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Review

Perspective of Hydrodynamics in Microbial-Induced Carbonate Precipitation: A Bibliometric Analysis and Review of Research Evolution

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Abstract: Microbial-induced carbonate precipitation (MICP) is a promising process with applications in various industries, including soil improvement, bioremediation, and concrete repair. However, comprehensive bibliometric analyses focusing on MICP research in hydrodynamics are lacking. This study analyses 1098 articles from the Scopus database (1999–2024) using VOSviewer and R Studio, identifying information on publications, citations, authors, countries, journals, keyword hotspots, and research terms. Global participation from 66 countries is noted, with China and the United States leading in terms of contributions. The top-cited papers discuss the utilisation of ureolytic microorganisms to enhance soil properties, MICP mechanisms, concrete deterioration mitigation, soil and groundwater flow enhancement, biomineral distribution, and MICP treatment effects on soil hydraulic properties under varying conditions. Keywords like calcium carbonate, permeability, and *Sporosarcina pasteurii* are pivotal in MICP research. The co-occurrence analysis reveals thematic clusters like microbial cementation and geological properties, advancing our understanding of MICP's interdisciplinary nature and its role in addressing environmental challenges.

Keywords: bibliometrics; biomineralisation; data analytics; environmental challenges; biocementation; MICP; permeability; research hotspots; Scopus database

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1. Introduction

Soil stabilisation plays a crucial role in addressing the challenges posed by poor soil strength and hydraulic properties [1]. Unstable soils can lead to various issues, including erosion, landslides, and compromised infrastructure integrity. Traditional ground improvement methods often involve energy-intensive processes with significant environmental impacts, such as emissions from cement manufacturing and the disruption of natural ecosystems [2,3]. Therefore, there is a pressing need for sustainable solutions that can enhance soil stability while minimising environmental harm [4]. This has led researchers to explore alternative approaches, such as microbial-induced carbonate precipitation (MICP), which offers promising eco-friendly solutions for soil stabilisation.

MICP enhances the hydromechanical behaviour of geomaterials lacking in hydraulic and strength qualities. MICP involves key chemical processes mediated by ureolytic bacteria, with *Sporosarcina pasteurii* being the most commonly used. The process begins with urease (EC 3.5.1.5) breaking down urea into ammonia and carbamate, which further decomposes into ammonia and carbonic acid [5]. Carbonic anhydrase (EC 4.2.1.1) then converts carbonic acid to bicarbonate [6,7]. These reactions increase the pH, encouraging calcium carbonate ($CaCO_3$) precipitation when soluble calcium is present. Additionally, in harsh environments, ureolytic bacteria protect themselves by accumulating calcium ions [8]. $CaCO_3$ biominerals from MICP fill soil pore spaces, binding particles together and enhancing the soil mass strength and stiffness, thereby reducing permeability [9].

MICP has numerous applications, including soil slope stabilisation [10,11], improving expansive soil stability [12,13], erosion mitigation [14,15], CO_2 sequestration and capture [16,17], remediation of heavy metals and pollutants [9,18], dust control [19], sealing of underground structures [20], and bio-concrete production/crack repair [21,22]. Successful MICP treatment hinges on managing ureolysis kinetics, reactant distribution, and injection rates, which influence the flow and distribution of $CaCO_3$ [23]. These considerations are crucial for optimising MICP effectiveness and ensuring the long-term stability and sustainability of treated soils.

MICP requires different treatment techniques such as pressure injection, spraying, submerged and surface percolation, which can influence the flow of the treatment reagents within the geomaterials, eventually affecting the solidification or $CaCO_3$ distribution and mechanical properties (i.e., permeability or strength) [21,24–26]. Injection rates affect reactant mixing and interaction with pore fluids, influencing the ureolysis pace and precipitate characteristics. Moreover, the rapid or uncontrolled injection of bacterial cultures or cementation solution (constituting urea and calcium ions) can affect preferential flow paths, bypassing certain areas/voids, which may lead to unwanted bio-clogging and result in undesired ineffectiveness [27,28]. Therefore, it is vital to use proper and optimal MICP methods. Monitoring and adjusting injection rates are crucial for pH management, minimising environmental impact, and ensuring treatment success.

While existing studies acknowledge the serious environmental effects of traditional ground improvement methods and the increasing usage of MICP to resolve these challenges, there remains a gap in the literature regarding a comprehensive analysis of the MICP global research landscape, especially concerning its hydrodynamics. The Scopus database, with its extensive coverage and rigorous curation, offers a detailed view of MICP research, essential for reliable bibliometric analysis [29,30]. Its global reach and advanced search features facilitate an in-depth understanding of trends, gaps, and collaborations in various research areas, including MICP.

Scopus was chosen due to its extensive coverage of scientific publications, including those not covered by other databases like Web of Science (WoS). Scopus includes a variety of bibliometric metrics such as citation counts, the h-index, and the SCImago Journal Rank, making it a comprehensive resource [31]. Additionally, Scopus covers a wide range of documents, including journal articles, conference proceedings, and book chapters, contributing to its usefulness in bibliometric analysis [32]. While WoS is also a renowned scientific database commonly used for bibliometric analysis [33], it has limitations in the number of terms/keywords allowed in the search field (50 terms), which can affect the coverage and functionality needed for the bibliometric analysis in this study. Google Scholar's lack of quality control limits its utility as a bibliometric tool, as its larger coverage includes items not comparable with those provided by other databases, such as papers in low-impact journals, popular scientific literature, and unpublished reports or teaching supporting materials [34]. Although Dimensions AI aims to provide comprehensive coverage, it may not yet have the same depth of coverage as Scopus. This could result in differences in the number of documents and sources available for analysis, potentially affecting the completeness and accuracy of bibliometric studies conducted using Dimensions AI [35]. Additionally, combining databases like Web of Science and Scopus in citation-based literature studies may not be entirely feasible due to limitations in the focus of this study. Combining bibliometric datasets leads to potential biases in search string selection, challenges in article inclusion and exclusion decisions, the risk of human errors in data processing, and limitations in computing capacity and tools for analysis, which can hinder the comprehensive assessment of general differences between the databases [36]. Scopus was also selected as the preferred database for the current study on MICP and its hydrodynamics for its extensive international coverage, robust citation tracking, user-friendly interface, data integrity, regular updates, integration capabilities, and support services, making it the preferred database for studies on MICP and its hydro-dynamics.

The objectives of this study include identifying key research trends, evaluating existing research gaps, and examining collaborations in MICP research related to hydrodynamics using the Scopus database from 1999 to 2024. Through bibliometric analysis using the VOSviewer program (version 1.6.17) and RStudio software (version 2021.09.1), it seeks to identify research trends, gaps, and connections across disciplines, fostering insights that can inform future research directions in MICP research. The significance of this bibliometric analysis lies in its ability to advance knowledge relevant to MICP by providing a comprehensive overview of research trends and gaps, thus guiding future research efforts.

2. Materials and Methods

2.1. Search Strategy and Keyword Selection

To comprehensively examine worldwide research advancements and trends in MICP research, this study sourced its publication dataset from the Scopus database. The final bibliometric data were retrieved from Scopus on 5 February 2024. Multiple sets of keywords related to the research area were selected to access relevant publications in the scientific database. The search command used was as follows: TITLE-ABS-KEY ((MICP) OR (microbial and induced and carbonate and precipitation) OR (microbial and induced and calcite and precipitation) OR (microbially and induced and calcium and carbonate and precipitation) AND (hydrology) OR (hydraulic conductivities) OR (fluid injection experiments) OR (infiltration) OR (cementation solution) OR (injection rates) OR (fracture development) OR (matrix flow) OR (permeability) OR (hydraulic properties) OR (porosity) OR (flow processes) OR (fracture patterns) OR (pore volume ratio) OR (injection rate) OR (soil-water repellency) OR (aquifer storage) OR (flow rate OR (water resources) OR (contaminant hydrology) OR (urea hydrolysis) OR (pore network) OR (crystal growth) OR (chemical precipitation) OR (adsorption) OR (ion exchange) OR (toxic metals) OR (groundwater hydraulics) OR (breakdown pressure) OR (viscous fluid) OR (infiltration dominance)). Using the Boolean operators ‘OR’ and ‘AND’ enhances search functionality and improves search precision within the Scopus database [37]. The selected keywords provide a comprehensive view of MICP-related research, focusing on its impact on water movement and permeability in porous media, including fluid flow rates, fracture development, and hydraulic properties. This research likely explores how MICP can alter water behaviour in geomaterials, affecting groundwater flow, contaminants, and water resource management.

2.2. Document Collection and Analysis

The search string retrieved 2522 documents from the Scopus database, with 677 (26.82%) classified as open access. The open access publications were further categorised into Gold (338), Hybrid Gold (80), Bronze (126), and Green (359). The majority of the publications indexed in the Scopus database were written in English (2370, 93.96%), with smaller numbers in other languages such as Chinese (145), Polish (2), Azerbaijani (1), French (1), German (1), Hungarian (1), Japanese (1), Korean (1), Russian (1), and Ukrainian (1). The documents were classified under different subject areas, with Earth and Planetary Sciences (1186), Engineering (755), and Environmental Science (591) being the most prominent. The search string and query steps used to attain the data are available in Table S1. After refining the search using the Scopus tool, the publication period was narrowed to focus on articles published between 1999 and 2024, with a focus on those written in the English language.

2.3. Visualisation Mapping through VOSviewer and RStudio

VOSviewer software (version 1.6.17) is a powerful tool developed at Leiden University in the Netherlands and is widely used for visualising bibliometric networks [32]. Operating in Java, VOSviewer facilitates the creation of visual representations of networks using bibliographic data, including co-authorship networks and keyword co-occurrence networks [38,39]. In VOSviewer maps, nodes are typically shown as circular or rectangular shapes, representing different parameters depending on the analysis context. These shapes visually distinguish elements like co-authorship, co-occurrence, bibliographic coupling, and co-citation analyses within the network [32]. The node size reflects the link strength for different parameters, while the lines connecting nodes indicate their relationships, with thicker lines indicating stronger connections. Node size is determined by centrality, with larger nodes indicating higher centrality [40]. Analysing the total link strength or occurrence level in VOSviewer helps identify and group items based on various parameters. This total link strength indicates the strength of relationships between items, such as countries, authors, journals, or keywords, with higher link strengths suggesting stronger relationships or more frequent co-occurrences, thus aiding in the grouping of related items [29,30].

