Two Decades of Research Trends in Microbial-Induced Carbonate Precipitation for Heavy Metal Removal: A Bibliometric Review and Literature Review

Armstrong Ighodalo Omoregie[a], Dominic Ek Leong Ong[b], Mansur Alhassan[c], Hazlami Fikri Basri[d*], Khalida Muda[d], Oluwapelumi Olumide Ojuri[e] and Tariq Ouahbi[f]

[a]Centre for Borneo Regionalism and Conservation, University of Technology Sarawak, No. 1 Jalan University, 96000 Sibu, Sarawak, Malaysia.

[b]School of Engineering and Built Environment, Griffith University, 170 Kessels Rd Nathan, Queensland, 4111, Australia.

[c]Department of Chemical Engineering, Faculty of Chemical and Energy Engineering, Universiti Teknologi Malaysia, 81310 Skudai, Johor, Malaysia.

[d]Department of Water and Environmental Engineering, Faculty of Civil Engineering, Universiti Teknologi Malaysia, 81310 Skudai, Johor, Malaysia.

[e]Built Environment and Sustainable Technologies (BEST), Research Institute, Liverpool John Moores University, Liverpool L3 3AF, United Kingdom.

[f]LOMC, UMR 6294 CNRS, Université Le Havre Normandie, Normandie Université, 53 rue de Prony, 76058 Le Havre Cedex, France.

[*]Corresponding Authors:

Hazlami Fikri Basri

Department of Water and Environmental Engineering, Faculty of Civil Engineering, Universiti Teknologi Malaysia, 81310 Skudai, Johor, Malaysia. Email: hazlami@utm.my; ORCID: 0000-0002-3398-1832

ABSTRACT

Amidst the increasing significance of innovative solutions for bioremediation of heavy metal removal, this paper offers a thorough bibliometric analysis of microbial-induced carbonate precipitation (MICP) for heavy metal removal, as a promising technology to tackle this urgent environmental issue. This study focused on articles published from 1999 to 2022 in the Scopus database. It assesses trends, participation, and key players within the MICP for heavy metal sequestration. Among the 930 identified articles, 74 countries participated in the field, with China being the most productive. Varenyam Achal, the Chinese Academy of Sciences, and Chemosphere are leaders in the research landscape. Using VOSviewer and R-Studio, keyword hotspots like "MICP", "urease", and "heavy metals" underscore the interdisciplinary nature of MICP research and its focus on addressing a wide array of environmental and soil-related challenges. VOSviewer emphasizes essential terms like "calcium carbonate crystal", while R-Studio highlights ongoing themes such as "soil" and "organic" aspects. These analyses further showcase the interdisciplinary nature of MICP research, addressing a wide range of environmental challenges and indicating evolving trends in the field. This review also discusses the literature concerning the potential of MICP to immobilise contaminants, the evolution of the research outcome in the last two decades, MICP treatment techniques for heavy metal removal, and critical challenges when scaling from laboratory to field. Readers will find this analysis beneficial in gaining valuable insights into the evolving field and providing a solid foundation for future research and practical implementation.

***Keywords*:** Biomineralization; MICP; Heavy metal pollution; Global research trends; Ureolytic microorganisms; Bibliometric visualisation

1. Introduction

Heavy metals pose a significant environmental concern globally due to their toxicity and persistence in the environment (Qiao et al. 2021; Jing et al. 2023). Drainage areas detect these contaminants, primarily from wastewater discharges from food factories, steel plating facilities, furniture manufacturing plants, and commercial plastics production (**Fig. 1**). Industrial effluents containing high concentrations of heavy metals are particularly hazardous because they are poisonous, mutagenic, carcinogenic, and resistant to degradation, even in small amounts (Mitra et al. 2022). Continuous discharge of heavy metals such as cadmium (Cd), arsenic (As), lead (Pb), copper (Cu), and nickel (Ni) results in their accumulation in natural resources, leading to bioaccumulation and posing severe threats to organisms (Zhang et al. 2022a). The toxicity of heavy metals is determined by their concentration levels, exposure duration, exposure pathway, and presence in organisms. Heavy metals accumulate in air, food, and water, posing a threat to human health and causing conditions such as hypophosphatemia, heart disease, liver damage, and neurotoxicity (Zhang et al. 2022b). These metals cannot be physiologically broken down or converted into non-toxic forms, leading to their accumulation in the environment and human bodies through the food chain (Adam et al. 2021; Dash and Kalamdhad 2021).

Industrial pollution, primarily from waste residues, wastewater, and exhaust gases, exacerbates heavy metal pollution due to outdated technology, equipment, and weak environmental awareness (Zhang et al. 2022b). Heavy metal contamination can have devastating consequences, including toxic and carcinogenic effects, contributing to the development of chronic and acute diseases such as hypertension, cardiovascular disease, endocrine dysfunction, renal failure, and infertility (Kaur and Roy 2021; Priya et al. 2022). Regulatory agencies, such as the Department of Environment under the Ministry of Environment and Water in the United Kingdom, monitor and control environmental pollution, including heavy metals. Reports have highlighted varying levels of heavy metals in different regions of the country (Yunus et al. 2020), indicating significant regional contamination that negatively impacts human health, wildlife, and the environment (Lin et al. 2021).

Among various remediation methods, microbial-induced carbonate precipitation (MICP) stands out as an innovative and sustainable approach for heavy metal removal. MICP involves a ureolysis-driven process that accelerates bio-cementation and facilitates the rapid precipitation of calcium carbonate ($CaCO_3$) (Li et al. 2022). The MICP technique converts free metal ions into stable binding states, reducing their mobility and toxicity (Dong et al., 2023). By immobilising heavy metals through the formation of stable $CaCO_3$, MICP mitigates the adverse effects of heavy metal pollution on both the environment and human health (Yuan et al. 2016). Several studies have highlighted the potential of various bacterial species for heavy metal immobilisation through the MICP process (Cáceres et al. 2021; Eltarahony et al. 2021; Wang et al. 2021a; Zhang et al. 2022a; Basri et al. 2023).

The urease-catalysed hydrolysis of urea breaks down urea ($CO(NH_2)_2$) into ammonia (NH_3) and carbonate ions (CO_3^{2-}), resulting in the production of ammonia (NH_4^+) and carbamic acid (NH_2COOH) in the surrounding medium (Liu et al. 2019; Arabani and Shalchian 2023) The NH_3) reacts with water, increasing the pH, which hydrolyses bicarbonate ions (HCO_3^-) from dissolved carbon dioxide (CO_2) (Ali et al. 2022). The alkaline conditions facilitate the production of hydroxide ions (OH^-) and CO_3^{2-}, which react with calcium ions (Ca^{2+}) from compounds like calcium chloride ($CaCl_2$) or calcium nitrate ($Ca(NO_3)_2$) (Xiao et al. 2020; Ouyang et al. 2022). This reaction forms $CaCO_3$, occurring in crystalline forms such as calcite, aragonite, or vaterite. During MICP, heavy metal ions (e.g., Cd^{2+}, Pb^{2+}, Cu^{2+}) are trapped within the CaCO3 matrix, reducing their mobility and bioavailability (Dong et al. 2023). This immobilisation transforms heavy metals into stable, less toxic forms, mitigating environmental harm (Tamayo-Figueroa et al. 2019; Gowthaman et al. 2022). Ureolytic microorganisms and $CaCO_3$ precipitation offer significant promise for heavy metal remediation.

To understand the research landscape and progress in this field, a bibliometric review provides a comprehensive analysis of the existing literature. A bibliometric review is a methodical analysis of a substantial number of publications in a specific study field, offering current information on the topic (Jiang and Yanbin 2018). Bibliometric analysis serves as a valuable tool for evaluating and tracking changes in research topics within a specific field, offering insights into bibliographic coupling, co-citation, and co-authorship networks, journals, subjects, research trends, and the development of emerging fields over time (Appiah et al. 2023). The Scopus database is widely regarded as a dependable and robust search tool for academic and scientific literature. Its extensive coverage of peer-reviewed journals, conference proceedings, patents, and other scholarly publications from various disciplines makes it a valuable resource for researchers and practitioners alike. The database's rigorous selection process for indexed content ensures a high level of quality and credibility for the included publications(Amusa et al. 2021). The citation tracking feature allows users to assess the impact and influence of specific articles and authors, further adding to the database's usefulness for conducting bibliometric analyses and gauging research significance (Hasan et al. 2023). Despite some limitations, such as possible omissions of certain regional publications, Scopus remains a dependable tool for comprehensive literature searches and evidence-based research, strengthening its position as a primary platform for scholarly investigations (Hong et al. 2023).

Recently, several bibliometric studies have focused on various aspects of MICP, contributing valuable insights to wastewater treatment research by identifying trends, gaps, and potential future directions. **Table 1** summarises several bibliometric articles focusing on MICP for heavy metal removal, highlighting both their aims and limitations. Jarwar et al. (2022) provided an extensive analysis of MICP literature, revealing significant growth in publications, particularly from China. However, its reliance on a single keyword and data collection up to August 2022 may limit its comprehensiveness. Omoregie et al. (2022) analysed trends in MICP publications and key contributors but were constrained by using only the Scopus database and a specific set of keywords, potentially excluding relevant articles. Pacheco et al. (2021) explored the use of artificial neural networks in cemented soils, focusing on leading research groups. Despite their thorough analysis, the study's limitations include potential gaps due to keyword selection and data collection only up to June 2020, which might overlook recent advancements. Similarly, Li et al. (2023) highlighted the progress and trend of MICP research but were limited by analysing data only from the WOS Core Collection. Al-Gheethi et al. (2022) assessed the life cycle environmental impact of bio-cementitious materials, but their study was limited to data from the WOS Core Collection and provided only a quantitative overview. Lastly, Omoregie et al. (2024) conducted a bibliometric analysis of MICP related to hydrodynamics, offering valuable insights but potentially overlooking other dimensions of the field.

Understanding the current research landscape and identifying promising directions within MICP can accelerate the development of this technology for effective heavy metal remediation. However, the limitations of previous MICP studies, as detailed in **Table 1**, range from the narrowness of keywords to restricted database scopes and limited year ranges. This article aims to improve upon these limitations by focusing specifically on MICP for heavy metal removal and employing comprehensive keywords. We examine the applications of MICP for heavy metal removal from 1999 to 2022, revealing research trends and patterns through publication and citation h-index data. By addressing the gaps in keyword scope and expanding the range of data, this study provides a more thorough understanding of the MICP research landscape and its potential for heavy metal remediation. It identifies the top countries, authors, institutions, journals, and subjects using Scopus database information. Utilising tools like VOSviewer and R-Studio, this review maps out hotspots and trends in MICP research. **Fig. 2** shows the data retrieval and analysis process. The review also explores the evolution of influential articles, recent advancements, the benefits and challenges of MICP, future research directions, and the study's significance and limitations.

