sustainability

MDPI

Article

Global Scientific Research and Trends Regarding Microbial Induced Calcite Precipitation: A Bibliometric Network Analysis

Mazhar Ali Jarwar [1,*], Stefano Dumontet [1], Rosa Anna Nastro [1], M. Esther Sanz-Montero [2] and Vincenzo Pasquale [1]

[1] Laboratory of Environmental Microbiology, Department of Science and Technology, Parthenope University of Naples, Centro Direzionale, Isola C4, 80143 Naples, Italy
[2] Department of Mineralogy and Petrology, University Complutense Madrid, 28040 Madrid, Spain
* Correspondence: mazharali.jarwar001@studenti.uniparthenope.it

Abstract: Microbial induced calcite precipitation (MICP) offers a host of interesting features, from both theoretical and practical standpoints. This process was firstly investigated as a geo-biological mechanism involved in carbonate mineral formation in both rocks and soil. The interest in its practical use has significantly increased in recent years, as MICP has been used in different fields, such as oil recovery, the improvement of soil geotechnical characteristics, and concrete healing. To the best of our knowledge, this work is the first attempt to carry out a bibliometric descriptive study of publications concerning MICP. We analyzed data from the Web of Science Core Collection (WoSCC), which provides comprehensive information for bibliometric analysis, including the Science Citation Index Expanded (SCI-E) and the Social Sciences Citation Index (SSCI). The bibliometric analysis was carried out on 1580 publications, from 2000 to August 2022, and included publication output; author; institution; country; collaborations between authors, institutes, and countries; and citation frequency. We created visualization maps, including research collaborations, using the VOSviewer program. MICP, carbonate precipitation, cementation, and soil improvement in terms of geotechnical properties are frequently used keywords. Although in the year 2000, only two papers were published on MICP, the number of publications has increased rapidly since 2014. In 2021, 333 papers were published. China leads the pack as the most productive country, followed by the USA and Australia. According to our results, the number of research papers has dramatically increased in the last 5 years. MICP use for concrete healing/cementation and soil geotechnical improvement, as well as the low environmental impact of such a technique, are becoming very popular topics among researchers. With the aging of concrete buildings, as well as with the worsening of environmental pollution and soil alterations, the research regarding MICP will play an ever increasing and crucial role in civil engineering and geotechnical fields, as well as in soil science. MICP also address Sustainable Development Goal 11, "building sustainable cities and communities." Nevertheless, our study pointed out a concentration of the MICP studies in just a few countries. Russia and Brazil, for instance, seem to poorly contribute to MICP research. Greater cooperation among countries, along with the extension of the research network on this topic, would foster more rapid progress in MICP studies, from both practical and speculative standpoints.

Keywords: environment; carbonate minerals; bibliometric analysis; VOSviewer; calcite precipitation

check for updates

Citation: Jarwar, M.A.; Dumontet, S.; Nastro, R.A.; Sanz-Montero, M.E.; Pasquale, V. Global Scientific Research and Trends Regarding Microbial Induced Calcite Precipitation: A Bibliometric Network Analysis. *Sustainability* **2022**, *14*, 16114. https://doi.org/10.3390/su142316114

Academic Editors: Jie Li, Jie Xue, Dengsheng Wu and Xiaolong Zheng

Received: 17 October 2022
Accepted: 30 November 2022
Published: 2 December 2022

1. Introduction

Carbonates represent a major reservoir of carbon on the Earth (about 41.9% of the total carbon on our planet) and microbially induced calcite precipitation (MICP) plays a prominent role within the global carbon cycle [1]. The study of the role of microbial mineral precipitation in a natural environment takes place at the interface between microbiology and geology and includes the understanding of both autotrophic and heterotrophic metabolic pathways. MICP played a crucial role in mineral deposition during geological eras, as proved by the geological record [2–4]. Calcium carbonate minerals forming stalactites, stalagmites, microbialites, stromatolites, and thrombolites represent examples of minerals produced by the activities of microorganisms, and the overall effect of such a microbial activity extends up to landscapes morphology [2,4].

The first published paper dealing with the ability of bacteria to induce carbonate precipitation dates back to the early 19th century [5]. Later, the ability to precipitate $CaCO_3$ has been considered as a general phenotype among bacteria [6,7]. According to Dupraz et al. [2], MICP includes two different processes: microbially induced mineralization (where metabolic activities of living microorganisms induce conditions for mineral precipitation), and biologically influenced mineralization (where dead or metabolically inactive microbial cells, along with environmental factors, lead to a passive precipitation of minerals).

The precipitation of Ca carbonates and, in general, of Ca minerals, is shared among different domains of microorganisms other than bacteria. Cyanobacteria [3,5,8], fungi [9], algae [10–12], and even some vascular plants have been proved to be involved in calcite precipitation [13]. Altermann et al. [14] estimated that cyanobacteria have been the main contributors to the production of carbonate rocks during nearly 70% of the Earth's history. Since then, the importance of cyanobacteria in carbonation has been extensively investigated, with particular regards to the molecular mechanisms driving calcite precipitation in *Synechocystis* spp and *Synecococchus* spp [3,5]. Over the years, *Bacillus subtilis, Pseudomonas nitroreducens*, and *Bacillus licheniformis*, *Bacillus megaterium, Sporosarcina pasteurii* [15–17] became the most studied bacteria, and have been widely used in practical applications for soil consolidation and concreate healing due to their ability to produce high amounts of calcite within a short period of time [16,18–20].

Since 2000, the relevance of MICP in the wider frameworks of environmental microbiology and engineering applications has greatly increased. Some significant studies involving microbial induced calcite precipitation, applied to the geotechnical improvement of soil and concrete healing, have been published within the first decade of the 2000s [21–26]. The interest in the potential geotechnical use of MICP is currently growing, and it is fueling research in the field of soil consolidation and the use of microorganism in concrete healing. Bu et al. [27] reviewed MICP soil improvement, discussing in detail the mineralization mechanism, its technological importance, and its effects on soil with different characteristics. As the concrete healing process through MICP is strongly dependent on the metabolic characteristics of the microorganism involved in the process, many current studies are focused on finding microbial strains with highly calcite-precipitating properties. Of particular interest is the work of Sohail et al. [28], who investigated the self-healing process in concrete through microbial induced calcite precipitation (MICP) carried out by a strain of *Bacillus cereus* isolated from soil in Qatar. However, soil stabilization, as well as biocementation, are not the only topics boosting the interest in MICP. MICP also addresses the United Nations Sustainable Development Goal 11, "building sustainable cities and communities" [29]. Such an interest spans a wide range of topics, from the role of MICP in fossil formation and the preservation of traces of life in ancient rocks, to the contribution of microorganisms to ancient and modern geochemical cycles of C and Ca, to the investigation of new methods to capture and store carbon, to the removal of heavy metal pollutants or radionuclides (e.g., Ra, Sr.) from environmental samples through co-precipitation with $CaCO_3$, to the use of carbonate biominerals to enhance oil recovery [5].