In this study, the co-authorship analysis of authors identified 3809 authors, with 71 meeting the threshold (the minimum number of documents is 4) for collaboration. Similarly, the co-authorship analysis of countries identified 70 countries, with 63 meeting the threshold (the minimum number of documents is 1) for collaboration. The co-occurrence analysis of author keywords identified 2694 keywords, with 110 keywords meeting the threshold (the minimum number of occurrences is 5). Similarly, the co-occurrence analysis of text data (titles and abstracts) identified 25,494 terms, with 416 terms meeting the threshold (the minimum number of occurrences is 20). VOSviewer selected 250 terms, representing the 60% most relevant terms for analysis. The co-citation analysis of cited authors identified 54,371 cited authors, with 188 cited authors meeting the threshold (the minimum number of citations is 100). Similarly, the co-citation analysis of cited references identified 44,812 cited references, with 9 cited references meeting the threshold (the minimum number of citations is 25). Bibliographic coupling analysis identified 333 total journals, with 24 journals meeting the threshold (the minimum number of documents is 10). Additionally, bibliographic coupling analysis of countries identified 70 countries, with 38 countries meeting the threshold (the minimum number of documents is 5) for collaboration. These analyses provide valuable insights into scholarly interactions and research patterns.

RStudio is a powerful bibliometric application that was established in 2011, combining data management, statistical analysis, and visualisation in one platform [41]. Bibliometrix is a specialised tool in RStudio that enables academics to evaluate bibliographic data effectively, perform descriptive and network analysis, and create visual representations to reveal patterns and trends in academic literature [42]. In this study, the bibliographic file was also analysed using RStudio software (version 2021.09.1), in conjunction with VOSviewer to identify the top relevant keywords with the highest occurrences or frequencies and other general information about MICP hydrodynamics.

3. Results and Discussion

3.1. Publication and Citation Trends

Figure 1 illustrates the trends in publications and citations in the research area, which has garnered significant interest in the academic community. Over the observed period, there were 1098 publications and 40,276 citations. Initially, a total of 2522 documents/publications were retrieved from the Scopus database using the search string. However, after refining the query to focus only on article publications, limiting the language to English and the source type to journal articles, and removing unwanted papers based on the Electronic Identifier, the final number of articles for analysis was 1098. This focus ensured a more specific and relevant dataset for the bibliometric analysis, allowing for a more targeted examination of citation trends in the context of the study. Refining and focusing on a more specific dataset is important to ensure that the analysis is conducted on relevant and accurate publications directly related to the research question or objective.

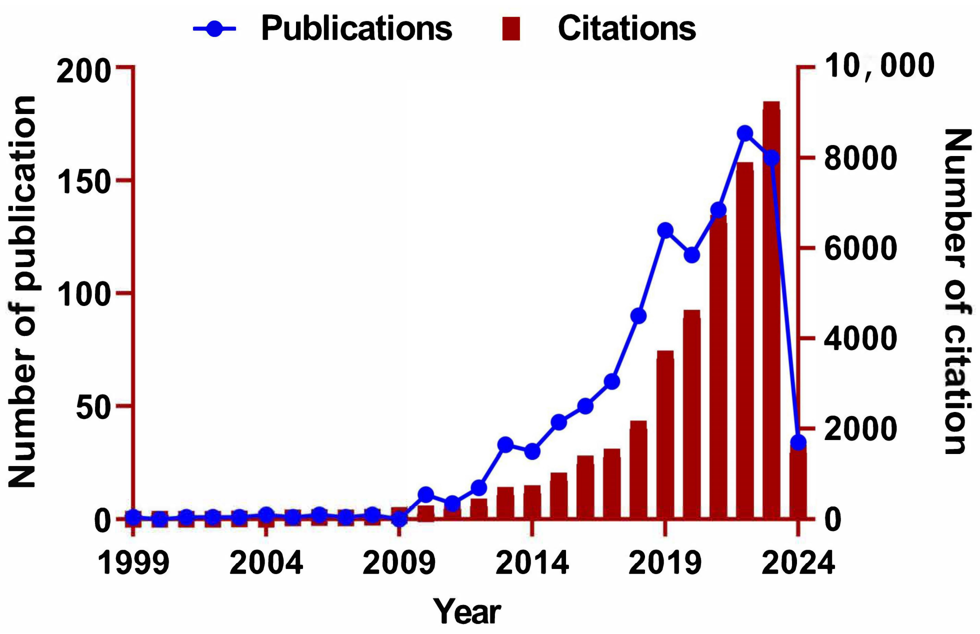

Figure 1. Trends in publications and citations from 1999 to 2024.

The number of publications has varied, with the lowest recorded in 2000 (0 publications) and the highest in 2022 (171 publications). Likewise, citations have fluctuated, with the lowest in 1999 (none recorded) and the highest in 2023 (9073 citations). The growth in publications and citations has followed distinct phases, starting with low activity and minimal citations, followed by a gradual increase. A significant increase in publications occurred around 2010, followed by a steady rise in citations. The period from 2013 to 2018 saw rapid growth in both publications and citations, indicating intensive research and high impact. However, after 2018, while publications continued to grow, the rate of citation growth slowed down, suggesting a possible saturation or maturation in the research area. The number of publications and citations has ranged widely, from single digits in the early years to triple or quadruple digits in recent years, reflecting the increasing interest and impact of MICP research over time.

The H-index, used to evaluate productivity and impact [43], stood at 93 in the Scopus database. This indicates that among the 1098 documents considered, 93 have been cited at least 93 times, highlighting the influence of seminal works in the research area. Among all the identified articles, only 123 of the total publications were not cited. Twenty-three of the articles have not received any citations, and these documents were published between 2015 and 2022. Conversely, for the articles published between 2023 and 2024, 95 publications have not received any citations, the majority being from 2023 (62 publications). This is probably because these are recent publications and researchers have not been familiar with these papers or they are not yet well known within the scientific community. Between 2012 and 2024, the number of documents receiving single-digit citations varied widely. In 2012, only one document received citations, while in subsequent years, the numbers increased gradually, reaching peaks in 2022 with 98 documents and in 2023 with 90 documents. However, there were notable exceptions, with 2015, 2016, and 2024 each seeing single-digit citations, with nine, five, and two documents, respectively. This trend suggests fluctuations in citation rates over the years, with certain periods experiencing higher citation counts than others. The number of publications across different years that have received double-digit, triple-digit, and quadruple-digit citations varies considerably. Over the years, several publications have garnered significant attention, receiving substantial numbers of citations. For instance, some years, such as 2010, 2012, and 2013, saw a notable number of publications receiving citations in the triple digits, indicating a high level of impact and recognition within the academic community. In 2010, for example, three publications received triple-digit citations, while in 2012, five publications achieved the same feat, and in 2013, four publications received triple-digit citations. Additionally, there are instances where publications received quadruple-digit citations, indicating exceptional impact and influence. For example, in 2010, one publication received over 1000 citations, highlighting its significant contribution to the research domain. The years 2010, 1999, and 2006 were particularly notable for receiving quadruple-digit citations, with 1232, 1198, and 1191 publications, respectively. Conversely, there are also years where the majority of the publications received lower citation counts, such as 2019 and 2020, where the majority of the publications received double-digit citations, suggesting a more modest level of impact. This variation in citation counts across different years underscores the dynamic nature of academic research and the fluctuating levels of impact that publications can achieve over time.

The analysis in RStudio revealed that the bibliographic data, comprising 1098 documents, had an average publication age of 4.63 years, an average of 36.44 citations per document, and an average of 4.619 citations per year per document from 1999 to 2024. Furthermore, Figure 1 indicates that forecasts for publication and citation outcomes can be made cautiously, especially considering that the 2024 data only cover January and February. The anticipated growth in both publications and citations for 2024 suggests that there will be continued research activity and impact in the research domain. However, it is essential to interpret these forecasts with caution, as there are potential uncertainties introduced by the limited data for 2024 (34 publications and 1467 citations) and unforeseen events that could impact research trends. This highlights the importance of continuous monitoring and analysis to refine forecasts and adapt to changes in the research landscape, ensuring ongoing relevance and understanding of MICP's evolving role within scientific discourse. However, these forecasts should be interpreted with caution, considering the potential uncertainties introduced by the limited 2024 data and the unforeseen events that could impact research trends, as seen with the COVID-19 pandemic [44]. Finally, continuous monitoring and analysis of bibliometrics will be necessary for adapting to changes in the research landscape, ensuring the ongoing relevance of MICP's evolution within scientific discourse [40].

3.2. Most Cited Articles

Table 1 lists the top 10 cited articles in the research area. The research in this domain has been ongoing from 1999 to 2013, indicating a significant research timeline. Highly cited articles in the research area included, for example, that by Dejong et al. [45], who investigated the use of ureolytic microorganisms to improve soil properties like permeability and porosity, crucial for processes such as infiltration and groundwater recharge who investigated the use of ureolytic microorganisms to improve soil properties like permeability and porosity, crucial for processes such as infiltration and groundwater recharge. Stocks-fisher et al. [46] and Dejong et al. [47] provided insights into MICP mechanisms in soil, impacting water retention and flow dynamics. Santhosh et al. [48] discussed using ureolytic microorganisms to mitigate concrete deterioration caused by water ingress, which is important for understanding concrete's durability. Van Paassen et al. [49] explored the role of ureolysis in enhancing soil properties and groundwater flow. Harkes et al. [50] studied biomineral distribution in porous media, influencing hydraulic conductivity and groundwater flow. Al Qabany et al. [51] and Cheng et al. [52] addressed MICP's effects on soil permeability and hydraulic conductivity. Al Qabany and Soga [53] and Mortensen et al. [54] discussed MICP treatments' impact on soil hydraulic properties under varying conditions, relevant for engineering and environmental remediation.

Table 1. List of the top most cited articles in the research domain.

Title of Article	Citation	References
Bio-mediated soil improvement	1232	[45]
Microbiological precipitation of $CaCO_3$	1198	[46]
Microbially induced cementation to control sand response to undrained shear	1191	[47]
remediation of concrete using microorganisms	761	[48]
Quantifying biomediated ground improvement by ureolysis: Large-scale biogrout experiment	680	[49]
Fixation and distribution of bacterial activity in sand to induce carbonate precipitation for ground reinforcement	545	[50]
Factors affecting efficiency of microbially induced calcite precipitation	534	[51]
Cementation of sand soil by microbially induced calcite precipitation at various degrees of saturation	520	[52]
Effect of chemical treatment used in MICP on engineering properties of cemented soils	431	[53]
Effects of environmental factors on microbial induced calcium carbonate precipitation	430	[54]

Figure S1 depicts the co-citation analysis of top references, revealing three distinct research clusters. In the red cluster (Cluster 1), Dejong et al. [47] stand out with 96 citations and a total link strength of 51, along with studies by Cheng et al. [52] and Al Qabany and Soga [53]. This cluster explores MICP's efficacy in enhancing soil stability for construction by controlling the sand response to shear forces and mitigating liquefaction. In the green cluster (Cluster 2), Dejong et al. [45] and De Muynck et al. [55] contribute to discussions on microbial activity, MICP mechanisms, and their applications in construction materials. The blue cluster (Cluster 3) includes studies like those by Whiffin et al. [56] and Whiffin [57], which highlight MICP's potential in producing biocement and ground improvement, demonstrating its versatility in sustainable construction materials and soil stabilisation techniques like biogrouting. The co-citation analysis provides a deeper understanding of the connections between the articles, revealing thematic clusters and trends within a domain beyond simple citation counts. It uncovers hidden connections and emerging trends, offering insights into the intellectual structure and evolution of scientific knowledge.