2. Methodology

2.1. Data extraction

The literature data for this study were retrieved from the Scopus database, a comprehensive source of peer-reviewed literature across various disciplines. The search was conducted using the following terms: TITLE-ABS-KEY ((biodegradation) OR (immobilisation) OR (heavy AND metals AND removal) OR (absorption) OR (contaminant AND removal) OR (chemical AND removal) OR (remediation) OR (sequestration) AND (MICP) OR (biocementation) OR (ureolysis) OR (biogrouting) OR (biologically AND induced AND calcium AND precipitation) OR (microbial AND induced AND carbonate AND precipitation) OR (biocalcification) OR (microorganisms AND induce AND calcium AND carbonate AND precipitation) OR (microbiological AND carbonate AND precipitation) OR (bacteriogenic AND precipitation AND of AND minerals) OR (microbially AND mediated AND calcium AND carbonate AND precipitation) OR (bacterially AND induced AND carbonate AND mineralisation) OR (microbial AND urease)).

The search yielded 1,229 documents from the Scopus database as of November 11, 2022, encompassing a wide range of document types, including articles, reviews, conference papers, book chapters, and more (Supplementary Information, Fig. S1). Specifically, the dataset comprised 1,071 articles, 67 reviews, 65 conference papers, 16 book chapters, 3 conference reviews, 3 retracted papers, 2 errata, 1 book, and 1 note. We then applied inclusion and exclusion criteria to refine the dataset for bibliometric analysis. We excluded documents published before 1999 and after 2022, along with non-English publications and non-journal articles. This refinement resulted in a final selection of journal articles published between 1999 and 2022 in English. The resulting dataset was used for further bibliometric analysis, focusing on publication trends, research impact, and collaboration patterns. The steps used for the bibliometric search string are detailed in **Supplementary Information, Table S1**.

2.2. Bibliometric visualisation

The bibliometric analysis was mostly performed using VOSviewer (version 1.6.18) to visualise relationships between authors, publications, and research themes (Van Eck and Waltman 2010). After exporting metadata from Scopus, three analyses were performed using VOSviewer: (i) co-authorship analysis of nations and authors; (ii) co-occurrence of author keywords; and (iii) co-occurrence of terms. Out of 2,886 authors in the MICP domain, 374 met the criteria (a minimum of three publications and zero citations). These 309 authors formed 17 clusters, with 2,646 relationships and a total link strength of 3,468. From 72 countries, 65 met the requirements (minimum of one publication and zero citations), resulting in an overlay depiction of the MICP research regions. The co-authorship analysis was based on the number of co-authored documents. For the co-occurrence analysis, 2,558 author keywords were identified, with 951 meeting the threshold (minimum of two occurrences). Of these, 520 were connected and selected for the co-occurrence network visualisation. This analysis was based on the number of documents in which keywords occurred together. The results provide insights into the structure and dynamics of research domains, revealing frequently studied topics within each domain. R-Studio is a powerful data analysis tool for handling publication data. It features a user-friendly interface and built-in functions for efficient data analysis, boosting productivity and reproducibility (Alhassan et al. 2022). The process involves importing R packages like "bibliometrix" for data handling (Pacheco et al.2021). Using bibliometrix, Scopus data in BibTeX format is imported into R-Studio, cleansed, and examined for co-authorship networks and citation metrics. Abstracts and "Keywords Plus" are used to create word clouds, tree maps, and trend analyses. Up to 20 topics are identified annually, revealing emerging trends and keyword hotspots for 2022.

3. Results and discussion

3.1. Publication and citation patterns

This paper presents a comprehensive bibliometric analysis of publications and annual trends in the field of MICP from 1999 to 2022. A total of 930 documents were published during this period, averaging 39 publications per year. While the potential of MICP was recognised as early as 1972 (Hathaway and Nelson 1972), its practical application in heavy metal removal began to gain visibility in the early 2000s. Notably, the number of publications increased from just three papers in 1999 and 2001 to a peak of 170 papers in 2022, with expectations for further growth in 2023 (**Fig. 3A**). From 2020 to 2022, annual publication increases of 12.6% and 14.8% indicate a rising global interest in MICP for heavy metal remediation. Early challenges in the field, such as limited scientific output and a lack of microbiological research infrastructure (Okaiyeto et al. 2020), contributed to the slow initial recognition.

The increase in publications reflects MICP's potential as an eco-friendly method for heavy metal removal, as well as the growing emphasis on sustainable remediation techniques. Advances in molecular and engineering techniques have deepened our understanding of the mechanisms and applications of MICP(Lapierre et al. 2020, 2022; Erdmann et al. 2022). However, challenges remain, including the need for standardised protocols, better knowledge of microbial ecology, and field tests to confirm the effectiveness of MICP. Interdisciplinary collaboration is essential to address these challenges and ensure sustainable application.

The citation trend and h-index provide insights into MICP's research impact on heavy metal removal (**Fig. 3B**). Between 1999 and 2022, MICP research received 28,812 citations, with the highest count in 2016 (2,027 citations and 49 publications). Citations have steadily risen from 1,163 in 1999 to 2,219 in 2020, demonstrating growing interest and influence. The h-index increased from 3 in 1999 to 27 in 2017, highlighting the expanding impact of MICP on heavy metal detoxification. The slight decrease in citations in 2022 (359 citations) may be due to the typical delay in citing recent publications. Nevertheless, the citation trend and the h-index provide valuable insights into the research impact and visibility of MICP in heavy metal removal over time (Ganesan and Janjaroen 2022; Sharma et al. 2022).

3.2. Geographical distribution, leading researchers, and institutions

China leads the global distribution of publications on heavy metal removal via MICP with 498 publications, followed by the United States with 105 (**Fig. 4A**). In Europe, Spain and the United Kingdom each contribute 40 publications. Australia and Nigeria lead Oceania and Africa with 40 and 6 publications, respectively. Brazil and Mexico each have 7 publications in South America. China dominates in publications, citations, and h-index, establishing it as the research leader (**Table 2**). The United States, despite ranking second in publications, trails in citations and h-index, suggesting a lower research impact. Countries such as India, Spain, Australia, and the United Kingdom show similar publication counts but vary in citations and h-index, indicating different research impacts. The list (**Table 2**) also shows the most cited research articles from these top contributing countries in heavy metal contamination and soil quality improvement. The most cited article focuses on using urease-producing bacteria for biomineralisation (Stocks-Fischer et al. 1999). Other articles explore techniques like MICP with various amendments to immobilise heavy metals in soils (Garau et al. 2007; Pramanik et al. 2007; Lee et al. 2009; Li et al. 2013). Some articles also examine the impact of biochemical properties on soil quality and the effects of biochar on heavy metal availability and microbial activity (Raiesi and Beheshti 2014).

China has the highest total link strength at 148, with 33 connections to other countries, followed by the United States with a total link strength of 81 and 26 connections (**Fig. 4B**). These two nations lead in research collaborations, particularly in MICP and heavy metal removal. China also shares significant link strengths with Australia and the United Kingdom. This highlights China and the USA as primary scientific hubs, promoting research collaboration and innovation in MICP. China leads in publication output from 2010 to 2022, with the United States maintaining consistent output (**Fig. 5**). India, Spain, and Australia show fluctuating outputs; the United Kingdom and France exhibit slow but steady increases. South Korea has seen a significant recent increase, and Iran has steady growth. China has been the most cited country since 2016, peaking at 3832 citations in 2018. The United States consistently ranks high, peaking at 1001 citations in 2022. India, Spain, Australia, and the United Kingdom also receive significant citations. This trend reflects growing global interest, with increasing citations over the years. Seven of the top ten countries are developed economies, while China, India, and Iran are developing economies. Differences in research output are due to funding, infrastructure, and research culture.

The surge in heavy metal research in China, the USA, and India is driven by large populations and pollution issues. China's rapid urbanisation and industrialisation focus on heavy metal removal via MICP in universities and research institutions (Li et al. 2022). The focus of the USA on advanced technology contributes significantly (Islam et al. 2022). The industrial growth of India explains its substantial output. Factors affecting publication count include funding, policies, resources, expertise, and collaborations. Researchers should explore correlations with social and environmental factors beyond data presentation in MICP papers. Cultural attitudes, international collaboration, government funding, and R&D investments are crucial to understanding the leadership of China in MICP research. Analysing these factors provides insights into research success and global contributions to MICP research.

Varenyam Achal, from the Technion-Israel Institute of Technology, is the most prolific author with 23 papers, 1,243 citations, and an h-index of 16 (**Table 3**). His most cited article, “Biomineralisation based remediation of As(III) contaminated soil” (Achal et al. 2012), has 206 citations. This information underscores his significant contribution to the field. Amjad Abbas Ali of Xi’an University of Architecture and Technology follows with 19 papers, 240 citations, and an h-index of 8. His highest-cited article, “Isolation of biosynthetic crystals by microbially induced calcium carbonate precipitation and their utilisation for fluoride removal from groundwater,” has received 39 citations (Wang et al. 2021b). Junfeng Su, also from Xi’an University, has 17 papers, 187 citations, and an h-index of 7. His highest-cited article is also the same as Ali's, with 39 citations. Six of the top ten authors are from China, with others from Israel, Spain, and the United States. Notable institutions include the Technion-Israel Institute of Technology, Montana State University, and Zhejiang University of Technology. The six papers in **Table 3** focus on microbial solutions for environmental challenges, covering topics such as biomineralisation for soil cleanup, fluoride removal with biosynthetic crystals, heavy metal immobilisation, saline soil recovery, carbon capture, and cement restoration (Tejada et al. 2006; Mitchell et al. 2010; Qian et al. 2010; Achal et al. 2012; Peng et al. 2020; Wang et al. 2021b). These studies underscore the potential of microorganisms in providing sustainable and effective environmental solutions. They contribute to the field in several ways by providing foundational knowledge on the mechanisms and efficiency of MICP in various environmental contexts, building a solid theoretical base for future research. The innovative methodologies introduced through the exploration of different microbial species and conditions for MICP pave the way for enhanced heavy metal removal techniques. Additionally, the research highlights practical applications of MICP, such as in-situ soil and water remediation, demonstrating the real-world potential of this technology for mitigating environmental pollution. The diverse applications of MICP presented in these papers encourage interdisciplinary research, combining microbiology, environmental science, and engineering, fostering a holistic approach to tackling environmental challenges.

Changes in publication output for top prolific authors over time reveal varying trends (**Fig. 6A**). Varenyam Achal has consistently published since 2011. Amjad Abbas Ali and Su Junfeng, starting in 2017, have increased their output. Zhao Wang and Heng Xu saw significant increases in recent years, while Xiangliang Pan and Manuel Tejada peaked in the mid-2000s and then declined. Changes in citation output from 1999 to 2022 show that Achal and Tejada experienced consistent citation increases, while Amjad Abbas Ali initially had no citations but has seen significant growth (**Fig. 6B**). Nonetheless, the field of heavy metal removal via MICP shows steady growth, with these authors' work being increasingly cited. This data helps identify influential authors and track the impact of their research over time, considering factors like research focus, competition, and shifts in the research landscape.