The conspicuous number of studies and review articles concerning MICP and its practical applications makes it necessary to organize, summarize, and quantify the recent developments in the field in order to have a clear overall picture of the present state, as well as the future directions of the research. Bibliometric analysis, defined as the use of mathematical methods to analyze published articles in terms of quantity, quality, and impact, is an important and common method used to assess research activity on a certain topic [30]. Further, it has proved to be a useful tool to quantitatively assess trends and patterns of scientific literature [31,32]. Bibliometric analysis can help to interpret the research trend and the development status by assessing the authors, institutions, countries, and link strength based on keywords associated with publications, paving a pathway for future studies [32,33].

Even though bibliometric analysis has been widely used in the field of environmental sciences, very few studies focus on environmental microbiology or geomicrobiology. Some examples of bibliometric analysis in the field of microbial ecology are given by Qi et al. [34], who analyzed the research status and development trend of algae-bacteria symbiotic wastewater treatment technology between 1998 and 2017, and of Vanzetto and Thome [35], who investigated the toxicology of nanoscale zero valent iron used in soil remediation by bibliometric analysis. However, to best of our knowledge, no studies have yet attempted to analyze the structure, links, and future research avenues in regards to MICP. This paper aims at exploring the scientific literature on MICP based on keywords analysis; the most productive authors; the most cited published paper; the most productive institutes and countries; collaboration between authors, countries, and institutes; as well as to highlight the interest of the scientific journals in this topic over the past 22 years.

2. Materials and Methods

2.1. Data Source

Scientific output data was extracted from the Web of Science Core Collection (WoSCC), one of the most widely used daily updated databases in academic and bibliometric studies, allowing the download of full citation records [36]. WoSCC can provide comprehensive information for bibliometric analysis, including the Science Citation Index Expanded (SCI-E) and the Social Sciences Citation Index (SSCI). In this study, the WoSCC database was used to retrieve the related research on microbial induced calcite precipitation (MICP) for the period from 2000 to 2022, filtered within the scope and research based strictly on MICP. The language of the analyzed papers is limited to English, with an overall number of 1580 publications. We downloaded and exported the collected data (which included full records) in text format for further analysis. All data were exported on 30 August 2022, to avoid deviations caused by the daily updates of this database.

2.2. Bibliometric Network Analysis

We performed the study of the global scientific research and trends regarding MICP through a bibliometric network analysis carried out according to Reuters [37]. We based our study on the visualized analysis of mapping knowledge domain (MDK) and on the implementation of a social network analysis (SNA) [38]. While MKD can be used to establish a reference information and research basis for the application and development of methods of a chosen domain, SNA is defined as the process of investigating social structures using networks and the graph theory [31,38]. SNA and maps based on network data allow the application of systems thinking in bibliometric science. The outputs of such analysis are network maps and statistics based on the relationships among countries, journals, organizations, authors, and keywords related to the investigated topic [39].

In this study, we used the VOSviewer software (version 1.6.18) to perform the bibliometric analysis. This software, using the VOS (visualization of similarities) mapping technique, is especially useful for displaying large bibliometric maps in an easy-to-interpret way, while allowing the creation and exploration of maps based on bibliometric network data. The output results are displayed in clusters to visualize the existing connections among the analyzed bibliometric data. VOSviewer software is a useful tool for the elaboration of distance-based maps in which the distance between two items reflects the strength of the relationship between the items. Unlike graph-based maps, in distance-based maps, a smaller distance generally indicates a stronger relationship [40].

Table 1 summarizes the main technical terms used by the software. We implemented co-authorship, co-occurrence, and citation analyses to create distance-based network maps showing: (1) the co-authorship among researchers and the collaborations of countries, (2) the co-occurrence of keywords, and (3) cited scientific journals.

Table 1. Terminology used by VOS viewer software version 1.6.18 [41].

Term	Description
Items	Objects of interest (e.g., publications, researchers, keywords, authors).
Link	Connection or relationship between two items (e.g., co-occurrence of keywords).
Link strength	Attribute of each link, expressed by a positive numerical value. In the case of co-authorship links, the higherthe value, the higher the number of publications the two researchers have co-authored.
Network	Set of items connected by their links.
Cluster	Sets of items included in a map. One item can belong to only one cluster.
Number of links	The number of links of an item with other items
Total link strength	The cumulative strength of the links of an item with other items.

3. Results and Discussion

3.1. Document Types

As of 30 August 2022, 1580 articles related to MICP were identified and classified into eight document types indexed in the Web of Science (Table 2). The article was the most frequently used document type, consisting of 86.01% of the total publications, followed by conference proceeding papers (11.13%). Review papers contributed 4.11%, early access, 1.9%; book chapters, 0.06%; editorial materials, 0.31%; and meeting abstracts 0.06%, all of which showed lower numbers than articles and conference proceedings. It is obvious that the articles and conference proceedings, with the largest proportion of results, may satisfactorily reflect the development trends and changes in this research field. Some research reports on original works were classified as article and proceedings at the same time, which caused the sum of the percentile of all types to be greater than 100%.

Table 2. Types of publications concerning microbial induced calcite precipitation (MICP) from 2000 to August 2022.

Rank	Document Types	Numbers	Percentage (%)
1	Articles	1359	86.013
2	Proceedings Papers	176	11.139
3	Review Articles	65	4.114
4	Early Access	30	1.9
5	Book Chapters	1	0.063
6	Editorial Materials	5	0.316
8	Meeting Abstracts	1	0.063

3.2. Publications and Citations Trend Analysis

The Web of Science database search resulted in 1580 publications on "MICP" in the period from 2000 to 31 August 2022 (date on which the analysis was performed). Both the cumulative citation index and number of publications show an increasing trend in the investigated timeframe. Over the last 10 years, the number of publications has increased significantly, and the topic of calcite precipitation has been studied more frequently. From the year 2000 to 2015, as it can be seen in Figure 1, the number of publications dramatically increased and therefore, so do the citations. In 2010, only 10 papers were published on the topic of MICP, but in 2021, 333 papers were published worldwide covering this topic, proving the emerging importance of MICP.

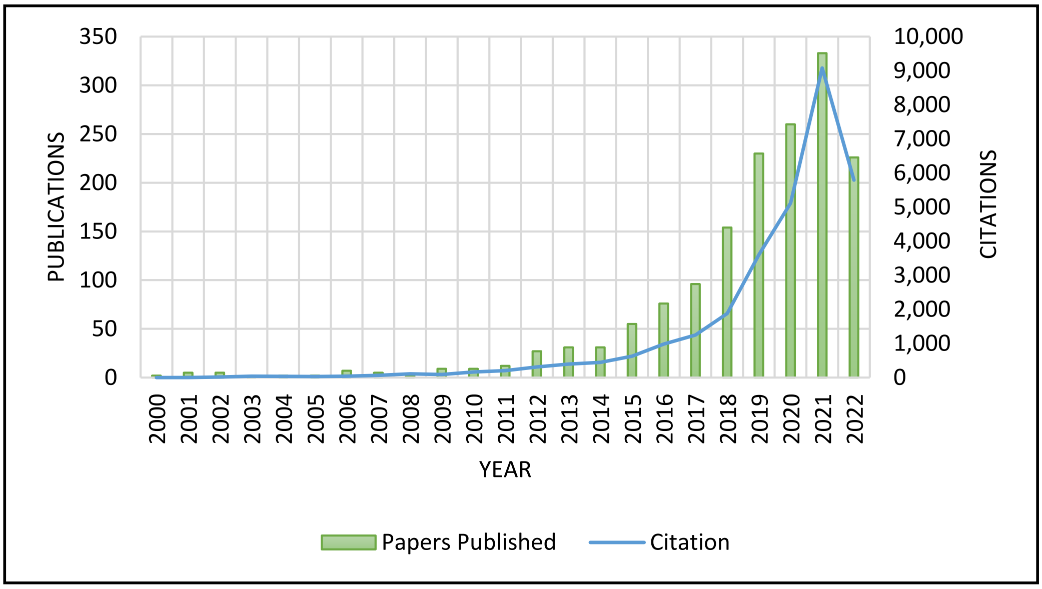

Figure 1. Number of publications and citations in the field of MICP from 2000 to August 2022.