3.3. Global Distribution and Leading Countries

MICP research has garnered interest worldwide, with 66 countries contributing to publications and citations. Figure 2A illustrates the global distribution, showing Asia as the primary contributor with 29 countries, followed by Europe with 21, Africa with 8, South America with 4, North America with 2, and Oceania with 2. This distribution highlights the global interest and research activity in MICP. The data show that China leads in the number of publications with 494, followed by the United States with 234 publications. India, the United Kingdom, and Australia also feature prominently with 75, 67, and 51 publications, respectively. It is interesting to note that while some countries have a significant number of publications, others including Armenia (1), Botswana (1), Brunei Darussalam (1), Chile (2), Cyprus (4), and Finland (1) have limited article output in research on MICP, indicating variations in research focus and activity across different regions. Figure 2B shows the global distribution based on citations, with the United States leading with 17,358 citations, followed by China with 11,008. India, the United Kingdom, and Australia also had notable citation counts with 1921, 3507, and 2475 citations, respectively. European countries like the Netherlands (2451) and Germany (730) had moderate citation counts, while some countries like Finland, Latvia, and Brunei Darussalam had no citations in this context. Countries with lower citation counts include Armenia with (51) citations, Botswana with (8), Brunei Darussalam with (2), Ghana with (7), Greece with (2), Latvia with (0), Lebanon with (4), Libya with (4), Mongolia with (11), and Uzbekistan with (1). This figure indicates the varying degrees of research impact and citation rates across different countries involved in MICP research.

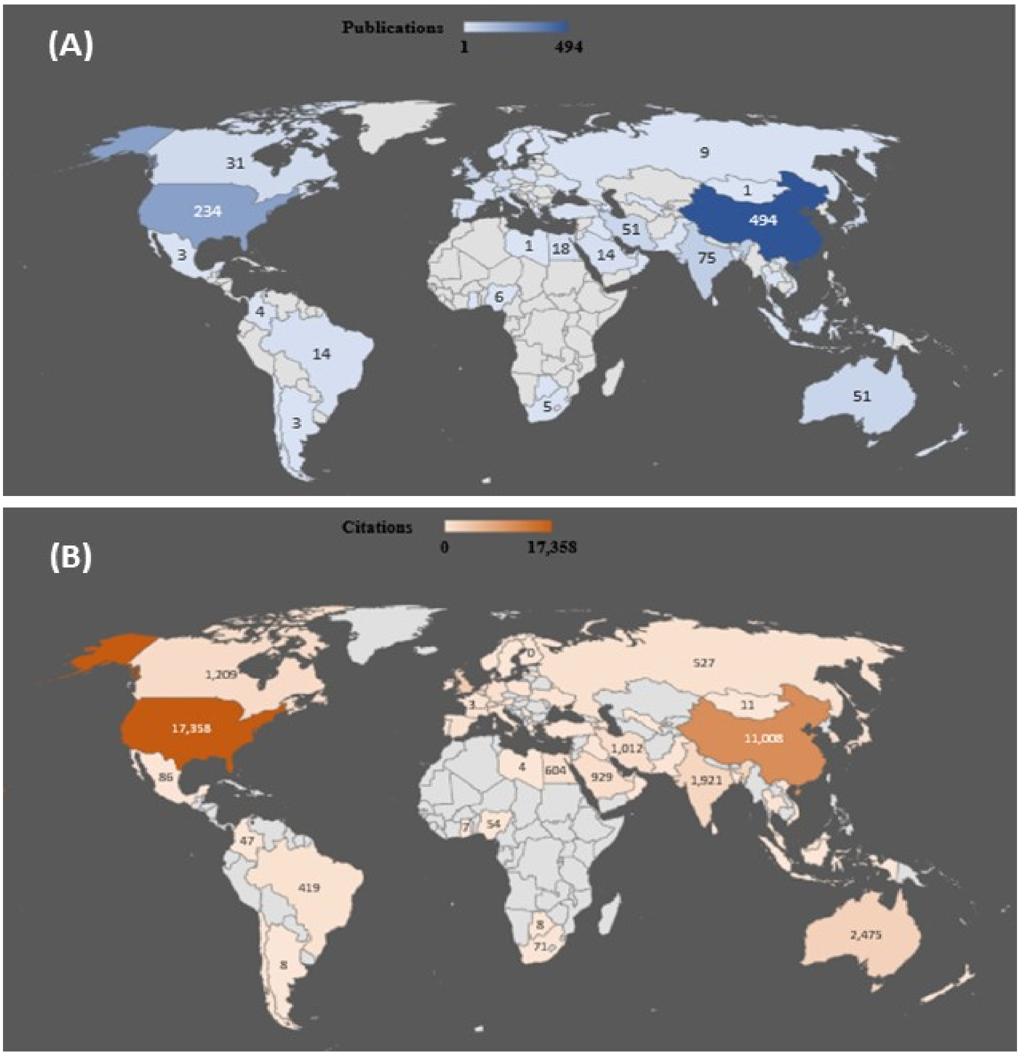

Figure 2. Global distribution of 66 countries contributing to MICP research. (**A**) Publications and (**B**) citations.

The leading countries in MICP research, such as China, the United States, India, the United Kingdom, and Australia, come from both developed and developing economies. This diversity in leading contributors reflects the global interest and importance of MICP research across different regions. Typically, countries with significant publication outputs, such as China and the United States, likely have more resources, funding opportunities, and research infrastructure to conduct extensive experimental studies on MICP hydrodynamics. Their research findings and methodologies can significantly influence the development and implementation of MICP technologies worldwide. On the other hand, countries with limited article output and lower citation counts may have less focus on experimental research in MICP hydrodynamics. This could be due to various factors, including limited research funding, infrastructure, or expertise in conducting such experiments. However, their participation in MICP research, albeit limited, still contributes to the global knowledge base and highlights the diverse research landscape in this research domain.

With VOSviewer, we conducted a co-authorship analysis of the countries to reveal the collaboration patterns between them, shedding light on international scientific cooperation and knowledge exchange. In Figure 3, the colours representing each continent cluster are used to visually differentiate and categorise the countries identified based on their continental regions. This classification helps viewers quickly identify which countries belong to which continent, providing a geographical context to the co-authorship analysis of countries conducted with VOSviewer.

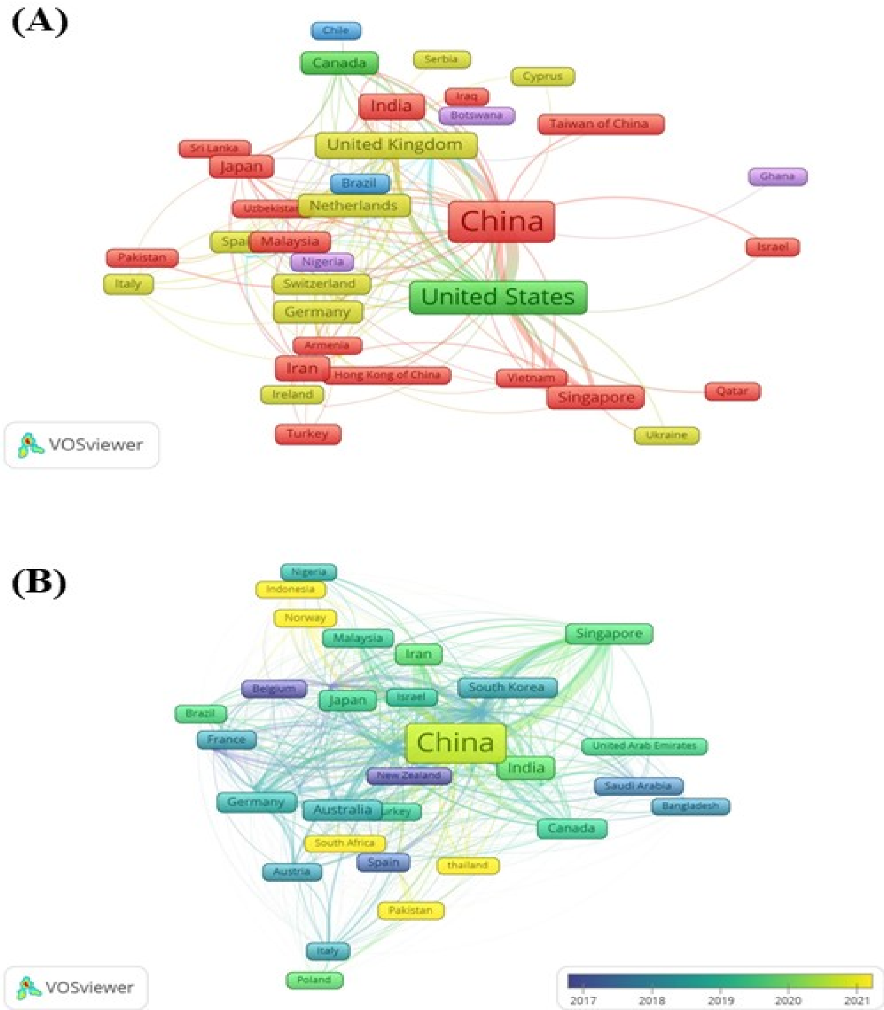

Figure 3. VOSviewer map shows (**A**) network visualisation of co-authorship analysis of countries and (**B**) overlay visualisation of bibliographic coupling of countries in the research domain. In (**A**), six interconnected clusters represent different continents, with colours corresponding to each cluster continent: red for Asia, green for North America, blue for South America, yellow for Europe, purple for Africa, and turquoise for Oceania. In (**B**), Countries classified before and during 2017 are depicted in purple, those from 2018 to early 2019 are in turquoise, those from mid-2019 to 2020 are in green, and those from 2021 onwards are in yellow. The online maps are available at https://bit.ly/3I62Sa3 and https://bit.ly/3uHfdyw (accessed on 20 February 2024).