Prominent institutions include the Chinese Academy of Sciences, the Ministry of Education China, and the University of Chinese Academy of Sciences (**Supplementary Information, Table S2)**. These institutions have made substantial contributions to research on heavy metal removal via MICP, with the Chinese Academy of Sciences leading with 93 articles and 3026 citations. The strong commitment of these institutions to environmental protection and sustainable development has driven significant advancements in this field. The nine research papers listed in (**Supplementary Information, Table S2**) cover various bioremediation techniques for contamination in soil, sediment, water, and paddy fields. Topics include investigating microbial activity in MICP (Zhang et al. 2011), the effects of biochar on soil microbial communities and enzyme activity (Demisie et al. 2014; Huang et al. 2017), using MICP to immobilise contaminants like lead and cadmium (Achal et al. 2012; Jiang et al. 2019; Peng et al. 2020; Wang et al. 2021b), and employing organic amendments for saline soil remediation (Tejada et al. 2006). The publication output and citation trends of top institutions from 1999 to 2022 are depicted in **Supplementary Information S3**. The Chinese Academy of Sciences increased its publications, peaking at 17 in 2021. Other institutions, such as the Ministry of Education China and Xi'an University of Architecture and Technology, also showed promising growth and citation attributes. This data corroborates the growing interest in this research area and highlights these institutions' significant contributions to heavy metal removal through MICP.

3.3. Leading journals subject areas and author keywords hotspots

The field of MICP for heavy metal removal has seen significant contributions from leading journals, as shown in **Table 4**. Among the top ten most prolific journals, nine are published by Elsevier Ltd., and one by Springer Nature. Notably, *Chemosphere* emerges as the most prolific, with 66 documents and 2478 citations, yielding an h-index of 24. Its highest-cited article, "Monitoring of bioremediation by soil biological activities" (Margesin et al. 2000), is cited 374 times. *Chemosphere* maintains a strong position with a CiteScore of 13.3, SJR of 1.727, and SNIP of 1.624, solidly within the Q1 quartile. Another prominent journal is *Science of the Total Environment*, publishing 52 documents and accumulating 1573 citations with an h-index of 24. It remains firmly in the Q1 quartile with a CiteScore of 16.8, SJR of 1.946, and SNIP of 2.026. *Journal of Hazardous Materials* has significantly contributed with 46 documents and 1307 citations, boasting an h-index of 21. It holds a CiteScore of 20.2, SJR of 2.570, and SNIP of 2.136, firmly in the Q1 quartile.

Other leading journals in the research field include *Environmental Science and Pollution Research, Ecotoxicology and Environmental Safety, Journal of Environmental Management, Construction and Building Materials, Bioresource Technology, Environmental Pollution,* and *Ecological Engineering*. These journals are also in the Q1 quartile, with CiteScores ranging from 7.6 to 19.0, SJRs from 0.44 to 2.473, and SNIPs from 1.141 to 2.214. These journals have been instrumental in advancing research on MICP for heavy metal removal, providing valuable insights to researchers and the scientific community. Top-cited articles in these journals focus on various approaches to remediate contaminated soil, emphasising heavy metals and microplastics. Some papers focus on bioremediation techniques, such as the use of bacteria, biosorption, and biomineralisation, while others investigate phytoremediation and amendments (Achal et al. 2012; Zhao et al. 2017). Studies explored the response of soil biological activities and microbial communities to pollution (Margesin et al. 2000; Huang et al. 2019; Fei et al. 2020), while others examined the effects of liming and microbial inoculants on organic waste composting (Pramanik et al. 2007). Articles focused on the use of $CaCO_3$ biodeposition to modify recycled concrete and induce carbonate precipitation in limestone (De Muynck et al. 2010; Pan et al. 2015; Huang et al. 2019).

Publications also investigated the optimisation of phytoremediation and stabilisation techniques for heavy metal-contaminated mine tailings and cadmium-contaminated soils (Sun et al. 2016; Li et al. 2019).

The research trend in heavy metal remediation through MICP has fluctuated over time, as depicted in **Fig. 7A**. The first document was published in 1999, but the trend gained momentum in the mid-2000s, driven by journals like *Bioresources Technology* and *Environmental Pollution*. Before 2010, few journals were actively published on this topic. In 2011, the research trend grew exponentially with numerous active journals. Prominent journals like *Chemosphere*, *Journal of Hazardous Materials,* and *Science of the Total Environment* eventually surpassed early leaders in publication output. Since 2018, the trend has surged, with nearly 80 documents published annually in 2022. From 1999 to 2022, the top 10 journals published 333 documents related to heavy metal remediation through MICP. *Chemosphere* leads with 16 publications in 2022, followed by the *Journal of Hazardous Materials* and *Science of the Total Environment* with 9 and 13 publications, respectively. This increasing pattern suggests that MICP-based heavy metal research will continue to gain global attention and opportunities for publication in high-impact journals.

The number of citations received by the top 10 journals between 1999 and 2022 is shown in **Fig. 7B**. Initially, there were few citations in the early 2000s. Growth began in 2003, and from 2014, yearly citations consistently ranged from zero to 250, with 2014 being the first to exceed 250. Subsequently, yearly citations increased steadily, reaching 500 in 2017. Within two years, citations doubled to 1,000 per year before surging to 1,500 in early 2020. This data underscores the growing interest in the topic, with the top 10 journals amassing a total of 11,272 citations. The increasing citations indicate the growing relevance and importance of this research area, which could have significant implications for future research and policy development.

The subject areas of articles in Scopus-indexed journals are shown **in Supplementary Information, Fig. S4**, and **Table S3**. Environmental Science leads with 559 articles, followed by Agricultural and Biological Sciences (160), Immunology and Microbiology (118), Engineering (115), Chemistry (106), and Medicine (106). Other significant contributors include Earth and Planetary Sciences, Biochemistry, Genetics and Molecular Biology, Materials Science, and Chemical Engineering. Less represented fields are Neuroscience, Decision Sciences, Economics, Health Professions, Nursing, Computer Science, and Mathematics. This highlights the interdisciplinary nature of MICP research and the value of cross-disciplinary collaboration, while also reflecting differing research priorities and applicability challenges in certain areas.

Author keywords encapsulate the essence of research and indicate trending areas within a field as shown in **Fig. 8A**. The most frequently encountered keyword, "MICP", appeared 124 times, with significant associations with "heavy metal", "urease", "bio-mineralisation", "*Sporosarcina pasteurii*", and "cadmium". This indicates its versatile applications in diverse domains such as MICP for heavy metal removal, geology, microbiology, civil engineering, and materials science. "Urease", another pivotal keyword, surfaced 92 times, establishing connections with keywords like "MICP", "bio-cementation", "bio-mineralisation", "bio-remediation", and "microorganisms". It serves as a central keyword in the MICP context, aligning with various techniques and processes integral to bio-cementation and bio-mineralisation. "Heavy metals" appeared 52 times, fostering connections with keywords in bioremediation, soil science, and MICP for heavy metal removal. Keywords related to plant species and the rhizosphere suggest implications for agriculture and plant growth. "Bio-mineralisation" appeared 44 times, connecting to keywords in bioremediation, carbon capture, construction materials, and wastewater treatment. Exploring these dynamics could lead to valuable insights and advancements.

R-Studio analysis highlights key research areas, with "calcium carbonate" indicating a strong focus on its role in geotechnical engineering, soil improvement, or wastewater treatment as demonstrated in **Fig. 8B**. The significance of "cadmium" underscores interest in heavy metal removal or immobilisation. The frequency of "urease" implies a substantial focus on the enzyme's role in biomineralisation and MICP processes. Keywords like "biochar", "charcoal", and "denitrification" indicate research in microbial activities, soil amendment, and nitrogen removal. "Heavy metal" keywords highlight the importance of MICP in addressing environmental contamination. "Bioremediation" reflects MICP's use in contaminated site remediation. "Compressive strength" suggests research on MICP's impact on soils or construction materials. Techniques like "scanning electron microscopy" and "X-ray diffraction" are used to characterise MICP products. "Adsorption" indicates research on contaminant immobilisation. Keywords like "microbiology" and "biomineralisation" underscore the interdisciplinary nature of MICP research. "Solid waste" suggests potential MICP applications in waste management. These keywords reflect MICP's multidisciplinary research, converging microbiology, chemistry, and engineering to address environmental and soil-related challenges. The joint VOSviewer and R-Studio analysis reveals critical research themes, with common keywords like "MICP", "urease", and "heavy metals" highlighting the field's multidisciplinary nature.

3.4. Research trends or future direction

Both “VOSviewer” and “R-Studio” software are essential tools for identifying the most relevant research terms within a specific field (Omoregie et al. 2022; Pacheco et al. 2021). They help evaluate and validate the co-occurrence or frequency of research terms within the scientific literature. In this context, 215 research terms were pinpointed through the co-occurrence analysis of text data (title and abstract) using “VOSviewer”. It was found that “calcium carbonate crystal” emerged as the most prominent research term, as shown in Fig. 9A. This term displayed 319 occurrences, a total link strength of 2643, and 192 connections to other terms, including “organic matter”, “absorption”, “urea”, “isolate”, “heavy metal”, “accumulation”, and “stabilization”. “Heavy metal”, “catalase activity”, “soil enzymatic activity”, “glucosidase activity”, “soil pH”, and “microbial community” were also highlighted in **Fig. 9A**, emphasising their role in MICP for heavy metal immobilisation and bioremediation (Wang et al. 2020; Wei et al. 2022) Other significant research terms include “soil enzymatic activity”, “biochar”, “unconfined compressive strength”, “self-healing”, “bioavailability”, and “abundance” that have emerged since 2019. This analysis unveils evolving trends and research directions in the field, demonstrating its diverse applications and potential beyond heavy metal removal (Galishnikova et al. 2021; Xu et al. 2023; Zakrzewska et al. 2023).

The analyses of research trends following the “R-Studio” analysis, include both word cloud analysis of abstracts and trend topics in 2022 (the latest year of the bibliometric data), reveals several significant themes and areas of focus within the field of “MICP” as shown in **Fig. 9B** and **Fig. 10**. These trends provide valuable insights into the evolving landscape of research in this field. In the word cloud analysis of abstracts (**Fig. 9B**), “soil” and “organic” dominate, emphasizing “MICP”'s application in soil research, particularly concerning organic matter interactions (Chung et al. 2021; Liu et al. 2021). Terms like “MICP” and “PHB” indicate research on $CaCO_3$ and biopolymers (i.e., polyhydroxybutyrate), highlighting their role in bioremediation and pollution control (Ramachandran et al. 2021; Dubey et al. 2022). “Manure” and “CD” signify the use of organic sources like manure and the immobilisation of contaminants such as cadmium, promoting sustainable environmental approaches. Also, “degradation” and “effective microorganisms” showcase the exploration of “MICP” for environmental degradation and the effectiveness of microbial communities in pollution control and soil improvement. The terms “mineral” and “rocks” suggest research on the formation and mineralogical changes in geological materials due to “MICP”, reflecting the field’s multidisciplinary nature. Keywords like “alkanes”, “fertilizer”, and “lime” indicate research on applications of “MICP” in hydrocarbon remediation, soil fertility improvement, and pH modification, demonstrating its versatility in addressing diverse environmental challenges (Disi et al. 2022).

