2.0-84938542221*) AND NOT EID (*2-s2.0-84891521507*) AND NOT EID (*2-s2.0-84870388290*) AND NOT EID (*2-s2.0-70849120192*) AND NOT EID (*2-s2.0-33744471377*) AND NOT EID (*2-s2.0-85064408658*) AND NOT EID (*2-s2.0-0035246242*) AND NOT EID (*2-s2.0-0041418444*) AND NOT EID (*2-s2.0-85111481609*) AND NOT EID (*2-s2.0-85077943903*) AND NOT EID (*2-s2.0-85105629411*) AND NOT EID (*2-s2.0-85075916537*) AND NOT EID (*2-s2.0-85065388870*) AND NOT EID (*2-s2.0-0000960909*) AND NOT EID (*2-s2.0-0036319901*) AND NOT EID (*2-s2.0-34247561338*) AND NOT EID (*2-s2.0-85095948097*) AND NOT EID (*2-s2.0-85088836419*) AND NOT EID (*2-s2.0-84858009912*) AND NOT EID (*2-s2.0-84857030312*) AND NOT EID (*2-s2.0-84856321942*) AND NOT EID (*2-s2.0-84874517907*) AND NOT EID (*2-s2.0-84874517907*) AND NOT EID (*2-s2.0-84919644173*) AND NOT EID (*2-s2.0-77956892577*) AND NOT EID (*2-s2.0-85074007715*) AND NOT EID (*2-s2.0-* *84896547597*) AND (EXCLUDE (SRCTYPE , *"k"*) OR EXCLUDE (SRCTYPE , *"d"*) OR EXCLUDE (SRCTYPE , *"p"*)) AND (EXCLUDE (PUBSTAGE , *"aip"*)) AND (EXCLUDE (DOCTYPE , *"cp"*) OR EXCLUDE (DOCTYPE , *"ch"*) OR EXCLUDE (DOCTYPE , *"cr"*) OR EXCLUDE (DOCTYPE , *"no"*) OR EXCLUDE (DOCTYPE , *"er"*) OR EXCL UDE (DOCTYPE , *"ed"*) OR EXCLUDE (DOCTYPE , *"bk"*) OR EXCLUDE (DOCTYPE , *"sh"*) OR EXCLUDE (DOC TYPE , *"tb"*)) AND (EXCLUDE (PUBYEAR , *2000*) OR EXCLUDE (PUBYEAR , *1999*) OR EXCLUDE (PUBYEAR , *1998*) OR EXCLUDE (PUBYEAR , *1997*) OR EXCLUDE (PUBYEAR , *1996*) OR EXCLUDE (PUBYEAR , *1995*) OR EXCLUDE (PUBYEAR , *1994*) OR EXCLUDE (PUBYEAR , *1993*) OR EXCLUDE (PUBYEAR , *1992*) OR EXC LUDE (PUBYEAR , *1991*) OR EXCLUDE (PUBYEAR , *1990*) OR EXCLUDE (PUBYEAR , *1989*) OR EXCLUDE (P UBYEAR , *1988*) OR EXCLUDE (PUBYEAR , *1987*) OR EXCLUDE (PUBYEAR , *1986*) OR EXCLUDE (PUBYEAR	

	, *1985*) OR EXCLUDE (PUBYEAR , *1984*) OR EXCLUDE (PUBYEAR , *1983*) OR EXCLUDE (PUBYEAR , *1979*) OR EXCLUDE (PUBYEAR , *1977*) OR EXCLUDE (PUBYEAR , *1976*) OR EXCLUDE (PUBYEAR , *1975*) OR EXCLUDE (PUBYEAR , *1974*) OR EXCLUDE (PUBYEAR , *1972*) OR EXCLUDE (PUBYEAR , *2022*)) AND (EXCLUDE (LANGUAGE , *"Chinese"*) OR EXCLUDE (LANGUAGE , *"Spanish"*) OR EXCLUDE (LANGUAGE , *"Hungarian"*) OR EXCLUDE (LANGUAGE , *"Portuguese"*) OR EXCLUDE (LANGUAGE , *"French"*) OR EXCLUDE (LANGUAGE , *"Polish"*) OR EXCLUDE (LANGUAGE , *"Czech"*) OR EXCLUDE (LANGUAGE , *"Estonian"*) OR EXCLUDE (LANGUAGE , *"Japanese"*) OR EXCLUDE (LANGUAGE , *"Persian"*) OR EXCLUDE (LANGUAGE , *"Russian"*) OR EXCLUDE (LANGUAGE , *"Turkish"*))	