By using colour-coded clusters, the figure enhances the understanding of international scientific collaboration patterns and highlights the distribution of collaborative networks across different continents. Figure 3A depicts six interconnected clusters representing different continents, with colours representing each cluster continent: red for Asia, green for North America, blue for South America, yellow for Europe, purple for Africa, and turquoise for Oceania. Figure 3A reveals that China leads with 30 links and a total link strength of 183, indicating its strong network collaboration and investment in knowledge dissemination. The United States follows closely with 31 links and a total link strength of 169, highlighting its research and innovation prowess. Other notable countries include Singapore, with 9 links and a total link strength of 51, and Australia, with 17 links and a total link strength of 50, showcasing their active participation and collaboration in MICP research. Interestingly, some countries with lower link counts and total link strengths, such as Botswana, Mongolia, and Uzbekistan, also contribute to the global network, albeit to a lesser extent. These data provide valuable insights into international scientific cooperation and knowledge exchange in MICP, emphasising the importance of collaboration among countries for advancing research in this area.

The VOSviewer map in Figure 3B displays an overlay visualisation of the bibliographic coupling of countries, organised by continent clusters. In the overlay visualisation of the bibliographic coupling of countries, the colours signify the classification of countries based on different periods. The countries classified before and during 2017 are depicted in purple, those from 2018 to early 2019 are in turquoise, those from mid-2019 to 2020 are in green, and those from 2021 onwards are in yellow. This colour scheme helps to distinguish the collaboration patterns and trends among countries over time, providing insights into the evolution of scientific collaboration in MICP. Figure 3B demonstrates that China also emerges as a dominant player, with 37 links and a substantial total link strength of 33,451, demonstrating its extensive collaboration and influence in the research area. The United States follows closely behind with 37 links and a total link strength of 30,200, highlighting its significant research contributions and impact. Other notable countries include the United Kingdom, with 37 links and a total link strength of 11,339, indicating its strong presence and collaboration in MICP research. Australia, Canada, and Germany also show strong bibliographic coupling, with total link strengths of 6743, 3553, and 4743, respectively, reflecting their active engagement and collaboration in the research domain. Countries with lower total link strengths, such as Indonesia, Pakistan, and Poland, also contribute to the global network, albeit to a lesser extent. These data provide valuable insights into the international collaboration and knowledge exchange in MICP research, highlighting the importance of global cooperation for advancing research and innovation in this area.

The countries identified in this bibliographic analysis are at the forefront of scientific research and innovation, especially in research related to MICP. They possess strong academic and research institutions, substantial funding for scientific endeavours, and a high level of expertise in relevant disciplines [29]. The active participation of China and the United States in international collaborations and knowledge exchange has propelled the advancement of MICP research and its applications. Singapore has also made remarkable progress in research and development, aligning with its focus on technology and innovation. Australia's commitment to environmental research aligns well with MICP's applications in soil and water management. Japan's advanced technology sector and research capabilities position it as a key player in MICP research. While countries like Iran, Canada, and the Netherlands may have smaller link strengths, they have demonstrated a strong commitment to MICP research, making meaningful contributions to the global research landscape.

3.4. Top Prolific Authors

Table 2 and Figure 4 present pertinent information about authors who have contributed to the area of study, as identified from the bibliometric data. Identifying influential authors in the research domain through bibliometric analysis is crucial for understanding research trends and fostering collaboration. The RStudio findings show 2923 authors in MICP research, contributing to 5347 publications. Of these authors, 13 have authored documents on their own, while 2910 have contributed to multi-authored documents. On average, each author has contributed to about 0.376 documents, and each document has about 2.66 authors. The collaboration index, averaging 4.87 co-authors per document, highlights a high level of collaboration among authors. RStudio's versatility in handling large datasets and performing detailed statistical analysis makes it particularly useful for analysing author information compared to VOSviewer, which is more focused on visualising author networks and co-authorship patterns [39,41].

Table 2. List of top 10 prolific authors in the research area based on publication output.

Authors	Publications	Citations	City and Country	References
Chu, Jian	31	1609	Singapore City, Singapore	[58]
Su, Junfeng	23	368	Xi'an, China	[59]
Wang, Zhao	21	320	Xi'an, China	[60]
Ali, Amjad	20	332	Xi'an, China	[60]
Achal, Varenyam	18	1552	Shantou, China	[13]
Cheng, Liang	18	1325	Zhenjiang, China	[52]
Kawasaki, Satoru	16	478	Sapporo, Japan	[13]
Dejong, Jason T.	14	3380	Davis, United States	[45]
Gerlach, Robin	14	961	Bozeman, United States	[61]
Liu, Hanlong	14	704	Chongqing, China	[62]

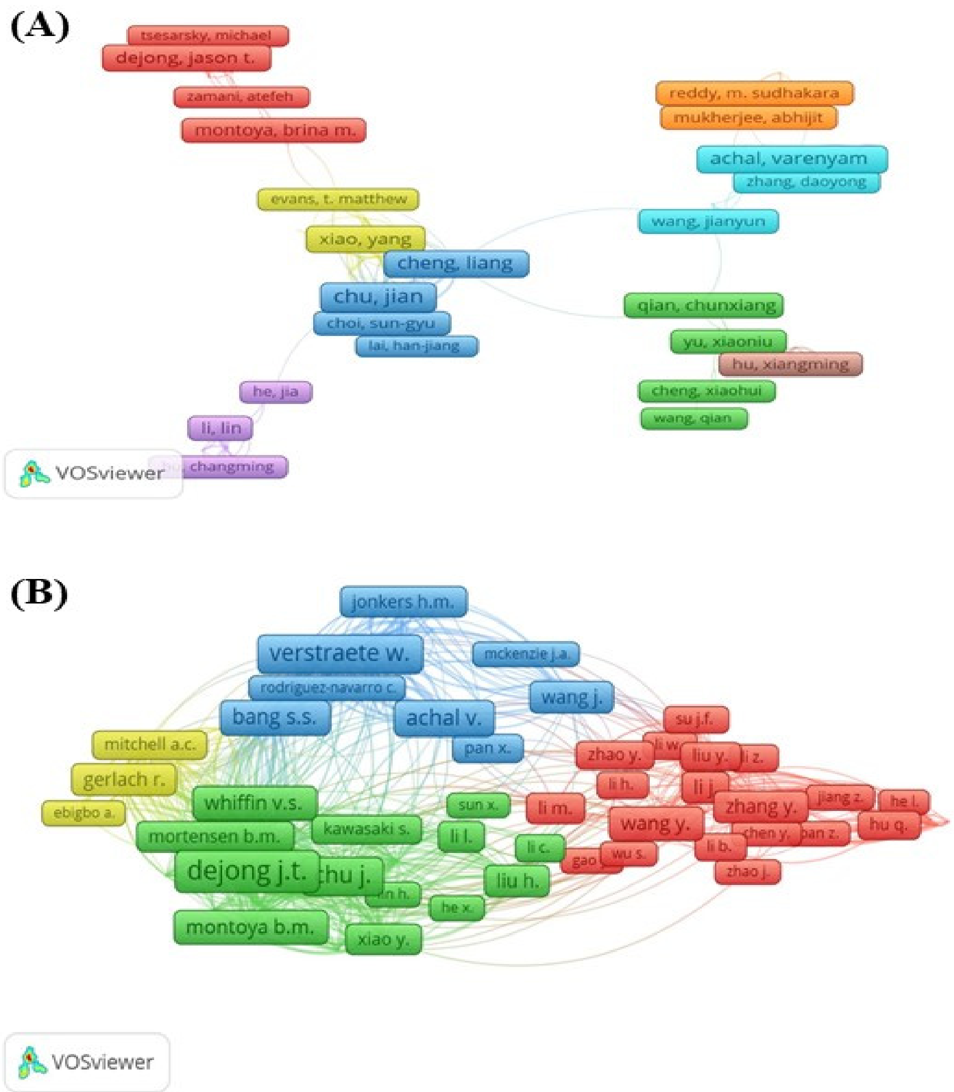

Figure 4. Network visualisation of (**A**) co-authorship analysis of authors, and (**B**) co-citation analysis of cited authors. In (**A**), the clusters and their corresponding colours are as follows: Cluster 1 is represented in red, Cluster 2 in green, Cluster 3 in blue, Cluster 4 in yellow, Cluster 5 in purple, Cluster 6 in turquoise, Cluster 7 in light brown, Cluster 8 in chocolate, and Cluster 9 in pink. In (**B**), each cluster is represented by a different colour: red for Cluster 1, green for Cluster 2, blue for Cluster 3, and yellow for Cluster 4. The online maps are available at https://bit.ly/4bIiwpA and https://bit.ly/3I6gdix (accessed on 20 February 2024).

Table 2 highlights the top prolific authors in the research area, with Chu, Jian from Nanyang Technological University leading with 31 publications and 1609 citations, followed by Su, Junfeng from Xi'an University of Architecture and Technology with 23 publications and 368 citations. Other notable authors include Achal, Varenyam from Guangdong Technion-Israel Institute of Technology, Cheng Liang from Jiangsu University, and Dejong, Jason T., who is affiliated with the University of California, United States. These authors, representing diverse affiliations, demonstrate the global collaboration within the MICP research community (see Table S2). Identifying the top prolific authors in the research area is significant as their work likely represents a substantial contribution to the advancement of MICP research. These authors may have developed innovative techniques, published seminal papers, or provided critical insights that have influenced the direction of research and the practical applications of MICP.

The co-authorship analysis of the co-authors (Figure 4A) reveals collaborative patterns among 71 authors, forming nine distinct clusters. VOSviewer classified the identified authors into nine different clusters, each represented by a distinct colour. The clusters and their corresponding colours are as follows: Cluster 1 is represented in red, Cluster 2 in green, Cluster 3 in blue, Cluster 4 in yellow, Cluster 5 in purple, Cluster 6 in turquoise, Cluster 7 in light brown, Cluster 8 in chocolate, and Cluster 9 in pink. These colours are used to visually differentiate between the different clusters of authors based on their collaboration patterns and relationships within the dataset. This colour coding helps to highlight the various groups of authors and their connections, enabling a clearer understanding of the co-authorship networks within the research domain. Cluster 1, led by Dejong, Jason T. and Gomez, Michael G., boasts a total link strength of 28, reflecting their significant contributions, with 14 documents and 3380 citations. Cluster 2, featuring authors like Qian, Chunxiang and Yu, Xiaoniu, shows moderate collaboration with a total link strength of 10. Cluster 3, led by Chu, Jian and Cheng, Liang, demonstrates a robust network with a total link strength of 76, indicating influential contributions with 31 documents and 1609 citations. Similarly, Cluster 4, led by Liu, Hanlong and Xiao, Yang, shows a strong network with a total link strength of 49, maintaining impact through collective publications and citations. Clusters 5 to 9 include nine, eight, seven, six, and two authors, respectively, showcasing varying degrees of collaboration.