"Bacteria" and "immobilization" underscore the importance of microbial activities in immobilising contaminants and the bioremediation potential of "MICP" in environmental restoration and pollution control.

The trend topics derived from the analysis using "R-Studio" software are primarily based on the latest publication year. This approach serves as a valuable indicator for potential future research directions, drawing upon the recommendations and insights from the analysed literature. The analysis of research trends reveals (**Fig. 10**) significant areas of focus within the field of MICP for heavy metal removal. Terms such as "calcium carbonate" and "cadmium" emphasise ongoing research on the role and applications of $CaCO_3$ in various processes, including soil improvement and environmental remediation. This aligns with the goal of MICP in geotechnical engineering and environmental applications. The presence of "urease" underscores the exploration of enzyme activity in biomineralisation and MICP processes, while "denitrification" highlights the use of MICP for nitrogen removal, contributing to environmental sustainability. "Bioremediation" indicates the application of MICP for contaminated sites and pollution control. The recurrence of "compressive strength" underscores its significance in construction and engineering applications, focusing on the impact of MICP on soil strength. The utilization of advanced characterization techniques, such as "scanning electron microscopy" and "X-ray diffraction," reflects the need to understand microstructural and mineralogical changes induced by MICP, essential for assessing its effectiveness. Both "VOSviewer" and "R-Studio" software identified common terms, including "MICP" and "heavy metal", reflecting their significance in the field. Additionally, terms like "biochar" and "bioremediation" were prevalent in both analyses, indicating the ongoing exploration of biochar's role and the potential for bioremediation in MICP processes. These common terms emphasize the interdisciplinary nature of MICP research, encompassing aspects of microbiology, chemistry, and environmental engineering.

4. The transformative journey of highly cited articles in the field from 1999 to 2022

This section provides an insightful journey through the world of highly cited articles in environmental remediation, spanning the years from 1999 to 2022, as shown in **Table 5**. Organised into four distinct phases, this section offers a comprehensive exploration of the evolutionary trajectory of these influential works, each contributing uniquely to the research domain. Understanding the most cited articles in the field from 1999 to 2022 holds significant value for both readers and scholars, as these articles serve as the cornerstones of knowledge, encapsulating the foundational concepts and groundbreaking methodologies that have shaped this specialised area of environmental remediation.

4.1. Phase 1: Early Investigations (1999-2003)

During the early investigations of MICP from 1999 to 2003, several pivotal studies were conducted to understand the mechanisms and potential applications of MICP. Fischer et al. (1999) were among the first to investigate microbial $CaCO_3$ precipitation, demonstrating that *Sporosarcina pasteurii* could efficiently induce $CaCO_3$ precipitation much faster than conventional chemical methods. Their study also explored the critical role of urease in the kinetics of this microbiological process. Following this, Margesin et al. (2000) monitored soil biological activities during the bioremediation of mineral-oil-contaminated soil, finding significant correlations between various biological parameters and hydrocarbon residue levels, suggesting that certain soil biological parameters could serve as reliable indicators of the decontamination process.

Warren et al. (2001) explored the potential of microbial urea degradation as a catalyst for carbonate precipitation and groundwater contaminant capture. Their findings revealed that bacterial urea degradation increased pH and promoted carbonate precipitation, which has significant implications for groundwater remediation. Bachmeier et al. (2002) further delved into the role of microbial urease in $CaCO_3$ precipitation, confirming that urease activity is essential for MICP. They also found that by adding low concentrations of nickel, the urease cofactor enhanced $CaCO_3$ precipitation. Lastly, Navarro et al. (2003) investigated the use of MICP as a strategy for conserving deteriorated ornamental stone. Their study found that *Myxococcus xanthus*-induced $CaCO_3$ precipitation effectively protected and consolidated porous ornamental limestone. Collectively, these studies laid the groundwork for understanding the mechanisms and potential applications of MICP.

4.2. Phase 2: Enhancing Soil Quality, Remediation, and Carbon Capture (2004-2010)

During this phase, numerous studies explored how manipulating soil properties and microbial activities could improve soil quality, remediate contaminated soils, and enhance carbon capture and storage processes. Yoshiko Fujita et al. (2004) demonstrated that bacterial ureolysis could incorporate strontium into $CaCO_3$ at a much higher rate than other methods, such as pump and treat or phytoremediation. This was particularly important for remediating groundwater contaminated with radioactive isotopes like strontium. Their findings suggested that bacterial ureolysis could offer a new method for groundwater remediation. Gil-Sotres et al. (2005) reviewed trends in using soil biochemical properties as indicators of soil quality, identifying that these properties, related to the biocycles of elements like carbon, nitrogen, phosphorus, and sulphur, could be used individually or in combination to assess soil quality. Tejada and colleagues (2006) investigated the use of organic amendments to remediate saline soil, finding that organic amendments positively impacted the soil's physical, chemical, and biological properties, including increased plant cover and improved soil physical properties. Garau and co-workers (2007) compared the efficiency of different soil amendments in immobilising heavy metals in contaminated soil, concluding that all amendments significantly reduced the solubility of heavy metals and increased soil pH, though only red mud increased the number of culturable, fast-growing heterotrophic bacteria.

Fujita and team (2008) showed that adding molasses and urea to groundwater could stimulate microbial urea hydrolysis, leading to $CaCO_3$ precipitation and the sequestration of divalent trace metal and radionuclide contaminants. However, they noted the need to consider collateral impacts, such as reduced permeability. Lee et al. (2009) examined the effects of different soil amendments on heavy metal extractability, microbial activities, plant uptake of heavy metals, and heavy metal availability to the human gastrointestinal system, finding significant reductions in soluble and extractable heavy metals. Mitchell et al. (2010) investigated the potential of microorganisms to enhance carbon capture and storage through mineral-trapping and solubility-trapping, finding that bacterial ureolysis effectively precipitated dissolved CO_2 as $CaCO_3$, enhancing the solubility-trapping capacity of brine.

4.3. Phase 3: Biocalcification, Biomineralisation, and Soil Remediation (2011-2016)

From 2011 to 2016, research focused on understanding the impact of ocean acidification on estuarine ecosystems, using microbial biomineralisation for remediating contaminated soils, and the potential of indigenous bacteria in heavy metal bioremediation. Waldbusser et al. (2011) analysed 23 years of Chesapeake Bay water quality monitoring data, finding that reduced pH levels significantly affected oyster biocalcification rates, demonstrating the vulnerability of estuarine calcifiers to ocean acidification. Achal et al. (2012) used the *Sporosarcina ginsengisoli* CR5 strain to immobilise arsenic in contaminated soil, significantly reducing arsenic mobility and suggesting microbial biomineralisation as a viable remediation technology.

Li et al. (2013) investigated using metal-resistant microbial biomass from nursery garden soil to remove heavy metals through biomineralisation. The biomass produced urease, which increased soil pH and converted soluble heavy metal ions into carbonates. Demisie et al. (2014) examined the effect of adding oak wood and bamboo biochar to degraded red soil, finding increases in organic carbon fractions, aggregate stability, ureolytic activities, and microbial biomass, which are essential for improving soil quality. Sun et al. (2015) demonstrated that adding bentonite to paddy soils reduced the mobility and bioavailability of Cd and Pb, resulting in decreased concentrations in rice seedlings. Huang et al. (2016) used sodium alginate-modified nanoscale zero-valent iron to remediate Cd-contaminated river sediments, finding that mobile fractions of Cd were transformed into less mobile forms, reducing bioavailability and positively impacting soil enzyme activity.

4.4. Phase 4: Impacts of Biochar, Microplastics, and Environmental Remediation (2017-2022)

From 2017 to 2022, studies focused on the effects of biochar on microbial communities and enzyme activities in heavy metal-contaminated sediment, the impact of sugarcane bagasse-derived biochar on heavy metal bioavailability, the effects of microplastics on soil enzymatic activities and bacterial communities, and using *Bacillus subtilis* for MICP in self-healing concrete. Huang et al. (2017) investigated rice straw biochar's effects on indigenous microbial communities and enzyme activities in heavy metal-contaminated sediment, finding significant alterations in physicochemical properties, enzyme activity, and microbial community composition.

Nie et al. (2018) examined the impact of sugarcane bagasse-derived biochar on the bioavailability of Cd, Cu, and Pb in contaminated soil, finding that biochar application increased plant yield and reduced heavy metal bioavailability in plant roots and shoots, significantly enhancing soil enzyme activities and ureolytic microbial populations. Huang et al. (2019) studied the effects of polyethylene microplastics on soil performance via MICP, observing that microplastic amendments significantly increased urease and catalase activities and induced taxonomic changes in the microbial community.

Fei et al. (2020) explored the effects of polyethylene and polyvinyl chloride microplastics on soil efficiency through MICP, noting that both types of microplastics affected soil enzyme activities and reduced the richness and diversity of MICP bacterial communities. Feng et al. (2021) researched the use of *Bacillus subtilis* for MICP in self-healing concrete, finding that the self-healing concrete exhibited improved flexural strength, indicating potential for concrete repair and rehabilitation. Feng et al. (2022) investigated the impact of different types of microplastics on Pb-Zn-contaminated soil via MICP, discovering that microplastics, especially at higher doses, altered soil properties, heavy metal availability, and bacterial communities, affecting soil pH, dissolved organic carbon, nutrient availability, and enzyme activities. These studies provide insights into the complex interactions between biochar, microplastics, heavy metals, and microbial communities in various soil environments.

5. Recent advancements in MICP treatment for heavy metal removal

MICP may be beneficial for heavy metal removal and immobilisation in contaminated areas. Recent experiments into MICP for heavy metal removal have cast light on its performance and possible environmental applications (Table 6). These examples show a variety of heavy metal remediation applications and approaches that use MICP to provide an eco-friendly solution to pollution and environmental sustainability.