3.3. Countries and Collaborations Network Analysis

In 2000, only two papers were published on the topic of MICP, and both were published by researchers from China. Meanwhile, 71 countries carried out research on MICP by the end of 2021, which indicates the increasing amount of research possibilities and interest this topic possesses. Among all participated countries, 9 countries have published more than 50 papers until August 2022, as shown in Figure 2. China is leading the research on MICP, with a total of 648 publications, followed by the USA (415), Australia (103), and India (87), respectively. The high output of publications in these countries can be explained by their strong economic strength and their huge investments in research, development, and innovation.

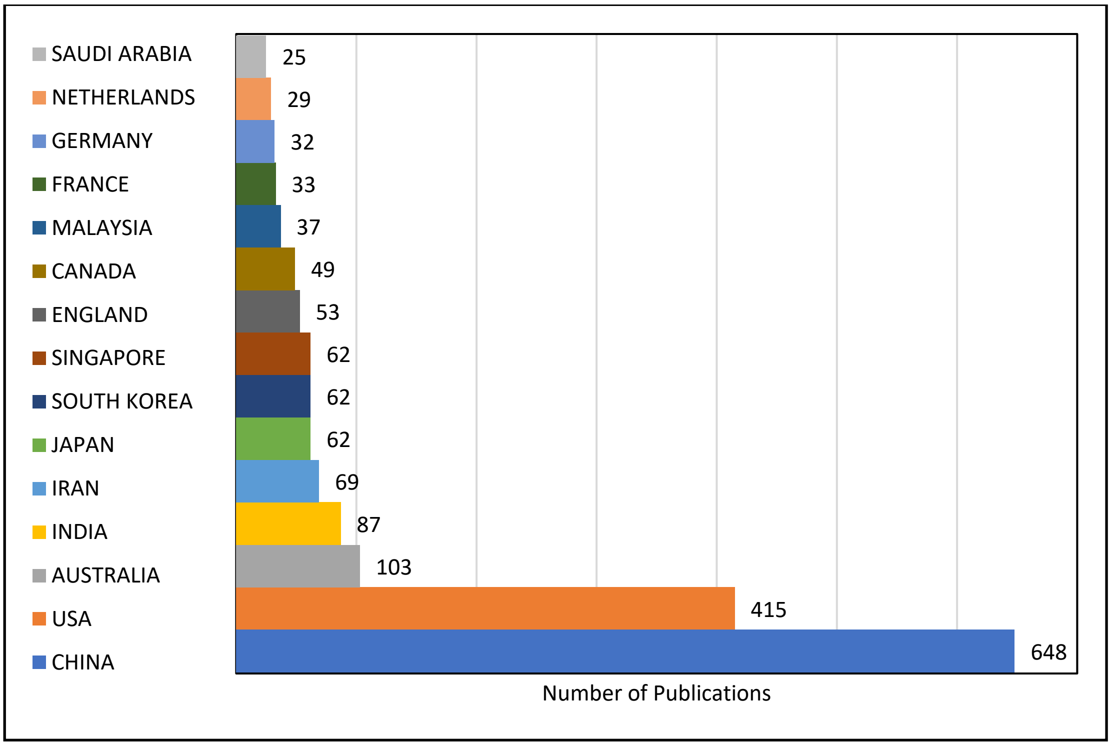

Figure 2. Top 15 countries with the highest number of publications from 2000 to August 2022.

Academic cooperation between different countries or research institutions plays a guiding role in promoting the dissemination of knowledge and academic exchange among scholars [42]. The academic cooperation relationship among the top 10 countries of origin for publications from 2000 to 2022 is shown in Figure 3. The nodes in the figure represent different countries, the lines connecting the nodes indicate international cooperation between countries, and the thickness of the line represents the closeness of cooperation.

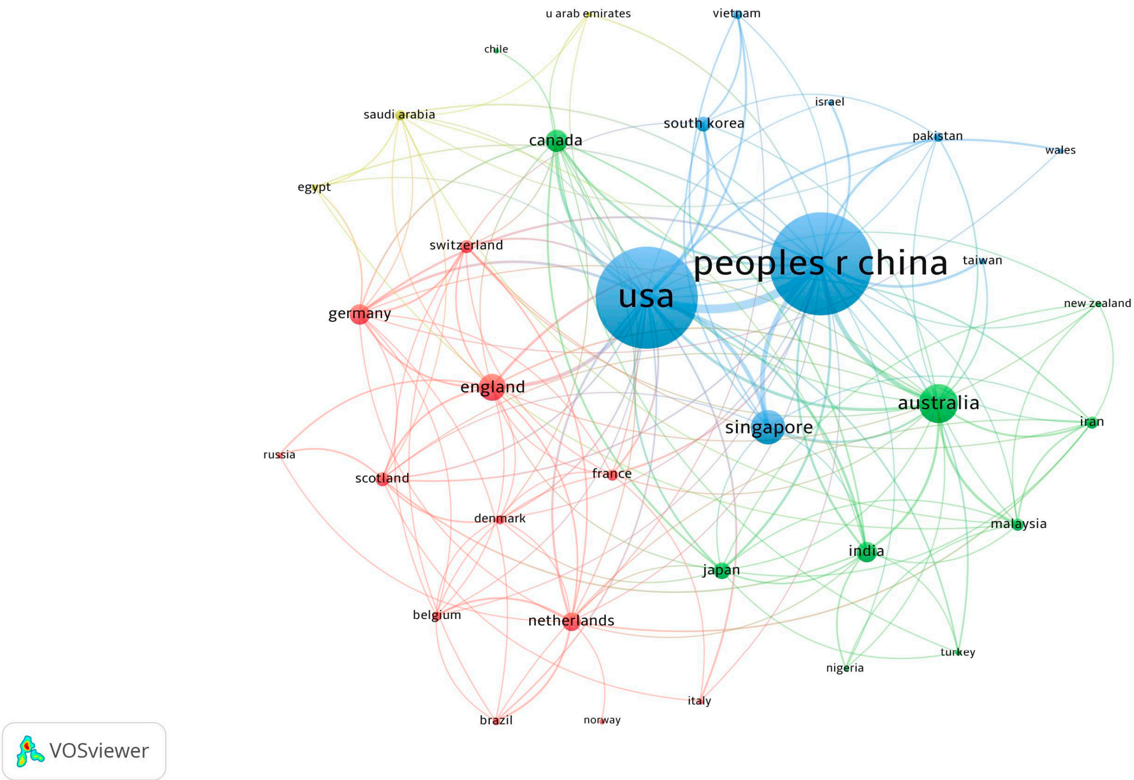

Figure 3. The academic collaboration networks among the top productive countries.