On the other hand, the co-citation analysis of the authors (Figure 4B) highlights scholarly influence and thematic connections. The VOSviewer result shows the network visualisation of the co-citation analysis of the cited authors, classified into four clusters. Each cluster is represented by a different colour: red for Cluster 1, green for Cluster 2, blue for Cluster 3, and yellow for Cluster 4. These colours are used to visually distinguish between the different clusters of cited authors based on the co-citation patterns in the dataset. The clustering helps to identify groups of authors whose work is frequently cited together, providing insights into the influential authors and key research themes in MICP.

Cluster 1, with authors like Wang Y. and Cheng L., features high co-citation counts, indicating significant contributions in areas such as MICP applications in geotechnical engineering and environmental remediation. Cluster 2, including authors such as Dejong J.T., Van Paassen L.A., and Soga K., shows substantial co-citation links, indicating collaborative efforts in MICP technology and biogeotechnical engineering. Cluster 3, with authors like Verstraete W., De Belie N., and Achal V., focuses on microbiology, cementitious materials, and sustainable construction, exploring environmental implications and infrastructure durability. The collaborative patterns among authors, as revealed by the co-authorship analysis, indicate the level of cooperation and knowledge exchange within the MICP research community. These collaborations may have resulted in more comprehensive studies, innovative approaches, and interdisciplinary research that have contributed to the study's growth and development.

3.5. Top Preferred Journals

Table 3 presents the leading Scopus-indexed journals in the research domain. *Construction and Building Materials*, published by Elsevier in the UK, stands out with 62 publications, 3124 citations, and a CiteScore of 13.5, ranking in Q1. Other notable journals include *Journal of Petroleum Science and Engineering* (Elsevier, The Netherlands), with 45 publications and a CiteScore of 11.1 in Q1, and *Journal of Geotechnical and Geoenvironmental Engineering* (American Society of Civil Engineers, USA), with 38 publications and a CiteScore of 7.3 in Q1. These journals, along with the others listed, demonstrate strong publication and citation counts, high CiteScores, and Q1 rankings, indicating their significance and impact in the research domain. Targeting reputable journals for submission can enhance the accessibility, credibility, readership, and impact of research findings within the scientific community. These top 10 journals are suitable for MICP researchers due to their focus on construction materials, geotechnical engineering, environmental science, and related disciplines, aligning well with the multidisciplinary nature of MICP research and offering a platform for impactful dissemination. Other relevant information regarding the preferred journals for publishing MICP-related articles is presented in Table S3.

Table 3. Leading journals in the research domain that are indexed in the Scopus database.

Journals	Publications	Citations	Publisher
Construction and Building Materials	62	3124	Elsevier
Journal of Petroleum Science and Engineering	45	914	Elsevier
Journal of Geotechnical and Geoenvironmental Engineering	38	5291	American Society of Civil Engineers
Marine and Petroleum Geology	37	1528	Elsevier
Journal of Materials in Civil Engineering	20	779	American Society of Civil Engineers
Journal of Natural Gas Science and Engineering	19	516	Elsevier
Chemosphere	17	391	Elsevier
Geomicrobiology Journal	16	1244	Taylor & Francis Ltd.
Acta Geotechnica	15	448	Springer Nature
Journal of Environmental Management	15	242	Elsevier

The bibliographic coupling analysis of the MICP journals reveals distinct thematic clusters and research interconnections (Figure S2). Cluster 1, with journals like *Ecological Engineering* and *Journal of Environmental Management*, centres around Construction and Building Materials, highlighting its pivotal role in disseminating research in this area. Cluster 2, including journals such as *Journal of Geotechnical and Geoenvironmental Engineering*, features interdisciplinary research in geotechnical and civil engineering, with Water Resources Research as a notable node. Cluster 3, comprising *Marine and Petroleum Geology* and the *Journal of Petroleum Science and Engineering*, focuses on energy exploration and geological studies, especially in petroleum and coal geology. Cluster 4, with journals like *Acta Geotechnica* and *Applied Microbiology and Biotechnology*, suggests moderate thematic coherence, possibly highlighting niche areas within MICP applications, such as geotechnical engineering and environmental remediation. This clustering based on bibliographic coupling indicates similarity between journals, as they often cite similar references, reflecting interconnectedness and thematic coherence in their respective area of study. Additionally, citing impactful papers from reputable journals can strengthen researchers' manuscripts and demonstrate an awareness of key contributions in MICP.

3.6. Keywords and Textual Co-Occurrence Analyses via VOSviewer

In the co-occurrence analysis of the author keywords (Figure 5), VOSviewer examined how often the keywords chosen by the authors can be used to encapsulate the main themes of their research publications. VOSviewer identifies patterns in scholarly publication metadata, revealing common themes and relationships between different research areas based on their frequency of discussion by authors [63]. The result indicated that 110 keywords were identified, and reappeared at least five times in the literature. The VOSviewer program identified the top 15 author keywords with the highest frequency, presented in Table S4. Among the listed keywords, certain terms emerge as particularly significant due to their high occurrences. Notably, "MICP" (microbial-induced carbonate precipitation) stands out with the highest number of occurrences (162), followed by keywords such as "calcium carbonate", with 63 occurrences; "permeability", with 60 occurrences; and "*Sporosarcina pasteurii*", with 57 occurrences, which demonstrate substantial relevance and frequency in the literature.

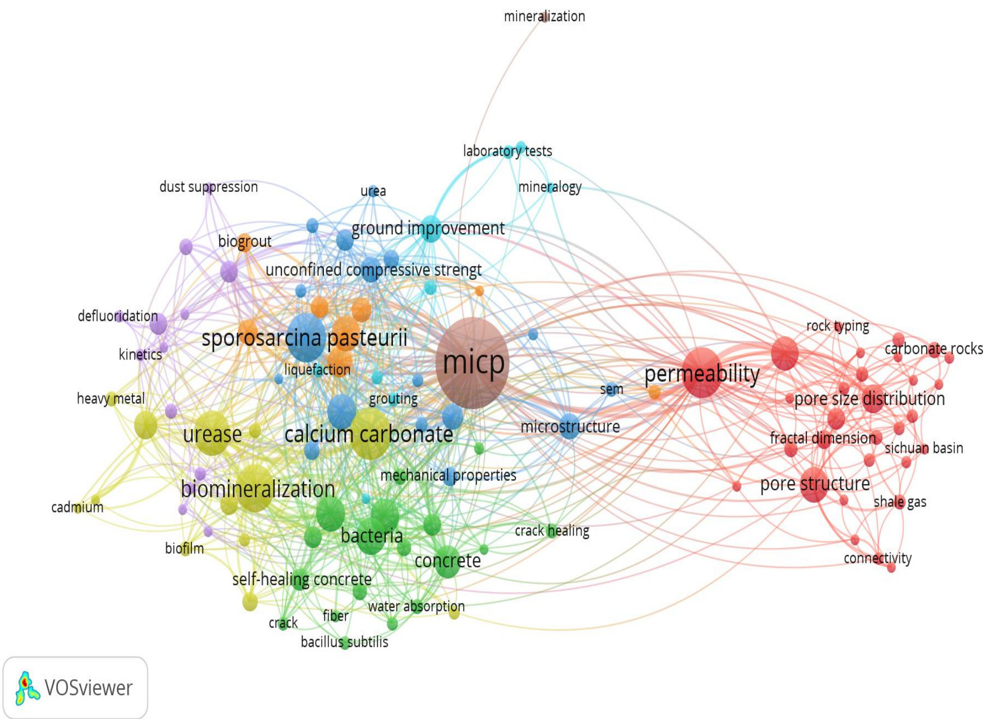

Figure 5. Network visualisation of co-occurrence of author keywords in the research domain. The clusters in the figure and their respective colours include Cluster 1 (red), Cluster 2 (green), Cluster 3 (blue), Cluster 4 (yellow), Cluster 5 (purple), Cluster 6 (turquoise), Cluster 7 (brown), and Cluster 8 (chocolate). The online map is available at https://bit.ly/49YOw7x (accessed on 20 February 2024).

The co-occurrence analysis in Figure 5 reveals eight distinct thematic clusters in MICP. Cluster 1 (red) focuses on "permeability" which is essential for understanding fluid flow in porous materials such as soil or rock, making it crucial to the hydrodynamics of MICP studies [64]. Cluster 2 (green) focuses on "bacteria", particularly in construction materials and durability, highlighting MICP applications for enhancing concrete structures [65,66]. Cluster 3 (blue) revolves around "*Sporosarcina pasteurii*", commonly used in MICP research, emphasising its role in environmental engineering and soil improvement [4,23,50,56,67]. Cluster 4 (yellow) explores the versatile mineral "calcium carbonate", pivotal in MICP processes and environmental applications, such as groundwater management/treatment [59,60,68].

Cluster 5 (purple) concentrates on "calcite precipitation", spanning microbial processes, environmental applications, and geotechnical engineering [62,69,70]. Cluster 6 (turquoise) centres on "ground improvement", employing multidisciplinary approaches to strengthen the soil and enhance ground stability [10,19,71]. Cluster 7 (brown) focuses on "soil improvement strategies", emphasising sustainability and mechanical properties to mitigate geological hazards [58,62,72]. Lastly, Cluster 8 (chocolate) centres on "MICP", exploring techniques, applications, and associated research themes to develop sustainable solutions for soil stabilisation and environmental remediation [3,48,73].

The co-occurrence analysis of text data involves examining word or phrase occurrences in research articles' titles and abstracts to uncover implicit relationships between terms. VOSviewer programs use this analysis to reveal common themes or topics within a document corpus. Unlike author keywords, co-occurrence analyses of text data allow researchers to uncover implicit relationships based on term occurrences within documents' text. Figure 6 shows two clusters identified through the VOSviewer analysis, offering insights into diverse research areas. Cluster 1 (Red), labelled as "Microbial Cementation", suggests a strong interest in microbial activities, biomineralisation processes, and the properties of $CaCO_3$ precipitates [74–76]. This cluster reflects a growing emphasis on the application of MICP in soil improvement, crack healing, and bioremediation. It indicates a continued interest in understanding microbial species, bacterial strains, and the mechanisms of bio-cementation and biogrouting [77,78].