5.1. Heavy Metal Removal by Single Bacteria

Yang et al. (2023) tackled the challenge of remediating soil contaminated with As, Pb, and Cd by employing a combination of amendment materials and microorganisms. They conducted comparative experiments using *Lysinibacillus fusiformis* and various amendment materials, analysing soil characteristics, speciation transformation, and element content. Their study demonstrated that the synergy of Loess and a microbial agent significantly improved the stabilisation of As and Pb, while compost sludge and a microbial agent enhanced the stabilization of As. This approach effectively stabilizes As, Pb, and Cd in contaminated soil. Jiang et al. (2023) investigated into the mechanisms of reducing and mineralizing Cr(VI) using *Sporosarcina saromensis* in conjunction with MICP. They investigated the impact of Ca^{2+} concentration on Cr(VI) reduction and mineralisation, alongside analysing urease activity and the formation of stable phases. Their research unveiled that a high Ca^{2+} concentration enhanced Cr(VI) reduction and mineralisation, achieving a remarkable reduction efficiency of 99.5% and mineralisation efficiency of 55.9% at 4 g/L Ca^{2+}. Hu et al. (2023) aimed to enhance the stability of heavy metals, particularly Pb, by employing biochar and MICP technology. Their strategy involved utilizing rice straw biochar and MICP to immobilize Pb^{2+} and conducting various tests and chemical analyses to validate their method. Their results showcased that MICP treatment significantly increased the stable fraction of immobilized Pb^{2+} on biochar. The "surface barrier" approach, which combines biochar and MICP, effectively enhances Pb^{2+} stability on biochar and reduces the mobility of Pb^{2+} in the environment. Xing et al. (2023) concentrated on remediating Zn-contaminated soil using MICP. They assessed the effectiveness of MICP in reducing Zn mobility and concentration in the soil through mechanical tests and chemical analyses. Their research revealed that MICP successfully reduced the mobility of Zn ions, decreased the exchangeable state Zn content, and lowered the leaching concentration of zinc ions in Zn-contaminated soil. The study identified the coprecipitation of $CaCO_3$ and $ZnCO_3$ as a mechanism for immobilising Zn, offering a cost-effective and environmentally friendly solution for heavy metal remediation.

5.2. Addition of Activated Carbon

Wang et al. (2023) explored the feasibility of using biochar and *Pseudomonas* sp WZ39 strain to remediate heavy metal-contaminated soils. They added various biochar doses to contaminated soil and analysed the impact on heavy metal forms, soil microbial activity, and other soil properties. The study found that biochar effectively passivated heavy metals, reducing the availability of Cd, Pb, Cu, and Zn. It also increased soil microbial activity and modified the forms of heavy metals, making it a promising option for remediating heavy metal-contaminated soil in mining areas. Wang et al. (2023) focused on the remediation of heavy metal-contaminated soils using biochar. Their study included the addition of different biochar doses to contaminated soil, and the impact on heavy metal forms, soil microbial activity, and other soil properties was analysed. The authors found that biochar effectively immobilised heavy metals, enhanced soil microbial activity, and modified the forms of heavy metals, making it a promising option for remediating heavy metal-contaminated soil in mining areas. Xue et al. (2023) investigated the use of self-healing MICP materials to prevent Pb migration in contaminated water bodies and soil. The authors described the process involving spore germination, spore-vegetative cell transformation, urease secretion, and urea hydrolysis to produce spore-containing precipitation. Their findings highlighted the importance of inosine and trace elements in preventing deterioration of Pb immobilisation. Xu et al. (2023) explored the use of a biochar-bacteria partnership for Cd immobilization in contaminated soils. The MICP system significantly reduced soil Cd mobility while improving soil fertility and bacterial diversity. The authors acknowledged the abundance of *Sporosarcina* and *Bacillus* species, emphasising the potential of this approach for effective Cd remediation. Dong and colleagues (2023) employed MICP technology to solidify and remediate lead-zinc tailings that contained heavy metals. Their investigation reported that MICP effectively reduced heavy metal pollution, particularly when the thickness of lead-zinc tailings was 2 cm. It achieved maximum unconfined compression strength and high $CaCO_3$ content, thus demonstrating the potential for remediating such tailings and reducing their environmental impact.

5.3. Different Effects of Mixed Bacteria

Venkatesan et al. (2023) investigated the application potential of different bacterial species (*Bacillus subtilis, Bacillus sphaericus,* and *Sporosarcina pasteurii*) combined with porous conch shell powder to enhance gypsum plaster strength, durability, and microstructure. Their research demonstrated that the developed plaster exhibited higher strength and durability, along with improved water tightness. Calcite precipitates filled pores and enhanced the plaster's microstructure, making it denser and more durable. Mao et al. (2023) explored using biological soil crusts for immobilizing metal(loid) in mining areas by co-inoculating *Leptolyngbya* sp XZMQ and *Bacillus* sp XZM. They successfully formed biological soil crusts that increased soil pH and microbial activity, resulting in enhanced As immobilisation. The authors proposed biological soil crusts as a novel method for remediating As-contaminated soil in mining areas. Anand et al. (2023) introduced a ready-to-use fly ash-based bacterial inoculum MICP in concrete structure repair. Their study focused on the application of this inoculum for repairing cracks in concrete structures with different orientations. Their results showed that the inoculum effectively promoted MICP to seal cracks in existing concrete structures, presenting a promising solution for structural repair. Cai et al. (2023) addressed the immobilization of Cd in paddy soil using MICP. Their approach involved the use of rice straw coupled with Sporosarcina pasteurii to treat Cd-contaminated paddy soil, effectively reducing Cd bioavailability. The process not only immobilised Cd but also enhanced soil fertility and ecological functions, mitigating the detrimental effects of MICP. Subitha et al. (2023) addressed the incorporation of microbial consortia into bio-concrete, emphasizing the importance of microbial traits such as high alkali resistance and endospore formation. The microbial consortia adapted to their construction environment and were used in the preparation of bio-concrete. Strength and toxicity tests showed the bio-concrete's potential for enhanced construction applications, providing an environmentally friendly alternative. Zhang et al. (2023) explored the immobilisation of Cd^{2+} and Pb^{2+} by a stable microbial consortium screed from soil contaminated with these heavy metals. The dominant genus *Sporosarcina* within the consortium was found to have a critical carbonate mineralization function. They reported their experiments led to the immobilisation of 91.52% of Cd^{2+} and 99.38% of Pb^{2+} using $CaCl_2$. Characterisation of the precipitates using various techniques validated their successful immobilisation. Diez-Marulanda and Brandão (2023) isolated urease-positive bacteria, containing *Serratia*, and *Acinetobacter* species capable of growing in the presence of Cd(II) and producing carbonate precipitates. Their findings suggested that these strains efficiently removed Cd from the solution, demonstrating their potential for bioremediation and contributing to the field of Cd removal from contaminated environments.

5.4. Removal Mechanisms of Different Heavy Metals

Xie et al. (2023) focused on the immobilisation of Cu in contaminated sites using MICP. They revealed that maintaining near-neutral pH conditions, as close as pH 7, was essential for maximising Cu immobilisation efficiency. The study also highlighted the importance of the coordination adsorption of Cu and its behaviour in alkaline environments. The findings indicated that MICP technology holds great promise for the remediation of Cu-contaminated sites. Zakrzewska et al. (2023) investigated the use of ureolytic bacteria to immobilise Cd in contaminated soil. They specifically focused on the role of metabolites containing carbonates produced by the ureolytic bacterium *Ochrobactrum* sp POC9 strain. The addition of metabolites containing carbonates to the soil significantly reduced the bioavailability of Cd by 27-65%, depending on the volume. This, in turn, led to an 86% reduction in Cd uptake by crop plants (*Petroselinum crispum*). Additionally, the researchers highlighted that the introduction of metabolites containing carbonates improved various soil properties and positively impacted soil microbiota and plant health, making it a promising method for Cd immobilization and soil enhancement. Zhang et al. (2023) developed a microencapsulated immobilisation reactor with *Aquabacterium* sp CZ3 strain. This reactor achieved impressive removal efficiencies of 100% for NO_3-N, 67.84% for Ca^{2+}, 88.67% for F^-, and 100% for phenol. The research attributed the removal mechanisms to co-precipitation and adsorption. Furthermore, the presence of phenol was found to enhance the production of extracellular polymers, improving bacterial tolerance and promoting denitrification. Su et al. (2023) delved into the removal of strontium (^{90}Sr) using MICP and its sensitivity to strontium-calcium (Sr/Ca) ratios. The researchers found that MICP could induce the formation of $CaCO_3$ and strontianite, with higher Sr/Ca ratios promoting strontium incorporation into minerals. This study is valuable for understanding the formation mechanisms of carbonate minerals and the bioremediation of strontium. Wang et al. (2023) explored the use of the *Bacillus cereus* BL4 strain, isolated from the *Miscanthus floridulus* strain growing near a pyrite mine, to phytoremediate Cd-contaminated soil. The study showed that this bacterium enhanced plant growth and health, increasing Cd accumulation in plant tissues. It also demonstrated the reduction of Cd bioavailability in soil and provided a promising solution for the remediation of Cd-contaminated soil. These studies primarily centre around the utilisation of MICP and related techniques to tackle environmental challenges, with a strong emphasis on enhancing soil quality. This involves remediating soil contaminated by a variety of heavy metals and enhancing material properties like gypsum plaster strength and durability through microbial processes. The research also looked into areas such as microbial partnerships, biochar application, and long-term stability.

6. Challenges and Future Direction of MICP

6.1. Challenges of MICP for heavy metal removal

A primary challenge is the need for standardised protocols and guidelines. As the field expands, establishing consistent and rigorous procedures for MICP becomes paramount. This includes defining optimal conditions for microbial activity, the right combination of microbial species, and the appropriate substrates and minerals (Subitha et al. 2023). Standardisation ensures the reliability and comparability of MICP studies across different environments and contaminants. Addressing the intricacies of various heavy metal interactions is another challenge. Each heavy metal exhibits unique chemical behaviours, and the microbial processes involved in their immobilisation may differ. Future research must look into the specifics of MICP for individual heavy metals, offering tailored solutions for contamination scenarios involving different metals. Despite the promising advancements of MICP in heavy metal remediation, its effectiveness in removing high concentrations of copper ions remains a significant challenge. Current research indicates that while MICP can immobilise various heavy metals, the removal efficiency for copper, especially at elevated concentrations, is relatively limited (Duarte-Nass et al. 2020; He et al. 2022, 2023). The unique chemical behaviour of copper ions can interfere with the microbial processes central to MICP, making it less effective for copper ion sequestration. Addressing this challenge will require further research to optimise conditions and explore new microbial strains or amendments that can enhance the capacity of MICP to handle high concentrations of copper ions.

6.2. Future directions for MICP research

Future research should focus on establishing standardised protocols and guidelines for MICP. This should include defining optimal conditions for microbial activity, the best combination of microbial species, and the appropriate substrates and minerals. Standardisation will ensure the reliability and comparability of MICP studies across different environments and contaminants, enabling more consistent and reproducible results. While significant progress has been made with well-known heavy metals like Cd and Pb, future research should explore the applicability of MICP for less-studied heavy metals and metalloids such as mercury and boron ions. These elements pose substantial environmental risks but have not been extensively studied in the context of MICP. Understanding how microbial processes can facilitate the immobilisation and remediation of these less common heavy metals will broaden the scope of MICP's environmental impact.

Given the current limitations of MICP in removing high concentrations of copper ions, future research should focus on optimising conditions and exploring new microbial strains or amendments that can enhance the capacity of MICP to handle high concentrations of copper ions. This may involve investigating the unique chemical behaviours of copper and finding ways to overcome the interference with microbial processes. Extending MICP to large-scale applications, such as agricultural lands and large bodies of water, presents both opportunities and challenges. Future research should focus on developing innovative delivery mechanisms, cost-effective technologies, and addressing regulatory considerations. Optimising these aspects will be crucial for the large-scale implementation of MICP in ecological restoration projects. The future of MICP could involve integrating it with other sustainable technologies, such as phytoremediation or biochar application. Combining MICP with these methods could enhance its effectiveness and provide comprehensive solutions for environmental remediation. Research should explore these synergistic approaches to develop innovative and multifaceted strategies for tackling heavy metal contamination.