China and the USA are the most active countries regarding global cooperation on research regarding microbial induced calcite precipitation, and both are located at the center of the collaborative network. The USA and China both cooperated with 27 countries to publish MICP research, Australia ranked second, cooperating with 17 countries, followed by The Netherlands (15), England (15), India (12), and Iran (10). China and the USA showed the closest collaborations, and both countries collaborated very closely with Singapore. China also cooperated closely with Australia. There is still a large gap and a great deal of room for the development of cooperation between countries. For example, the USA and China, the two countries with the most publications, have never collaborated with Russia or Brazil.

3.4. Institutions and Collaborations Network Analysis

More than 1270 institutions have contributed to research on microbial induced calcite precipitation (MICP). The top 10 institutes accounted for 37.24% of the total publications, with 549 published papers. China has 5 institutes in the top 10, followed by the USA, with 2 institutes. However, Japan, Singapore, and Australia each have 1 institute in the top 10. The China University of Petroleum ranked first, with 98 publications, followed by Nanyang Technological University, with 62 publications, the Chinese Academy of Sciences, with 59 publications, and the China University of Geoscience, with 56 publications.

The China University of Petroleum has had more papers published in the field of MICP, but Nanyang Technological University, Singapore, has collaborated with 18 institutes worldwide (Figure 4), followed by Chongqing University China, cooperating with 14 institutes, Jiangsu University, China, cooperating with 13 institutes, and the Chinese Academy of Sciences and the University of Hawaii, Manoa, each cooperating with 12 institutes. Most of the institutional collaborations are domestic, or with local institutes. Cooperation between institutions from different countries is crucial to the development and dissemination of knowledge; thus, international cooperation in this research field needs to be improved.

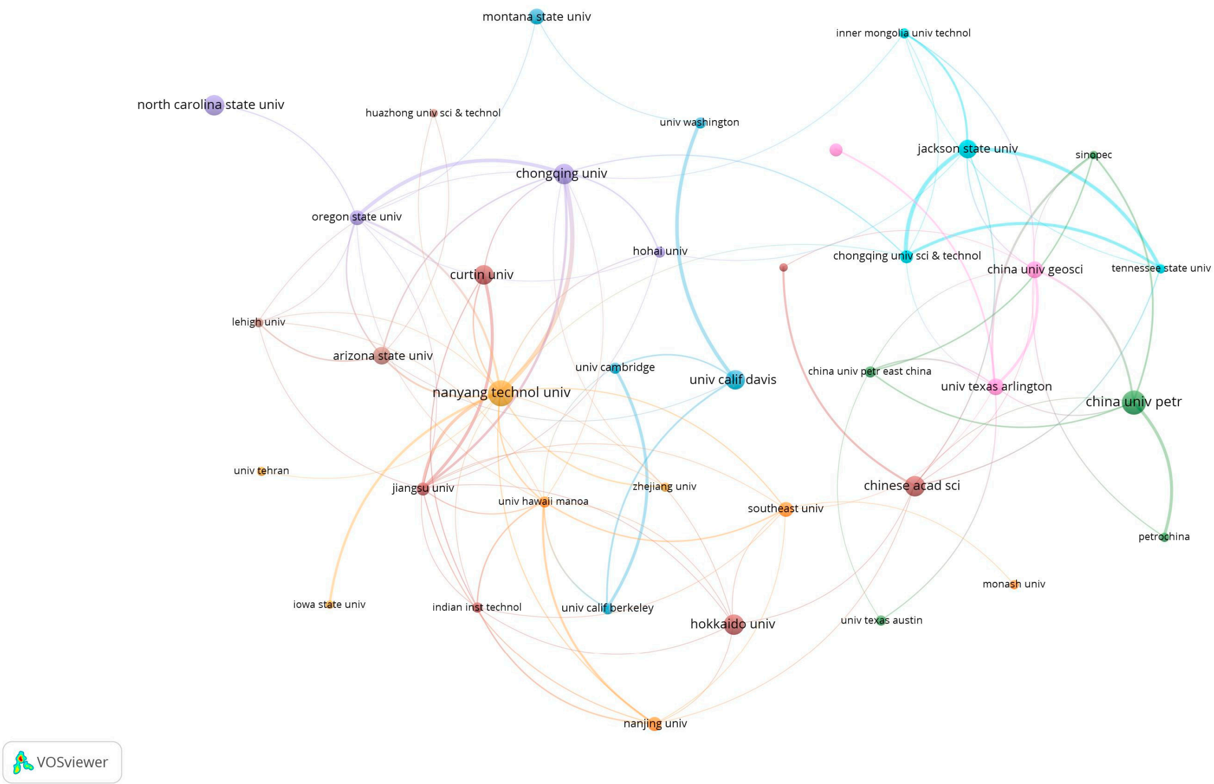

Figure 4. The academic collaboration networks among the top productive institutes.

3.5. Authors and Collaborations Network Analysis

Nearly 3900 authors contributed to the research regarding microbial induced calcite precipitation (MICP) from 2000 to 2022. In China, researchers have produced more studies in this field (Figure 5), as 4 out of 10 top producing authors are from China or are associated with Chinese institutes, whereas 3 researchers are from the USA, 2 from Japan, and 1 from Singapore. Chu Jian from Nanyang Technological University, Singapore, leads the pack, with 51 publications, followed by Kawasaki Satoru, from Hokkaido University, Japan, with 40 publications; Montoya Brina, from North Carolina State University, USA, and Cheng Liang, from Jiangsu University, both ranked third, with 36 Publications.

Figure 6 shows the collaboration between the top producing researchers. This network includes a large cooperation network and several small cooperation networks, which are not connected with each other. Chu Jian, from Nanyang Technological University of Singapore, collaborated with 23 different researchers around the world, tending to be the most productive and collaborative author. Liu Han Long, from Chongqing University, China, and Cheng Liang, from Jiangsu University, China, were the second-most collaborative researchers in the field of MICP, and they have collaborated with 16 researchers each. Xiao Yang, from Chongqing University, China, collaborated with 15 researchers. Surprisingly, Kawasaki Satoru (Hokkaido University, Sapporo, Japan), the second-most proliferative author in this field, after Chu Jian (Nanyang Technological University, Singapore), collaborated with only 8 researchers.