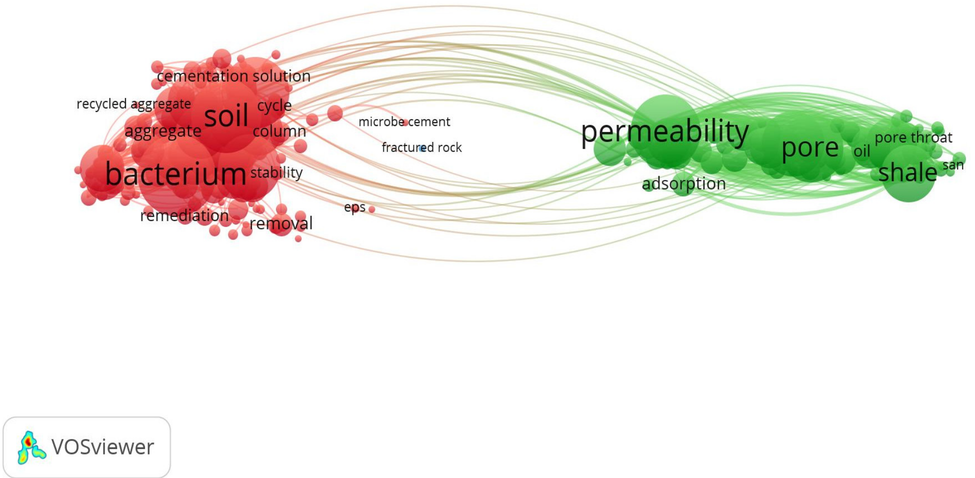

Figure 6. Network visualisation of co-occurrence of text data in the research domain. The two clusters in the figure and their respective colours are Cluster 1 (red), and Cluster 2 (green). The online map is available at https://bit.ly/3uEySit (accessed on 20 February 2024).

This cluster suggests that future research in the research domain may continue to explore the optimisation of MICP techniques and their application in various environmental and engineering contexts. On the other hand, Cluster 2 (Green), designated as "Geological Properties", highlights a focus on the physical and chemical properties of geological materials, particularly in carbonate reservoirs and shale formations [79,80]. This cluster indicates a growing interest in understanding the permeability, porosity, pore structure, and pore connectivity of these materials. It suggests that future research may focus on improving our understanding of the geological aspects of MICP, potentially exploring its application in enhancing the properties of geological formations for various purposes.

Recent research in MICP indicates a shift towards emerging areas, as reflected in keywords associated with articles published in 2024 (Figure S3). There is a clear focus on advancing materials and techniques, as evidenced by terms like "nano-silica", "chemical ductilization", and "secondary metabolite", suggesting innovative approaches to enhance MICP processes and properties. With concrete facing challenges such as shrinkage, permeability, and environmental pollution, and the cement industry being a significant contributor to global CO_2 emissions, the increasing interest in using MICP for environmental applications is evident. Keywords such as "soil ecological restoration", "soil–water separation", and "heavy metal removal" highlight a strong focus on leveraging MICP for environmental remediation and sustainability. These trends suggest a promising direction for the research domain, with continued emphasis on innovation and environmental stewardship.

3.7. Keyword Analysis via RStudio

The word cloud in Figure 7A illustrates the 50 most frequently used author keywords identified in the RStudio analysis, visually representing their frequency of occurrence. These terms, such as "calcium carbonate" (895), "calcite" (475), "biomineralization" (210), and "carbonate precipitation" (291), highlight their significance and prevalence in MICP research. Other notable keywords like "urea" (283), "carbonation" (238), and "bacteria" (227) indicate key areas of interest within the area of study. These keywords provide insights into the main themes and focus areas of research related to MICP. On the other hand, Figure 7B presents the 50 most frequently reoccurring author keywords identified in the RStudio analysis. Prominent keywords include "MICP" (162), "calcium carbonate" (63), "permeability" (60), "Sporosarcina pasteurii" (57), and "biomineralization" (55), reflecting major research themes within MICP. Other keywords like "pore structure", "porosity", and "compressive strength" further emphasise the diverse range of topics and research interests within the MICP domain. These results highlight a focus on chemical processes, microbial activities, and material properties relevant to MICP applications, validating the findings from the VOSviewer analysis (Figure 5) and offering a comprehensive view of the hydrodynamic interests driving MICP studies.

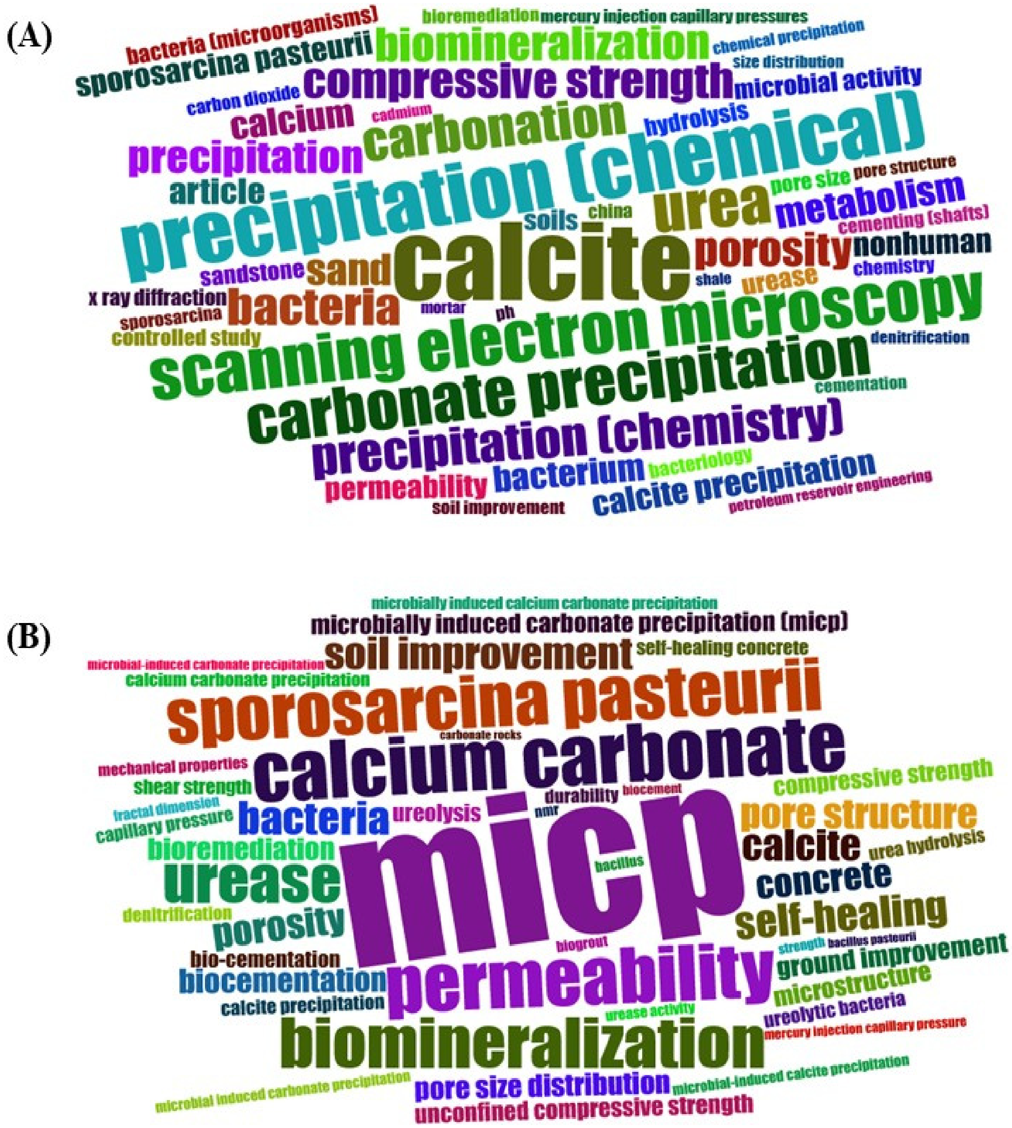

Figure 7. Author keyword analysis from a text file using RStudio. (**A**) Word cloud of top 50 frequently used keywords; (**B**) word cloud for top 50 recurring author keywords.

RStudio was chosen for keyword analysis to complement the VOSviewer analysis, particularly for the co-authorship analysis of the author keywords, due to its versatility and robustness in handling statistical and data visualisation tasks. RStudio's integration with R, a powerful programming language for statistical computing, allows for efficient data manipulation, statistical analysis, and the creation of visually appealing word clouds [31,41]. This makes RStudio effective in visually representing the frequency of occurrence of keywords. This combination of features makes RStudio a suitable tool for analysing and presenting the frequency and relationships of author keywords in bibliometric studies like the one conducted in this research. In addition, RStudio's capabilities in data visualisation can help validate the findings from the VOSviewer analysis. By providing a different perspective and analytical approach, RStudio's keyword analysis can corroborate the trends and insights identified in VOSviewer, enhancing the robustness and reliability of the overall bibliometric analysis.

The relationship between the keywords, authors, and countries was analysed using RStudio, as demonstrated in Figure 8. The analysis of the text file revealed that keywords such as self-healing, concrete, MICP, pore structure, porosity, pore size distribution, bacteria, biomineralisation, bioremediation, permeability, calcite, and ground improvement are frequently mentioned by scholars from China, the United States, Iran, India, Malaysia, Australia, Germany, the United Kingdom, Japan and Singapore.

The prominent authors that are affiliated with China include Wang Z. [60], Su J. [59], Zhang Y. [73], Hu Q. [81], Wang Y. [82], Zhao Y. [69], Li Z. [83], Liu H. [62], Wang X. [84], Wang J. [85], and Chu J. [58]. The authors who are affiliated with the United States include Ali A. [60], Zhang J. [78], Li Y. [62], Wang Z. [60], Li J. [84], Chu J. [58], Achal V. [13], Cheng L. [52], and Kawasaki S. [13]. The authors linked with India include Zhang Y. [73], Hu Q. [81], Wang Y. [82], Zhao Y. [69], Zhang J. [78], Li Z. [83], Liu H. [62], Li Y. [62], Wang X. [84], and Wang J. [85]. Figure 8 also showed there are some other authors (Kawasaki S. [13], Chu J. [58], Li Z. [83], Li J. [84] Zhang Y. [73], Wang Y. [82], Achal V. [13], Zhao Y. [69], Li Y. [62], Liu H. [62], Wang X. [84], Wang J. [85], Cheng L. [52], Gerlach R. [86], and Dejong J.T. [45]) that are associated with Japan, Malaysia, Singapore, The United Kingdom, Iran, Germany and Australia. These researchers have contributed to MICP by investigating studies covering various aspects of MICP and its applications, including the removal of pollutants (such as ammonia nitrogen, calcium, and heavy metals), soil stabilisation, slope preservation, and temperature-dependent MICP processes. They also explore the use of biomineralisation for effective and environmentally friendly remediation techniques [82,84,87,88]. MICP offers solutions to these challenges by providing methods for soil improvement, crack healing in concrete, the bioremediation of contaminated sites, and the enhancement of construction materials' properties [89].