Balancing eco-friendliness with performance remains a critical area of focus for MICP research. Future studies should explore ways to enhance the efficiency of MICP processes and reduce treatment times without compromising environmental sustainability. This might involve the development of faster-acting microbial strains or more effective amendments. The potential of MICP to promote soil health and microbial activity offers exciting opportunities for further research. Understanding the complex interactions between microorganisms, minerals, and heavy metals could lead to new strategies for sustainable agriculture, ecological restoration, and climate change mitigation. Future research should delve into these intricate relationships to harness the ecological benefits of MICP in broader environmental contexts. Ensuring the long-term stability of MICP-treated heavy metals is crucial. Future research should continue to investigate the effectiveness of MICP under various soil conditions and over extended periods. Monitoring the long-term behaviour of immobilised heavy metals will help ensure they remain sequestered and pose minimal risk to the ecosystem. By addressing these future directions, MICP research can continue to evolve, offering finely tailored solutions for heavy metal remediation and contributing to broader ecological sustainability. As researchers unlock the potential of MICP, they will expand the boundaries of what is achievable, paving the way for innovative applications that benefit both the environment and human health.

7. Significance and limitations of the study

This bibliometric analysis and literature review are of significant value to scholars and researchers in various fields, particularly bioremediation and materials science. It serves as a comprehensive repository of recent studies and applications of MICP and related techniques. By summarising key findings from a wide range of research articles, this review offers scholars a clear overview of the diverse applications and innovations in MICP technology, spanning from soil and water remediation to construction materials enhancement. For scholars in the field, gaining insights into primary authors, prominent journals, key subject areas, important keywords, emerging research trends, countries of origin, and influential institutions is immensely advantageous. The compilation also highlights the role of various microbial species and their unique contributions, as well as the successful integration of novel materials and methods in environmental conservation. For scholars, this review not only serves as a valuable resource for staying updated with recent advancements but also provides insights into potential research gaps and directions, fostering the development of more sustainable and effective solutions for heavy metal removal. It encourages interdisciplinary collaborations and facilitates the cross-pollination of ideas across different domains, ultimately contributing to the growth of knowledge and the development of eco-friendly technologies.

Limitations like this have plagued previous bibliometric research. Scopus may not index MICP-related heavy metal removal documents. The literature search terms may have overlooked some domain publications. Not included in the search criteria was “calcite precipitation”, which some writers use instead of “carbonate precipitation”. The exclusion of non-English publications could lead to the omission of significant studies. The study examined only documents published between 1999 and 2022, excluding those published after 1999. This constraint focused and deepened the study. The literature discussion persisted despite its limitation to the years 1999–2022. This update was necessary to document research output and evaluate the scholarly scene. We exclude papers published after November 2022 due to data mining and extraction termination. Clarivate Analytics' WOS or Digital Science's Dimensions citation index databases may help future researchers overcome these limits. These limitations are common in bibliometric studies. Thus, future studies will evaluate heavy metal removal MICP documents using larger datasets and more sophisticated keyword techniques.

8. Conclusion

This study presents a comprehensive bibliometric analysis of MICP for heavy metal immobilisation from 1992 to 2022. It provides insights into publication output, annual trends, and global collaborations, highlighting China, the United States, and India as leading contributors. Notably, Chemosphere stands out as the most influential journal, with prolific authors like Varenyam Achal making significant contributions. Chinese institutions, led by the Chinese Academy of Sciences, have played a substantial role in advancing MICP research, reflecting the method’s increasing prominence in cost-effective environmental remediation. This analysis underscores MICP’s importance and potential for addressing environmental challenges. The keyword hotspot analyses through VOSviewer and R-Studio illustrate the interdisciplinary nature of MICP research, with “MICP”, “urease”, and "heavy metals" bridging diverse domains. "Calcium carbonate crystal", "soil" and "organic" themes emerge as prominent keywords, emphasising MICP's adaptability for heavy metal removal and its continued development. The exploration of highly cited articles on transformative journeys from 1999 to 2022 highlights MICP's ongoing relevance in addressing environmental challenges. While MICP offers promise for contaminant immobilisation, challenges include scaling up lab experiments for field applications, managing environmental factors like temperature and pH, and ensuring the long-term stability of $CaCO_3$ minerals. Addressing these hurdles will enhance the reliability of the field as a sustainable solution for contaminant immobilisation in polluted environments, fostering innovation in MICP for heavy metal removal.

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Authors contributions

A.I. Omoregie: conceptualisation; data curation; methodology; software analysis; first to final draft writing. D.E.L. Ong and H.F. Basri: funding acquisition; administration; and review & editing. M. Alhassan, K. Muda, O.O. Ojuri, and T. Ouahbi: data validation; first to final draft writing, review & editing; and software analysis. All authors contributed to the manuscript revision and read and approved the submitted version.

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Competing interests

The authors declare no competing interests.

Availability of data and materials

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

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List of figures

Fig. 1: Potential heavy metals presence in drainage area evidenced by the wastewater discharge from various types of sources such as food factories, steel plating facilities, furniture manufacturing plants, and commercial plastics production in a commercial region. (A) View of the drainage area near the initial discharge point, showing dark-coloured water possibly containing organic waste and oils from food factories; (B) Adjacent perspective highlighting the extent of pollution and possible accumulation of contaminants from steel plating facilities; (C) Downstream view showing vegetation along the drainage sides, indicating interaction with pollutants from various sources, including furniture manufacturing plants; and (D) Further downstream perspective showing continued pollution flow, providing insight into the dispersion and settling of contaminants from commercial plastics production.

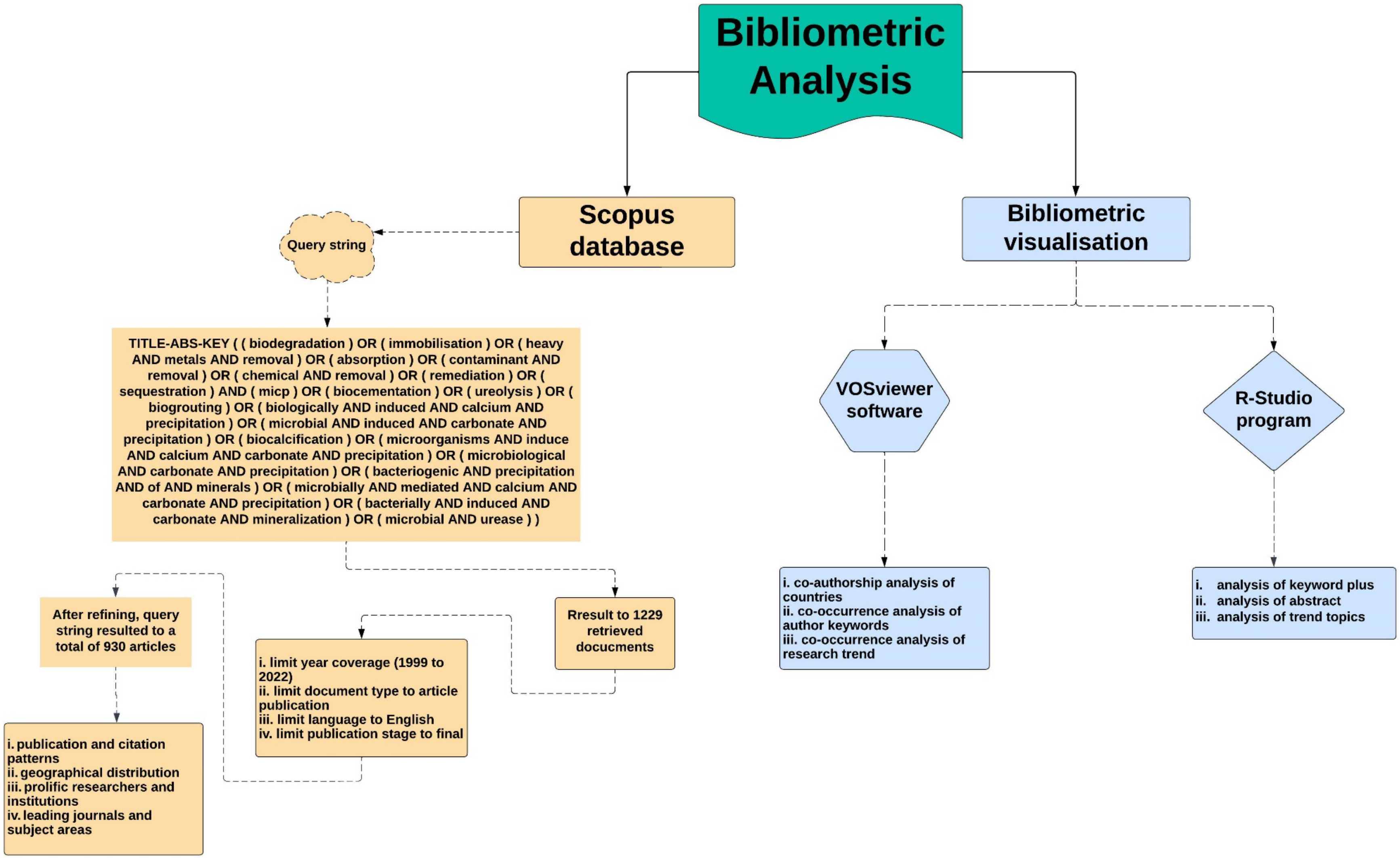

Fig. 2: Flowchart depicting the data retrieval process from the Scopus database and software tools (VOSviewer and R-Studio) for bibliometric analysis.