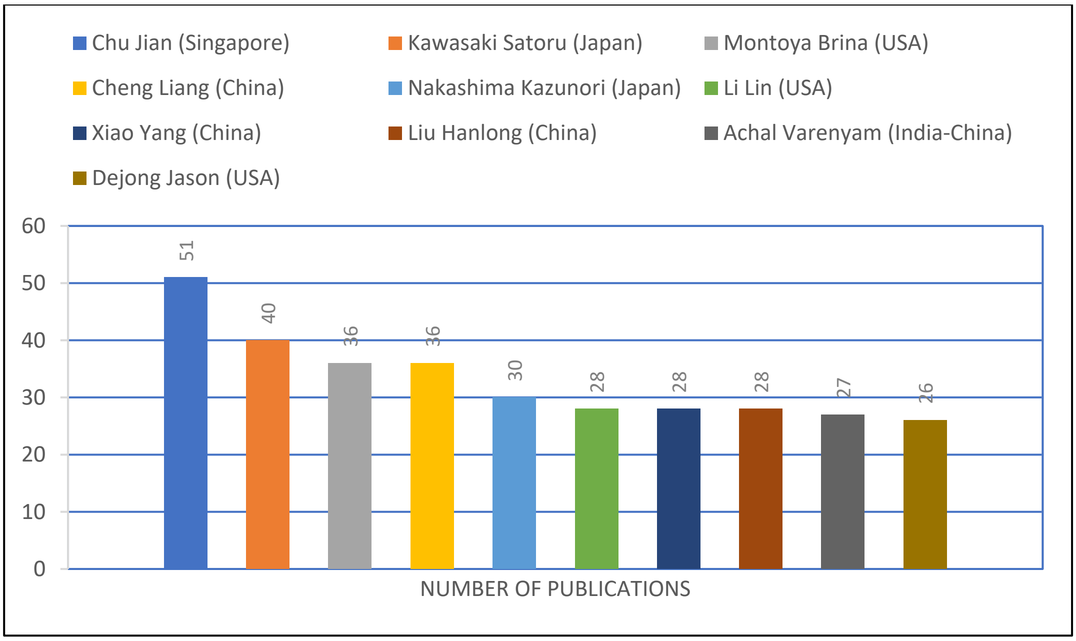

Figure 5. Most productive authors ranked by number of publications.

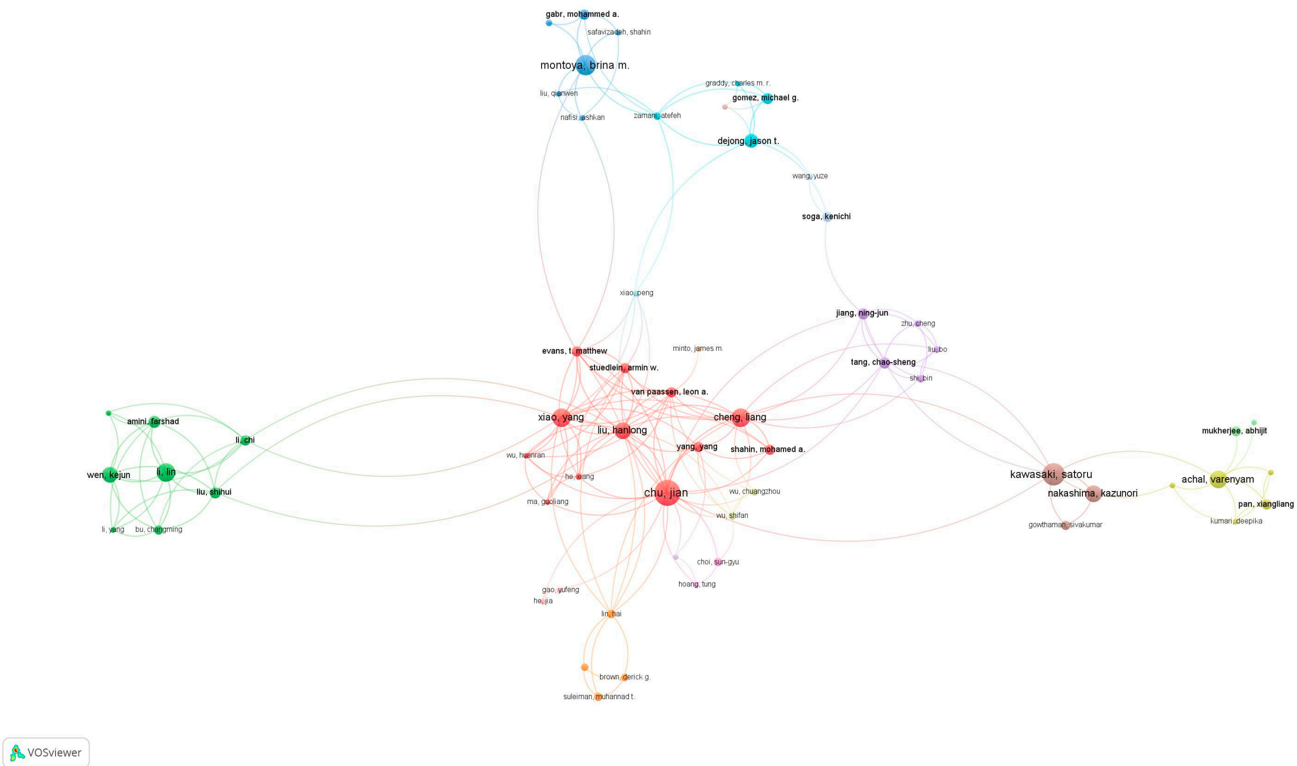

Figure 6. The academic collaboration networks among the top producing authors.

3.6. Most Cited Articles

Citation analysis is an important indicator to measure the quality of publications, and it represents both the interest raised by a research topic within academic circles and the attention scientific community pays to the work of a researcher [43]. The top 10 most-cited papers from 2000 until August 2022 in the field of MICP are listed in Table 3, in which the papers are classified according to the title, type, first author's name, journal, total citations, and year of publication.

Table 3. Top 10 most-frequently cited publications from 2000 to 2022.

Rank	Title	Paper Type	First Author	Journal/Conference	Total Citations	Year
1	Microbially induced cementation to control sand response to undrained shear	Article	Jason DeJong	Geotechnical and Geoenvironmental Engg.	788	2006
2	Microbial carbonate precipitation in construction materials: A review	Proceedings Paper	Willen De Maynck	1st Int. Conference on BioGeoCivil Engg.	699	2010
3	Quantifying Biomediated Ground Improvement by Ureolysis: Large-Scale Biogrout Experiment	Article	Leon van Paassen	Geotechnical and Geoenvironmental Engg.	457	2010
4	Fixation and distribution of bacterial activity in sand to induce carbonate precipitation for ground reinforcement	Proceedings Paper	Marien P Harkes	1st Int. Conference on BioGeoCivil Engg.	367	2010
5	Factors Affecting Efficiency of Microbially Induced Calcite Precipitation	Article	Ahmed Al Qabany	Geotechnical and Geoenvironmental Engg.	339	2012
6	Cementation of sand soil by microbially induced calcite precipitation at various degrees of saturation	Article	Liang Cheng	Canadian Geotechnical	336	2013
7	Effect of chemical treatment used in MICP on engineering properties of cemented soils	Article	Ahmed Al Qabany	GeoTechnique	288	2013
8	Effects of environmental factors on microbial induced calcium carbonate precipitation	Article	Brina Mortensen	Applied Microbiology	286	2011
9	Formations of calcium carbonate minerals by bacteria and its multiple applications	Article	Periasamy Anbu	Springerplus 5	278	2016
10	Experimental Optimization of Microbial-Induced Carbonate Precipitation for Soil Improvement	Article	Belen Carro Martinez	Geotechnical and Geoenvironmental Engg.	254	2013

Our analysis highlights that most of the top cited papers were published by journals in the geotechnical engineering area (geotechnical and geoenvironmental engg.) Only one paper was published by a journal in the biological area (Applied Microbiology). This result shows that, despite the fact that MICP is a geo-biological process, practical applications in soil improvement, as well as construction materials reparation, garner the highest interest from the scientific community.