Seto et al. [90] highlighted the importance of clay materials in construction and engineering. The study focused on the interaction between amorphous calcium carbonate and kaolinite to form complex composites with hierarchical structures, which is relevant to MICP. MICP uses similar principles of mineral precipitation to strengthen soil and concrete, making this research applicable to understanding the mechanisms behind MICP. Amorphous calcium carbonate is a precursor form of $CaCO_3$ that plays a crucial role in biomineralisation, serving as an antecedent for the formation of crystalline $CaCO_3$ polymorphs. Additionally, the Japanese pearl oyster (*Pinctada fucata*) n16 framework matrix protein has previously been shown to act as an anchor for aragonite formation and to regulate aragonite formation itself [91]. This is significant because aragonite, a stable form of $CaCO_3$, possesses high solubility compared to its counterparts like calcite, making it highly sought after for applications such as soil stabilization and crack healing in concrete. Therefore, researchers are actively involved in MICP studies to address these environmental issues and promote sustainable development. This bibliometric study has shown that researchers worldwide are also benefiting from MICP's vast potential to provide sustainable solutions to various issues.

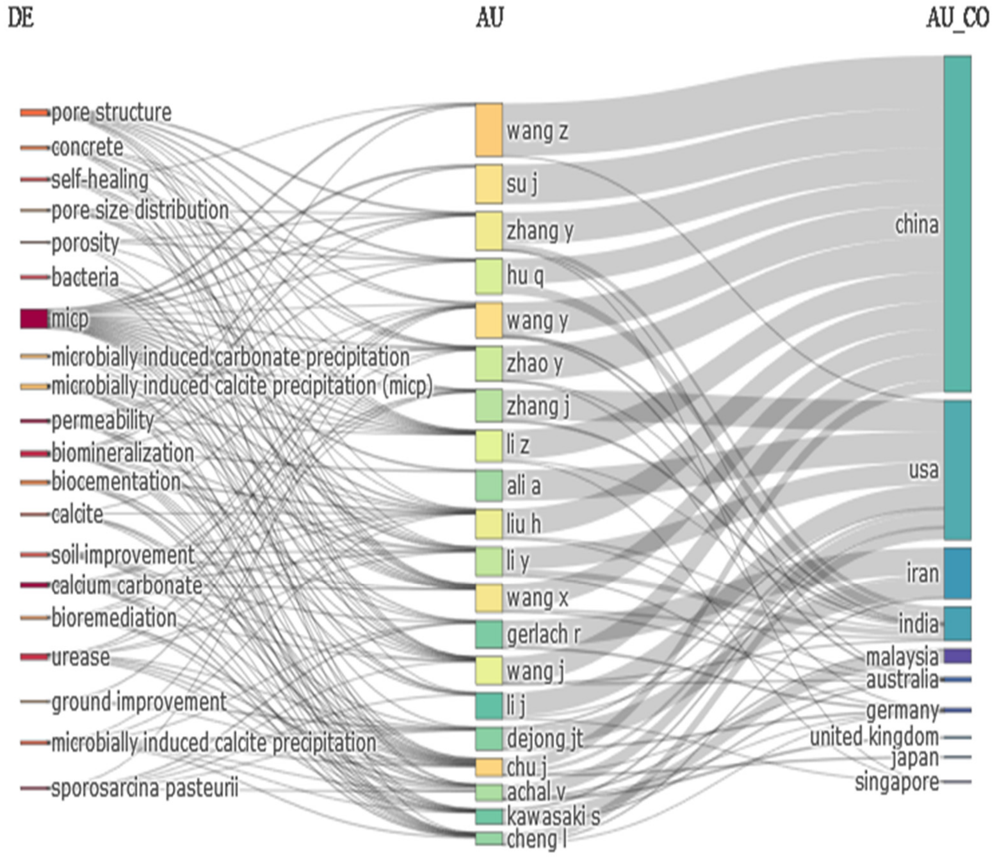

Figure 8. Three-field plot showing the highest-frequency author keywords (on the left), authors (in the centre), and countries (on the right), generated from text file analysis using RStudio. The most prominent author include Wang Z. [60], Zhang Y. [73], Su J. [59], Hu Q. [81], Wang Y. [82], Zhao Y. [69], Liu H. [62], Chu J. [58], Wang J. [85], Zhang J. [78], Li Z. [83], Ali A. [60], Gerlach R. [86], Wang X. [84], Li Y. [62], Li J. [84], Dejong J.T. [45], Cheng L. [52], Achal V. [13], and Kawasaki S. [13].

4. Evolutionary Trends in Hydrodynamics Research on MICP

Between 1999 and 2024, research in MICP has evolved significantly, reflecting a growing interest in sustainable construction and environmental management practices. The evolution of the studies was grouped into four different eras, as shown in Figure S4 and Table S5. Initially, from 1999 to 2005, MICP research was in its early stages, with limited publications focusing on the fundamental aspects of microbial species and chemical processes. Subsequently, from 2006 to 2012, there was significant growth in MICP research, driven by advances in biotechnology and environmental engineering. From 2013 to 2017, MICP research continued to mature, with a focus on practical applications and field-scale demonstrations. Efforts were made to optimise MICP processes for large-scale implementation in civil and environmental engineering projects. In the most recent period, from 2018 to 2024, MICP research has rapidly expanded and diversified, driven by the need for sustainable solutions. This phase has seen a focus on developing novel MICP techniques. Further discussion of the research evolution is shown below.

4.1. Early Direction (1999–2005)

Stocks-Fischer et al. [46] initiated a groundbreaking study into microbial mineral plugging, revealing how *Bacillus pasteurii* (now known as *Sporosarcina pasteurii*) significantly accelerates $CaCO_3$ precipitation, offering insights into environmental remediation applications. Santhosh et al. [48] applied these concepts to concrete repair, showing the ureolytic bacterium's ability to enhance mortar strength. Bachmeier et al. [92] explored the enzymatic processes behind microbial calcite creation, underscoring urease's key role.

Canet et al. [93] discovered the potential of MICP in high-temperature hydrothermal vents, broadening the known environments for microbial calcite formation. Chekroun et al. [94] investigated bacterial carbonate morphologies, aiming to distinguish between biotic and abiotic formations, while Mozley and Davis [95] focused on calcite concretions to infer paleo-groundwater flow, offering new insights into the environmental impacts on MICP. Collectively, these studies from 1999 to 2005 significantly advanced our understanding of MICP, demonstrating its diverse applications in environmental remediation, structural engineering, and geological exploration. This convergence illustrates how understanding the intricate relationships between microbes and mineral formation can lead to innovative solutions for environmental restoration and structural repair. The progression from fundamental microbial processes to practical applications in construction and environmental management highlights the critical role of foundational science in driving technological advancements and addressing complex challenges. More so, these fundamental MICP researches likely contributed to understanding how hydrodynamics influence microbial mineral precipitation, offering insights into how fluid flow patterns affect the distribution and formation of calcite in porous media.

4.2. Advancing MICP Potential Implementation (2006–2012)

The period from 2006 to 2012 marked a significant evolution in the area of study, with researchers exploring new methods and applications. DeJong et al. [47] investigated the use of natural microbial processes to engineer a cemented soil matrix, demonstrating enhanced shear behaviour and cementation levels through MICP. Jimenez-Lopez et al. [96] introduced a user-friendly method for stone consolidation using a sterile culture medium, activating ureolytic bacteria within decayed porous limestone to induce $CaCO_3$ precipitation. Bissett et al. [97] studied the role of biofilms in controlling stromatolite formation, showing how microbial activity influences chemical conditions and $CaCO_3$ precipitation rates. Van Paassen et al. [49] explored biogrouting as a ground improvement method, using *Sporosarcina pasteurii* to induce $CaCO_3$ in granular soils, resulting in increased strength and stiffness. De Muynck et al. [55] examined the influence of chemical parameters on stone consolidation, finding that the amount of $CaCO_3$ precipitated in limestone could be controlled by adjusting calcium salt and urea concentrations. Achal et al. [98] focused on microbially enhanced calcite precipitation on concrete, demonstrating that bacterial deposition of calcite can improve concrete durability. Burbank et al. [99] investigated the in-situ precipitation of calcite by indigenous microorganisms in potentially liquefiable soils, showing that biomineralised soils exhibit increased resistance to seismic-induced liquefaction. Finally, Weil et al. [100] studied the use of non-destructive measurements such as seismic velocity and resistivity to monitor the extent of MICP in sands, providing insights for the real-time monitoring of MICP processes in geotechnical applications. In this era, there is a shift towards practical MICP applications like ground improvement and stone consolidation, marking a move from theory to practice. Researchers optimised the MICP process by testing various ureolytic microbial strains, nutrients, and environmental conditions. They also study how microbial activity interacts with factors like pH, temperature, and nutrients, showing the complexity of MICP in different environments. Studies on hydrodynamics likely improve our understanding of how fluid flow affects microbial mineral precipitation, influencing calcite distribution in porous media.

While MICP is a well-established biomineralisation process for inducing $CaCO_3$ formation, enzyme-induced carbonate precipitation (EICP) has also emerged as a noteworthy alternative. Similar to MICP in terms of mechanism, EICP does not rely on microbial activity to induce $CaCO_3$ formation. This eliminates the need for maintaining specific microbial cultures, reducing the risk of contamination and allowing for easier application in various environments. EICP typically involves the use of pure urease, often sourced from plants like Jack bean, to catalyse urea hydrolysis [101,102]. This process produces carbonate ions and alkalinity, leading to calcium carbonate precipitation in the presence of calcium cations [103]. EICP has been shown to produce carbonate precipitates with higher ductility, indicating greater resistance to crack propagation. This property can lead to improved mechanical properties in treated materials, such as higher compressive strengths [104]. Additionally, studies have shown that adding a non-fat powdered milk solution containing plant urease can significantly enhance the strength of silica sand specimens at a low carbonate content [103]. Additionally, plant urease can also be sourced from other crude alternatives, such as soya beans and watermelon seeds [105–108]. This makes EICP cost-effective, requiring fewer resources and enabling it to be carried out without the use of commercially available urease enzymes.