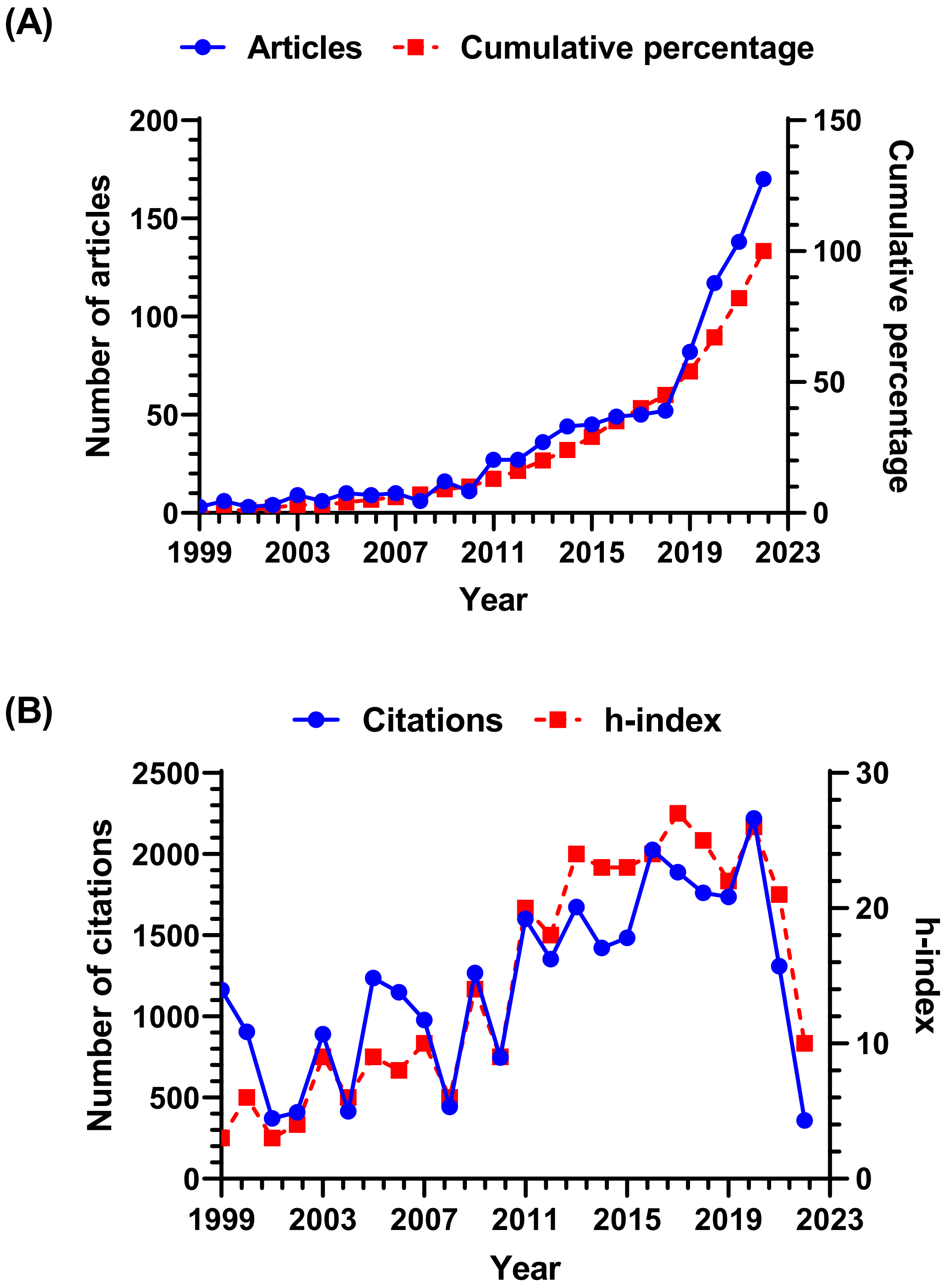

Fig. 3: Annual publications (A) and citations (B) on heavy metal removal through MICP from 1999 to 2022 in the Scopus database.

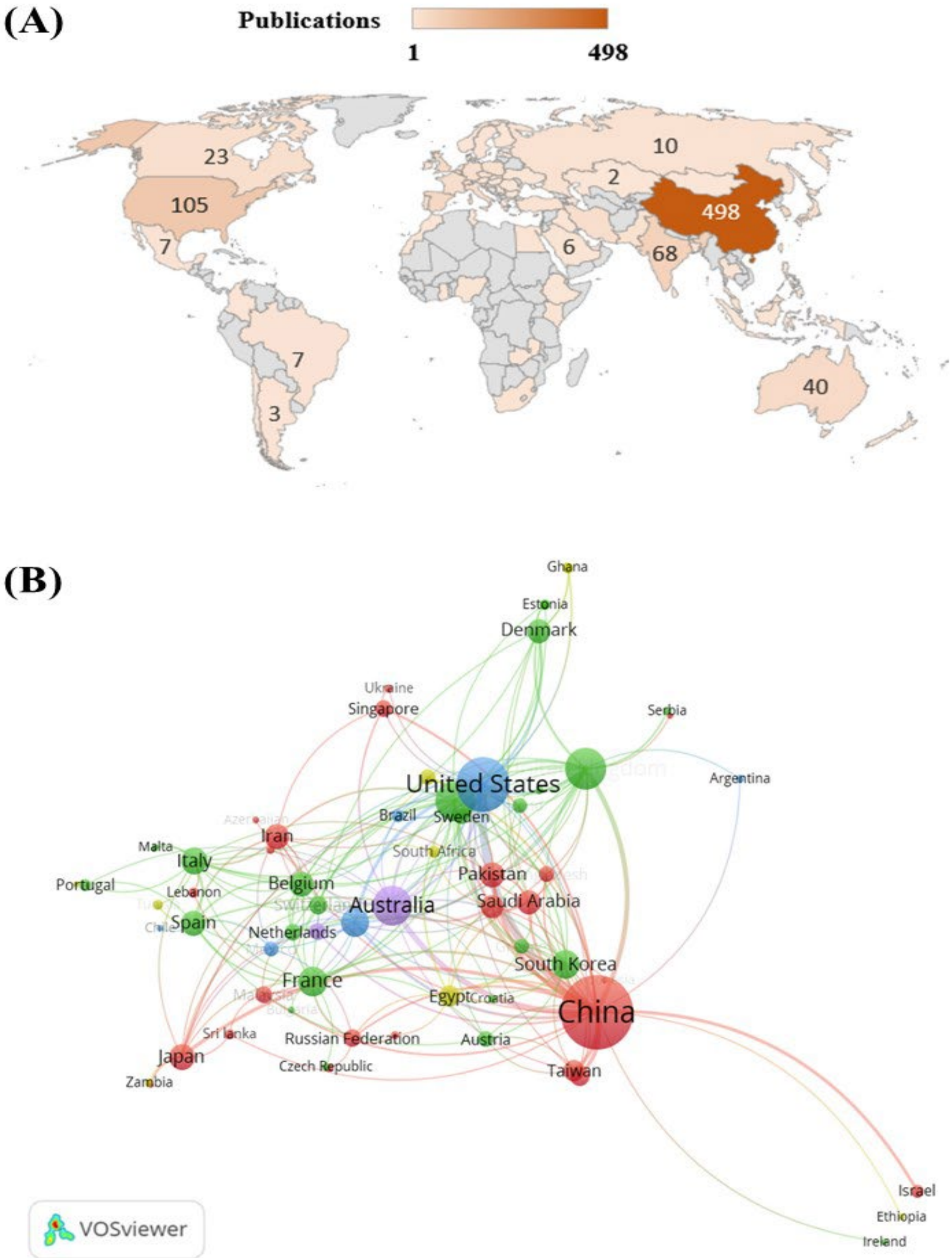

Fig. 4: Global distribution of publications by country (A), and network visualisation of the bibliometric map based on co-authorship analysis of countries (B). In the bibliometric map, the colour clusters are as follows: red for Asia, green for Europe, blue for America, yellow for Africa, and purple for Australia.

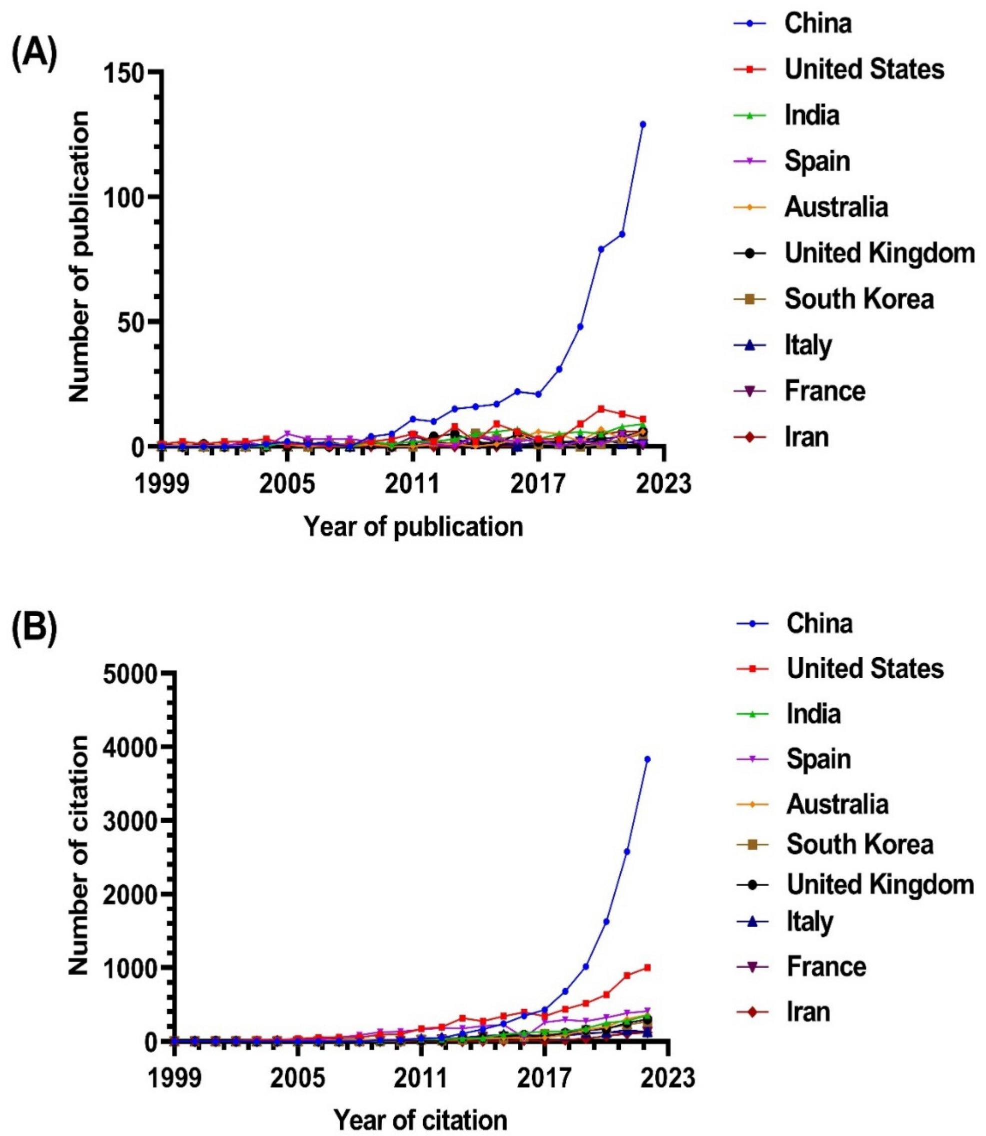

Fig. 5: Contribution of countries based on the number of articles published by each country (A), and the annual number of citations received by each country per year (B).