3.7. Journals Network Analysis

Figure 7 shows the top journals, in term of numbers of publications, regarding MICP. A total of 521 journals, with an impact factor (IF) ranging from 2 to 7, published papers on this topic. *Construction and Building Materials* (IF: 6.141) is the most productive journal, as it published 65 papers in this research area, accounting for 4.12% of the total papers published on this topic. It is followed by *The Journal of Petroleum Science and Engineering* (IF:4.346), with 61 published articles, accounting for 3.86% of the total publications. *The Journal of Geotechnical and Geoenvironmental Engineering* published 51 papers, followed by *Geotechnical Special Publications*, a collection of conference proceedings published by the

American Society of Civil Engineers (ASCE) library, which published 47 papers. These results confirm that the engineering area is the field leading the research regarding MICP.

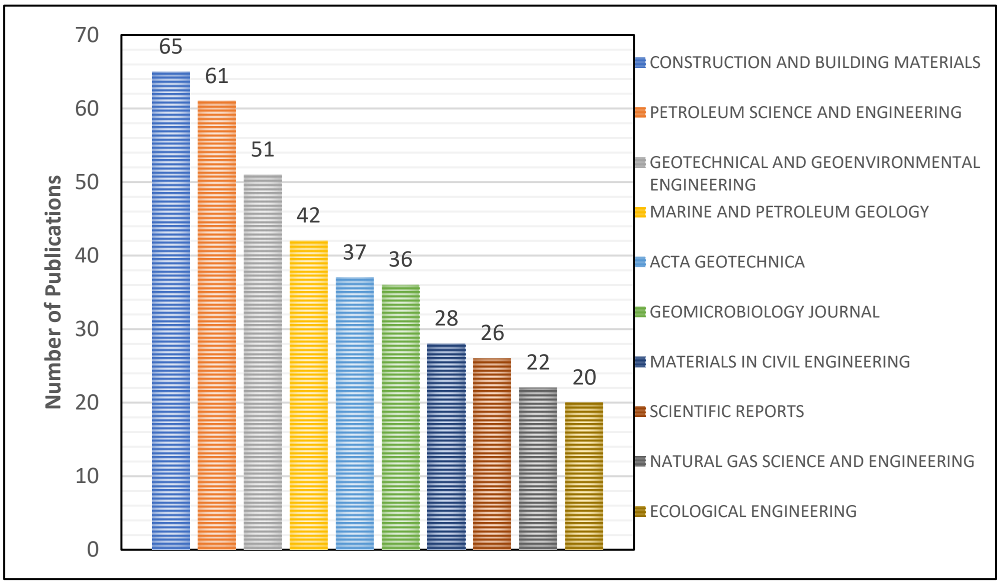

Figure 7. Top journals publishing work regarding microbial induced calcite precipitation (MICP).

3.8. High Frequency Keyword Analysis

The research hotspots and overall trends in the field are accurately revealed by the analysis of the high frequency keywords, their links, and their total link strength [34]. The analysis of the keywords related to MICP generated 3443 results. Among them, only 299 met the threshold of at least 5 co-occurrences, which is 8.68% of the total count. A total of 143 keywords appeared 10 times, and 522 keywords appeared 3 times, which is 4.15% and 15.16% of the total, respectively. MICP was used 251 times, with total link strength of 1600, as shown in Table 4, followed by carbonate precipitation, which co-occurred 213 times, with total link strength of 1361.

Table 4. Top 10 keywords, frequencies, and total link strength.

Keyword	Frequency	Link	Total Link Strength
MICP	251	257	1600
Carbonate Precipitation	213	218	1361
Cementation	171	188	1223
Improvement	165	195	1136
Sand	130	175	913
Bacteria	129	186	974
Biomineralization	114	176	879
Soil improvement	96	160	685
Urease	94	157	715
Bio Cementation	86	163	696

The co-occurrence network map of keywords is shown in Figure 8, in which the bigger the size of the circle, the higher the co-occurrence of an item. Moreover, the shorter the distance between items, the stronger their relationship. MICP was linked with 257 researched items, followed by carbonate precipitation, cementation, improvement, sand etc.

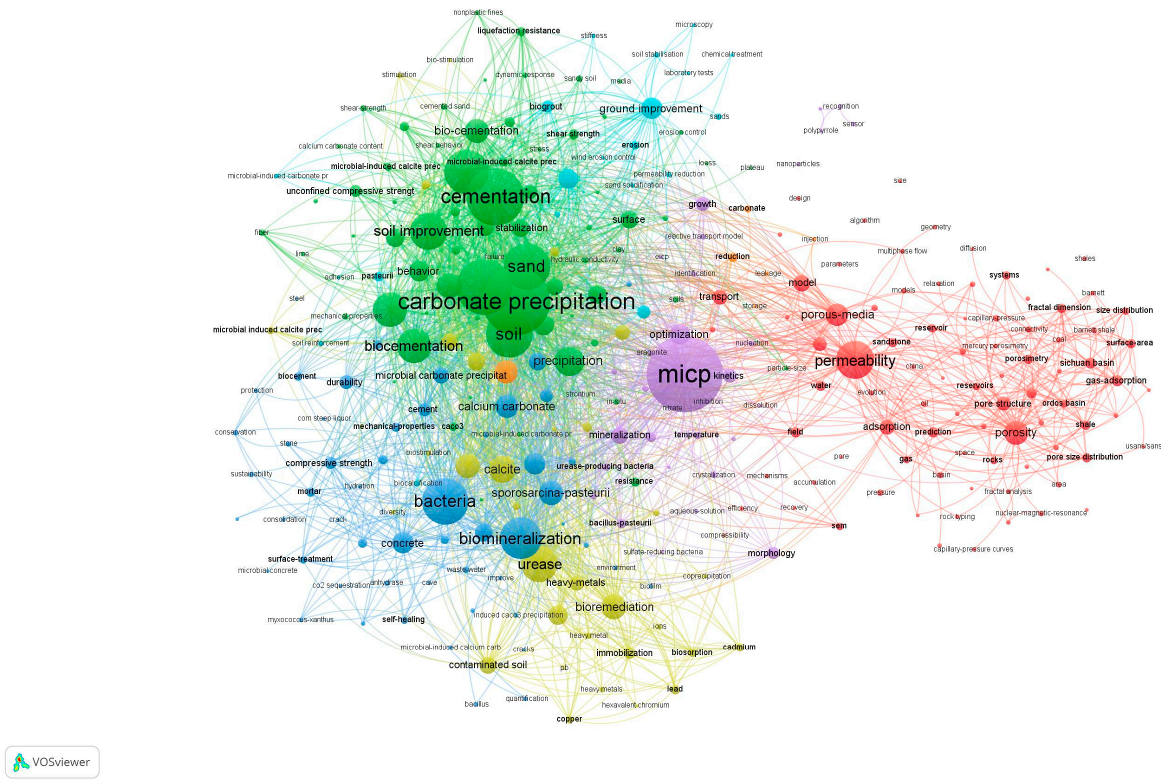

Figure 8. Keyword co-occurrence network map based on total link strength.