4.3. Laboratory to Field-Scale Applications of MICP (2013–2017)

The period between 2013 and 2017 saw significant advancements in the research domain. Researchers explored various strategies and applications of MICP, focusing on its potential for sealing high permeability regions in cap rocks for carbon dioxide (CO_2) storage, soil stabilisation, and concrete improvement. Phillips et al. [86] highlighted the use of low-viscosity fluids to distribute biofilm-induced-$CaCO_3$ precipitates for sealing fractured cores, suggesting potential applications for CO_2 leakage mitigation. Cheng et al. [52] investigated the geotechnical properties of bio-cemented sand under different degrees of saturation, demonstrating higher soil strength at low saturation levels. Abo-El-Enein et al. [109] studied the improvement in cement-sand mortar strength and water absorption through MICP, showing a significant increase in compressive strength with bacterial cell incorporation. Cuthbert et al. [110] presented field experiments applying MICP to reduce fractured rock permeability, demonstrating the technique's potential for pollution mitigation. Lauchnor et al. [111] explored ureolysis-driven strontium coprecipitation for groundwater remediation, suggesting a pulsed injection strategy for efficient precipitation. Keykha et al. [112] utilised electrokinetics to enhance soft clay soil strength by injecting carbonate produced by bacteria. Mountassir et al. [113] studied the influence of MICP in rock fractures, highlighting the feedback mechanism between fracture aperture reduction and fluid velocity. Senthilkumar et al. [114] reported significant enhancements in the compressive strength of cement mortar specimens through bacterial carbonate precipitation.

Ganendra et al. [115] investigated the effectiveness of MICP from formate oxidation for concrete protection, demonstrating reduced water absorption in bacterially treated specimens. Lee et al. [116] explored the role of *Sporosarcina pasteurii* in cement paste hydration, showing accelerated early hydration with a urea-$CaCl_2$ culture medium. Amidi and Wang [85] proposed a surface treatment method using mineral precipitation for concrete durability enhancement, using green solvent dimethyl carbonate to overcome MICP drawbacks. Lauchnor et al. [117] studied ureolysis kinetics with *S. pasteurii*, suggesting simplified first-order kinetics for urea hydrolysis. Sotoudehfar et al. [118] optimised MICP process parameters using the Taguchi method for soil improvement, demonstrating a significant increase in the unconfined compressive strength. Rowshanbakht et al. [119] investigated the effect of reducing the injected bacterial suspension volume on soil improvement, showing that up to a one-third reduction did not significantly affect performance improvement. Feng and Montoya [120] studied the behaviour of MICP cemented sand under different confining pressures, showing increased stiffness and strength with higher calcite content and confining pressure. Salifu et al. [121] applied MICP to mitigate erosion and stabilise foreshore slopes, demonstrating a significantly improved slope stability. Amin et al. [2] investigated MICP as a method for reducing hydraulic erosion in earth dams and embankments, showing a significant reduction in erodibility and increased critical shear stress. Tang et al. [122] studied loose sand consolidation using MICP, demonstrating improved bonding with optimised injection parameters. Wu et al. [123] investigated MICP for enhanced oil recovery, demonstrating significant permeability reduction and oil recovery improvement. Bao et al. [124] explored MICP as an erosion countermeasure, demonstrating the negligible erosion of treated sand in laboratory tests. These studies collectively represent the evolution of MICP from laboratory-scale demonstrations to field applications, highlighting its potential for a wide range of geotechnical and environmental engineering applications. Studies from 2013 to 2017 highlight MICP's effectiveness in geotechnical and environmental applications. They show that MICP improves soil strength, reduces permeability, and stabilises slopes. Researchers study parameters like the bacterial concentration, nutrient solution ratio, curing time, and flow rate's impact on MICP efficiency. To optimise MICP for soil stabilisation, and groundwater improvement, understanding hydrodynamic processes is crucial.

4.4. Emerging Frontiers and Directions in the Field (2018–2024)

From 2018 to 2024, research in the domain has advanced significantly, with studies focusing on various applications and methodological improvements. Tian et al. [125] evaluated the feasibility of using MICP to cement aeolian sandy soil and reduce wind erosion risk, demonstrating effective wind erosion resistance through MICP treatment. Song and Elsworth [79] explored the use of MICP to strengthen coal and enhance hydraulic fracturing, emphasising the importance of mineralisation distribution and particle bonding quality. Nassar et al. [126] developed a modelling approach to predict MICP behaviour under controlled conditions, highlighting the significance of transient nonuniform transport in natural soil. Gomez et al. [127] investigated the enrichment of native ureolytic microorganisms for bio-cementation, suggesting potential cost and environmental benefits. Zambare et al. [61] studied MICP under radial flow conditions, providing insights into the effects of fluid flow rates and calcium concentrations on the mass and distribution of calcite precipitation. Montoya et al. [128] examined the impact of MICP treatment on coal ash specimens, demonstrating reduced compressibility and hydraulic conductivity. Wang and Nackenhorst [129] developed a coupled bio-chemo-hydraulic model to predict MICP performance in permeability reduction, highlighting the importance of the maximum urease rate in biochemical hydraulic responses. Hataf and Baharifard [130] explored the reduction in permeability in landfill-based soil using MICP, indicating the potential of MICP as an eco-friendly method for reducing soil permeability. These studies collectively demonstrate the diverse applications and advancements in MICP technology, showcasing its potential for various engineering and environmental applications.

Shougrakpam and Trivedi [131] conducted submerged and surface percolation treatments in sand using a calcium–rich solution for MICP. The alkaline conditions promoted calcite precipitation, binding sand particles and increasing the soil matrix strength. Arpajirakul et al. [132] evaluated clays treated with urea–Ca^{2+} solutions, finding that optimal concentrations promoted calcite precipitation and improved soil strength. Elmaloglou et al. [133] studied MICP in microfluidic devices, showing heterogeneous networks had higher crystal growth rates but a lower overall efficiency than homogeneous networks. Fu et al. [134] studied *Sporosarcina pasteurii* growth and crack repair efficiency in seawater, finding reduced mineralisation but effective crack healing. Lu et al. [83] proposed a combined injection-diffusion method for crack repair, demonstrating superior performance to traditional injection methods. Huang et al. [89] used MICP to strengthen sandy slopes, reducing erosion and improving stability. Nagy and Kustermann [135] investigated MICP injections for building rehabilitation, finding increased strength and reduced porosity in the treated samples. Raveh-Amit et al. [14] used bio-stimulation to induce urea hydrolysis and MICP in loess soil, reducing erosion and crack formation. Liu et al. [136] demonstrated MICP's ability to suppress desiccation cracks in clayey soil, improving soil structure. Jin et al. [88] synthesised a vaterite-based calcium carbonate adsorbent using MICP for heavy metal removal, showing high efficiency and stability. Bu et al. [137] inhibited the alkali–silica reaction in concrete using MICP, with better results at lower saturation degrees. These studies provide valuable insights into the impact of hydrodynamics on MICP in various environmental and engineering applications. The studies also mention the impact of factors such as fluid saturation degree, cementation reagents rate, and seawater salinity on the efficiency and effectiveness of MICP. These factors influence microbial activity, calcium carbonate precipitation, and the overall performance of MICP in various applications, including soil stabilisation, crack suppression, and heavy metal remediation.

5. Conclusions

The comprehensive analysis of the publication and citation trends, global distribution, prolific authors, and preferred journals, and the co-occurrence analyses of the author keywords and research terms relevant to the impact of hydrodynamics on MICP reveals several key insights. The data illustrate a significant increase in both publications and citations, particularly from 2018 onwards, indicating a growing interest and recognition of MICP's potential applications in addressing contemporary challenges in environmental and civil engineering domains. This trend underscores the evolving nature of MICP research and its increasing prominence within the scientific community. The global distribution of research contributions highlights the participation of 66 countries, with notable leadership from China, the United States, and European nations like the United Kingdom, Germany, and the Netherlands. This widespread engagement reflects the global relevance and collaborative nature of MICP research, with diverse regions contributing to advancing knowledge and innovation in the research domain. The identification of top prolific authors and preferred journals underscores the collaborative and interdisciplinary nature of MICP research, with authors from various institutions and locations demonstrating global collaboration. Journals covering a wide range of topics related to MICP, geotechnical engineering, and environmental science serve as important platforms for disseminating research findings and facilitating knowledge exchange. The co-occurrence analyses of author keywords and research terms reveal thematic clusters and key research areas within the area of study, highlighting important themes such as permeability, bacterial activity, calcite precipitation, and ground improvement. These analyses provide valuable insights into the current research landscape and emerging trends within the research domain. In conclusion, the findings from this bibliometric review offer a comprehensive understanding of the research progression in MICP. The identified trends, patterns, and emerging research areas provide valuable guidance for future research directions, interdisciplinary collaborations, and strategic planning in advancing MICP research and its applications for addressing environmental challenges and enhancing civil engineering practices. As the research area continues to evolve, continuous monitoring and analysis will be essential to stay abreast of emerging trends and further contribute to advancing knowledge and innovation in MICP research.

In light of the findings from this bibliometric analysis and review of research evolution, several recommendations for future research emerge. Future research could explore MICP's practicality in calcareous and laterite soils. Further exploration is necessary to investigate its potential applications in cementing aeolian sandy soil, coal strengthening, hydraulic fracturing enhancement, and alkali–silica reaction inhibition in concrete. This will expand its potential to address engineering and environmental challenges. Research efforts should be directed towards optimising bacterial strains and biostimulation or bioaugmentation techniques to improve the efficiency and effectiveness of MICP processes. This will help in reducing treatment costs for field–scale needs. Furthermore, there is growing interest in the use of MICP in sustainable construction practices, suggesting a need for interdisciplinary collaborations between microbiologists, civil engineers, and environmental scientists. Finally, the continuous monitoring and analysis of emerging trends in MICP research will be essential to stay at the forefront of innovation and contribute meaningfully to addressing environmental challenges and enhancing civil engineering practices.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/hydrology11050061/s1, Table S1. Strategies used to refine and attain final documents from the Scopus database. Table S2. Important information about 10 prolific authors available in Scopus database. Table S3. Other information about top Journals in the field. Table S4. Top 15 author keywords. Table S5. Evolution of MICP research from 1999 to 2024. Figure S1. Network visualisation of the top most co-cited references in the field. The clusters and their respective colours are Cluster 1 (red), Cluster 2 (green) and Cluster 3 (blue). The online map is available at https://bit.ly/3UMSpYG (accessed on 20 February 2024). Figure S2. Network visualisation of bibliographic coupling of journals. The online map is available at https://bit.ly/3wgsZZa (accessed on 20 February 2024). Figure S3. Network visualisation of co-occurrence of author keywords from only 2024 publications. The clusters and their respective colors are Cluster 1 (red), Cluster 2 (green), Cluster 3 (blue), Cluster 4 (yellow), Cluster 5 (purple), Cluster 6 (turquoise), and Cluster 7 (brown). The online map is available at https://bit.ly/3OOqCDq (accessed on 20 February 2024). Figure S4. Research evolution and focus in the field.

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