4. Conclusions

In this study, we explored different aspects of the research on microbial induced calcite precipitation (MICP). We performed a bibliometric analysis based on 1580 publications, from the year 2000 to 2022, retrieved from the Web of Science Core Collection database. The bibliometric analysis allowed for the quantification and visualization of the multidisciplinary development of MICP, an understanding of the most productive authors, institutes, countries, and journals, along with future research directions. The most active research field is geotechnical engineering, and China is the leading country regarding published studies. Russia and Brazil are not highly involved in international networks, showing the presence of a great gap for the development of cooperation in this research field. An extension of the research network is needed to foster progress in the field of MICP.

Concrete healing or bio cementation, soil improvement, and consolidation through MICP are the main topics of focus. Further, our results show that a high scientific production by an author rarely occurs in the presence of a wide network of international collaboration.

We believe our paper provides important information to the scientific community, offering, for the first time, a relatively objective and comprehensive bibliometric analysis regarding the MICP research field. As with other studies, there are still some limitations due to incomplete search items, and some relevant articles may have been missed. In addition, only articles written in English were included, so there is a chance that some important articles, written in other languages, were also missed.

Author Contributions: Conceptualization, M.A.J.; methodology, M.A.J. and S.D.; software, M.A.J.; writing—original draft preparation, M.A.J. and S.D.; writing—review and editing, S.D., V.P., R.A.N. and M.E.S.-M. All authors have read and agreed to the published version of the manuscript.

Funding: This research is supported by the Department of Science and Technology, University of Naples, Parthenope and partially supported by Universidad Complutense de Madrid group 910404.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Zhu, T.; Dittrich, M. Carbonate Precipitation through Microbial Activities in Natural Environment, and Their Potential in Biotechnology: A Review. *Front. Bioeng. Biotechnol.* **2016**, *4*, 4. [CrossRef] [PubMed]
2. Dupraz, C.; Reid, R.P.; Braissant, O.; Decho, A.W.; Norman, R.S.; Visscher, P.T. Processes of carbonate precipitation in modern microbial mats. *Earth-Sci. Rev.* **2009**, *96*, 141–162. [CrossRef]
3. Lamérand, C.; Shirokova, L.S.; Bénézeth, P.; Rols, J.-L.; Pokrovsky, O.S. Carbon sequestration potential of Mg carbonate and silicate biomineralization in the presence of cyanobacterium Synechococcus. *Chem. Geol.* **2022**, *599*, 120854. [CrossRef]
4. Hoffmann, T.D.; Reeksting, B.J.; Susanne, G. Bacteria-induced mineral precipitation: A mechanistic review. *Microbiology* **2021**, *167*, 001049. [CrossRef] [PubMed]
5. Görgen, S.; Benzerara, K.; Skouri-Panet, F.; Gugger, M.; Chauvat, F.; Cassier-Chauvat, C. The diversity of molecular mechanisms of carbonate biomineralization by bacteria. *Discov. Mater.* **2020**, *1*, 2. [CrossRef]
6. Boquet, E.; Boronate, A.; Ramos-Cormenzana, A. Production of calcite (calcium carbonate) crystals by soil bacteria is a general phenomenon. *Nature* **1973**, *246*, 527–529. [CrossRef]
7. Krumbein, W.E. On the precipitation of aragonite on the surface of marine bacteria. *Die Nat.* **1974**, *61*, 167. [CrossRef]
8. Kamennaya, N.A.; Ajo-Franklin, C.M.; Northen, T.; Jansson, C. Cyanobacteria as biocatalysts for carbonate mineralization. *Minerals* **2012**, *2*, 338–364. [CrossRef]
9. Pasquale, V.; Fiore, S.; Hlayem, D.; Lettino, A.; Huertas, F.J.; Chianese, E.; Dumontet, S. Biomineralization of carbonates induced by the fungi Paecilomyces inflatus and Plectosphaerella cucumerina. *Int. Biodeterior. Biodegrad.* **2019**, *140*, 57–66. [CrossRef]
10. Nash, M.C.; Diaz-Pulido, G.; Harvey, A.S.; Adey, W. Coralline algal calcification: A morphological and process-based understanding. *PLoS ONE* **2019**, *14*, 0221396. [CrossRef]
11. Samuels, T.; Bryce, C.; Landenmark, H.; Marie-Loudon, C.; Nicholson, N.; Stevens, A.H.; Cockell, C. Microbial weathering of minerals and rocks in natural environments. In *Biogeochemical Cycles: Ecological Drivers and Environmental Impact*; American Geophysical Union: Washington, DC, USA, 2020; pp. 59–79.
12. Mulec, J.; Kosi, G.; Vrhovšek, D. Characterization of cave aerophytic algal communities and effects of irradiance levels on production of pigments. *J. Cave Karst Stud.* **2008**, *70*, 3–12.
13. Ostrofsky, M.L.; Miller, C. Photosynthetically mediated calcite and phosphorus precipitation by submersed aquatic vascular plants in Lake Pleasant, Pennsylvania. *Aquat. Bot.* **2017**, *143*, 36–40. [CrossRef]
14. Altermann, W.; Kazmierczak, J.; Oren, A.; Wright, D.T. Cyanobacterial calcification and its rock-building potential during 3.5 billion years of Earth history. *Geobiology* **2006**, *4*, 147–166. [CrossRef]
15. Ferral-Pérez, H.; Galicia-García, M.; Alvarado-Tenorio, B.; Izaguirre-Pompa, A.; Aguirre-Ramírez, M. Novel method to achieve crystallinity of calcite by Bacillus subtilis in coupled and non-coupled calcium-carbon sources. *AMB Express* **2020**, *10*, 174. [CrossRef] [PubMed]
16. Jarwar, M.A.; Dumontet, S.; Pasquale, V.; Chen, C. Microbial Induced Carbonate Precipitation: Environments, Applications, and Mechanisms. *Geomicrobiol. J.* **2022**, *39*, 833–851. [CrossRef]
17. Rajasekar, A.; Moy, C.K.; Wilkinson, S.; Sekar, R. Microbially induced calcite precipitation performance of multiple landfill indigenous bacteria compared to a commercially available bacteria in porous media. *PLoS ONE* **2021**, *16*, 0254676. [CrossRef]
18. Bang, S.S.; Galinat, J.K.; Ramakrishnan, V. Calcite precipitation induced by polyurethane-immobilized bacillus pasteurii. *Enzym. Microb. Technol.* **2001**, *28*, 404–409. [CrossRef]
19. Dhami, N.K.; Reddy, M.S.; Mukherjee, A. Biomineralization of calcium carbonates and their engineered applications: A review. *Front. Microbiol.* **2013**, *4*, 314. [CrossRef]
20. Wei, S.; Cui, H.; Jiang, Z.; Liu, H.; He, H.; Fang, N. Biomineralization processes of calcite induced by bacteria isolated from marine sediments. *Braz. J. Microbiol.* **2015**, *46*, 455–464. [CrossRef]
21. Baumgartner, L.K.; Reid, R.P.; Dupraz, C.; Decho, A.W.; Buckley, D.H.; Spear, J.R.; Przekop, K.M.; Visscher, P.T. Sulfate reducing bacteria in microbial mats: Changing paradigms, new discoveries. *Sediment. Geol.* **2006**, *185*, 131–145. [CrossRef]
22. Ben, C.K.; Rodriguez-Navarro, C.; Gonzalez-Muñoz, M.T.; Arias, J.M.; Cultrone, G.; Rodriguez-Gallego, M. Precipitation and growth morphology of calcium carbonate induced by Myxococcus xanthus: Implications for recognition of bacterial carbonates. *J. Sed. Research.* **2004**, *74*, 868–876. [CrossRef]
23. Wright, D.T.; Wacey, D. Precipitation of dolomite using sulphate reducing bacteria from the Coorong Region, South Australia: Significance and implications. *Sedimentology* **2005**, *52*, 987–1008. [CrossRef]
24. Visscher, P.T.; Reid, R.P.; Bebout, B.M. Micro scale observations of sulfate reduction: Correlation of microbial activity with lithified micritic laminae in modern marine stromatolites. *Geology* **2000**, *28*, 919–922. [CrossRef]
25. Dupraz, C.; Visscher, P.T.; Baumgartner, L.K.; Reid, R.P. Microbe-mineral interactions: Early carbonate precipitation in a hypersaline lake (Eleuthera Island, Bahamas). *Sedimentology* **2004**, *51*, 745–765. [CrossRef]
26. Riding, R.E. Microbial carbonate: The geological record of calcified algal mats and biofilms. *Sedimentology* **2000**, *47*, 179–214. [CrossRef]

27. Bu, C.; Lu, X.; Zhu, D.; Liu, L.; Sun, Y.; Wu, Q.; Zhang, W.; Wei, Q. Soil improvement by microbially induced calcite precipitation (MICP): A review about mineralization mechanism, factors, and soil properties. *Arab. J. Geosci.* **2022**, *15*, 863. [CrossRef]
28. Sohail, M.G.; Al Disi, Z.; Zouari, N.; Al Nuaimi, N.; Kahraman, R.; Gencturk, B.; Yildirim, Y. Bio self-healing concrete using MICP by an indigenous Bacillus cereus strain isolated from Qatari soil. *Constr. Build. Mater.* **2022**, *328*, 126943. [CrossRef]
29. UN DESA. *The Sustainable Development Goals Report 2022*; United Nations: New York, NY, USA, 2022. Available online: https://unstats.un.org/sdgs/report/2022/ (accessed on 18 November 2022).
30. Sweileh, W.M.; Shraim, N.Y.; Al-Jabi, S.W.; Sawalha, A.F.; AbuTaha, A.S.; Zyoud, S.E.H. Bibliometric analysis of global scientific research on carbapenem resistance (1986–2015). *Ann. Clin. Microbiol. Antimicrob.* **2016**, *15*, 56. [CrossRef]
31. Otte, E.; Rousseau, R. Social network analysis: A powerful strategy, also for the information sciences. *J. Inf. Sci.* **2002**, *28*, 441–453. [CrossRef]
32. Xiao, P.; Wu, D.; Wang, J. Bibliometric analysis of global research on white rot fungi biotechnology for environmental application. *Environ. Sci. Pollut. Res.* **2022**, *29*, 1491–1507. [CrossRef]
33. Li, C.; Wu, K.; Wu, J. A bibliometric analysis of research on haze during 2000–2016. *Environ. Sci. Pollut. Res.* **2017**, *24*, 24733–24742. [CrossRef] [PubMed]
34. Qi, Y.; Chen, X.; Hu, Z.; Song, C.; Cui, Y. Bibliometric analysis of algal-bacterial symbiosis in wastewater treatment. *Int. J. Environ. Res. Public Health* **2019**, *16*, 1077. [CrossRef] [PubMed]
35. Vanzetto, G.V.; Thomé, A. Bibliometric study of the toxicology of nanoescale zero valent iron used in soil remediation. *Environ. Pollut.* **2019**, *252*, 74–83. [CrossRef] [PubMed]
36. AlRyalat, S.A.S.; Malkawi, L.W.; Momani, S.M. Comparing bibliometric analysis using PubMed, Scopus, and Web of Science databases. *J. Vis. Exp.* **2019**, *152*, 58494. [CrossRef]
37. Reuters, T. Whitepaper Using Bibliometrics in Evaluating Research. 2008, Volume 12. Available online: http://openscience.ens.fr/MARIE_FARGE/CONFERENCES/2014_12_02_BIBLIOMETRIE_ET_EVALUATION_DE_LA_RECHERCHE_ABDU_PARIS/InCites_Thomson-Reuters.pdf (accessed on 18 November 2022).
38. Zou, X.; Yue, W.L.; Le Vu, H. Visualization and analysis of mapping knowledge domain of road safety studies. *Accid. Anal. Prev.* **2018**, *118*, 131–145. [CrossRef]
39. Chen, D.; Liu, Z.; Luo, Z.; Webber, M.; Chen, J. Bibliometric and visualized analysis of emergy research. *Ecol. Eng.* **2016**, *90*, 285–293. [CrossRef]
40. Van Eck, N.J.; Waltman, L. Software survey: VOSviewer, a computer program for bibliometric mapping. *Scientometrics* **2010**, *84*, 523–538. [CrossRef]
41. Van Eck, N.J.; Waltman, L. *Manual for VOSviewer Version 1.6.18, CWTS Meaningful Metrics*; Universiteit Leiden: Leiden, The Netherlands, 2022. Available online: https://www.vosviewer.com/documentation/Manual_VOSviewer_1.6.18.pdf (accessed on 18 November 2022).
42. Chen, W.; Geng, Y.; Zhong, S.; Zhuang, M.; Pan, H. A bibliometric analysis of ecosystem services evaluation from 1997 to 2016. *Environ. Sci. Pollut. Res.* **2020**, *27*, 23503–23513. [CrossRef]
43. He, M.; Zhang, Y.; Gong, L.; Zhou, Y.; Song, X.; Zhu, W.; Zhang, Z. Bibliometrical analysis of hydrogen storage. *Int. J. Hydrogen Energy* **2019**, *44*, 28206–28226. [CrossRef]