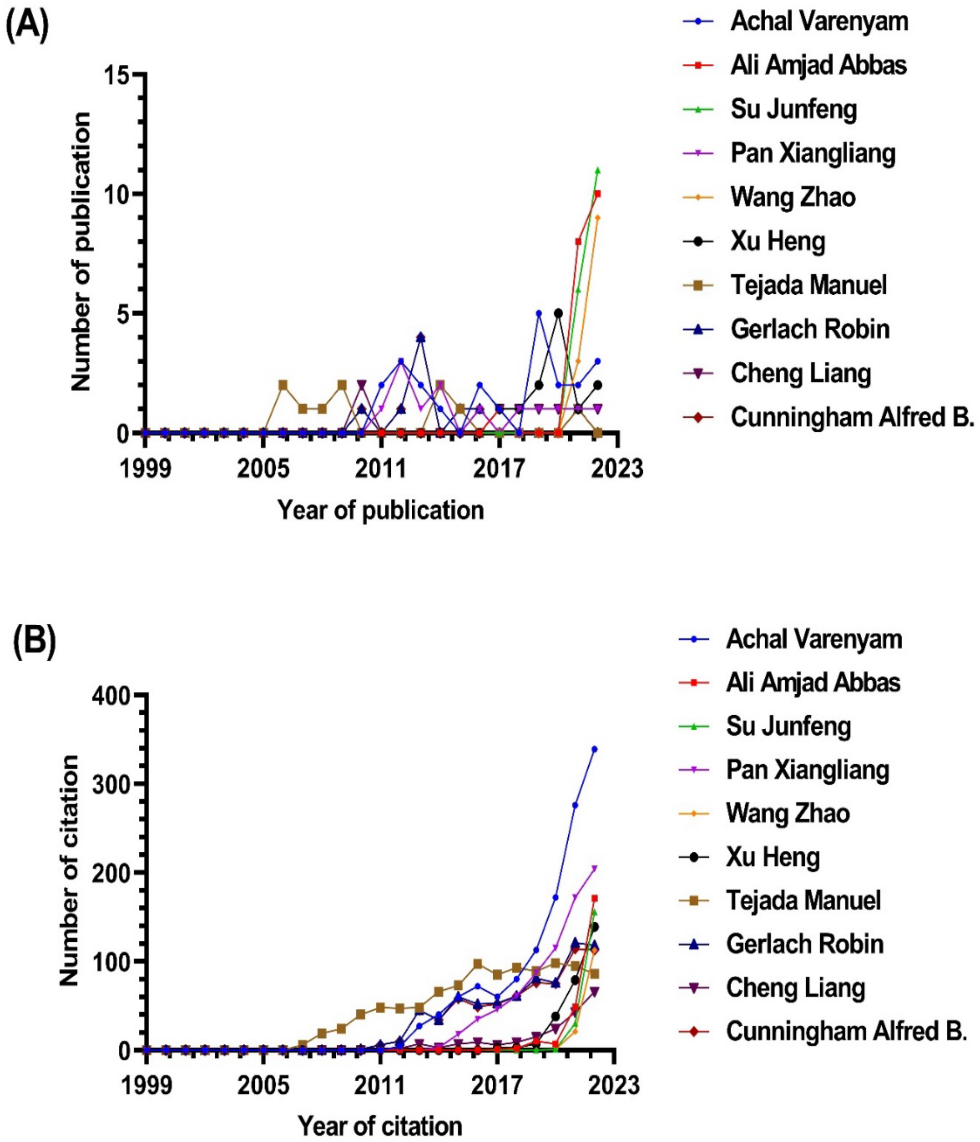

Fig. 6: The top prolific authors in the field. (A) the number of articles published by the authors between 1999 to 2022; and (B) the annual number of citations attained by the authors per year.

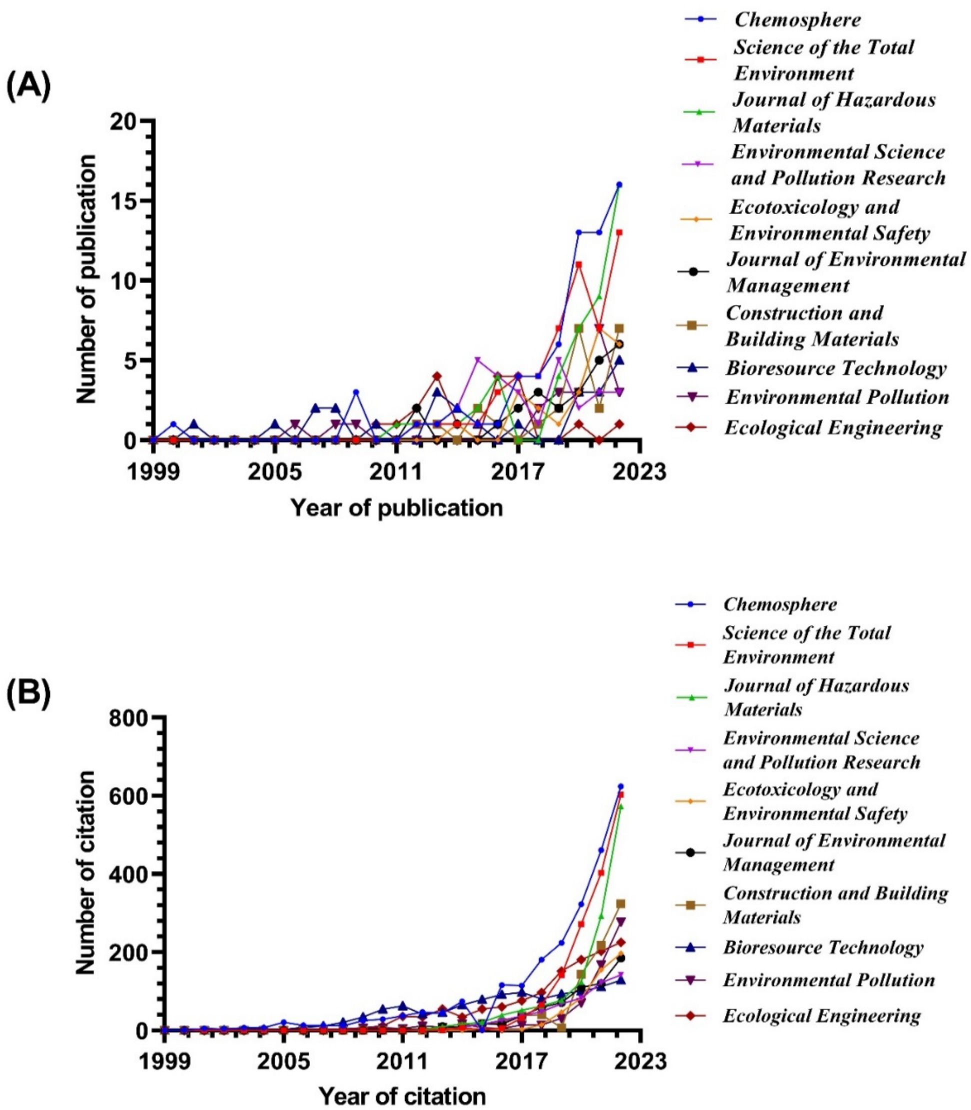

Fig. 7: The top productive journals in the field. (A) the number of articles published in the top journals from 1999 to 2022; and (B) the number of citations attained by the journals annually.

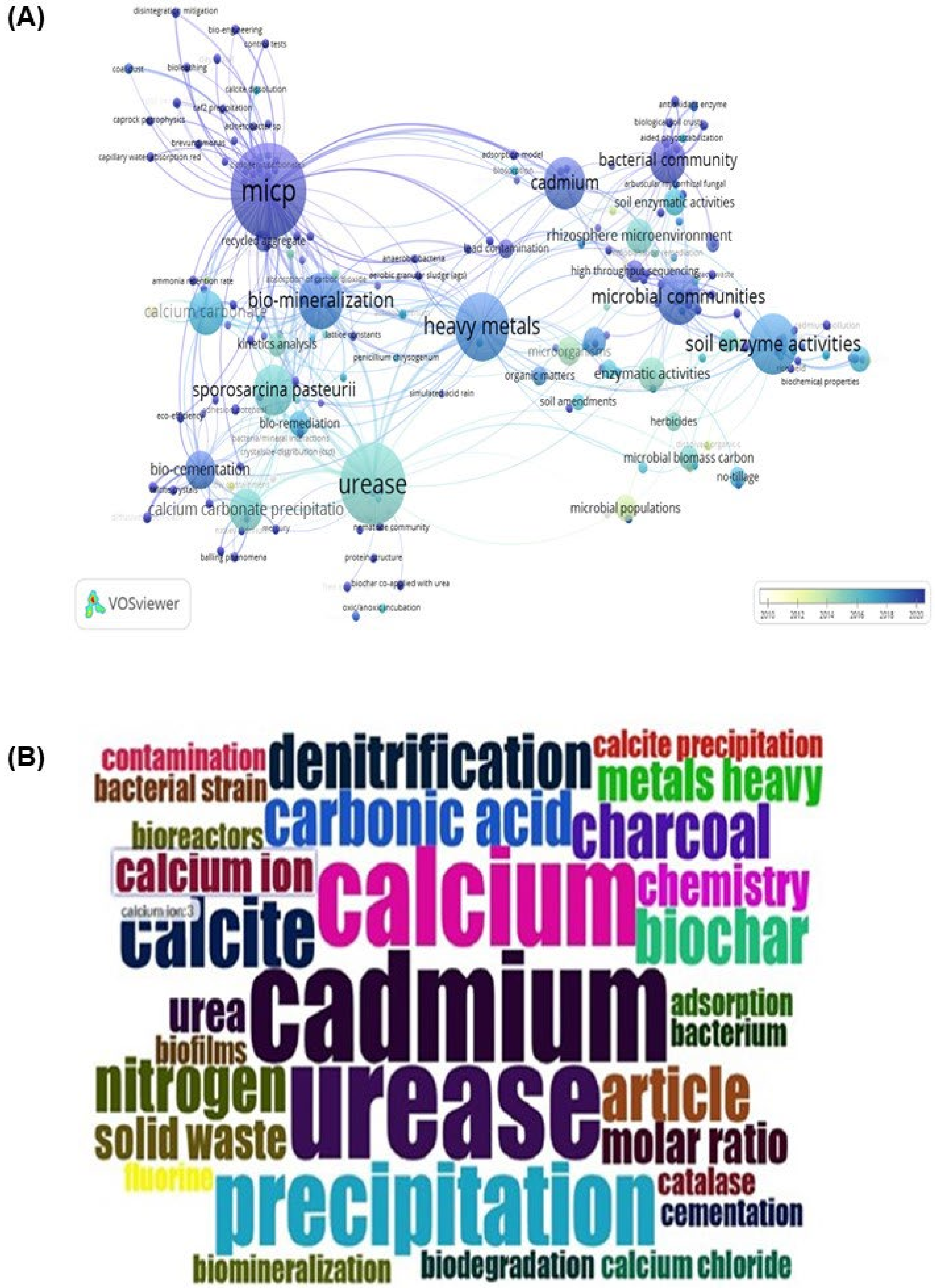

Fig. 8: Author keywords hotspots in the field. (A) overlay visualisation of author keywords co-occurrence using VOSviewer program; (B) word cloud analysis of keywords plus using R-Studio package.

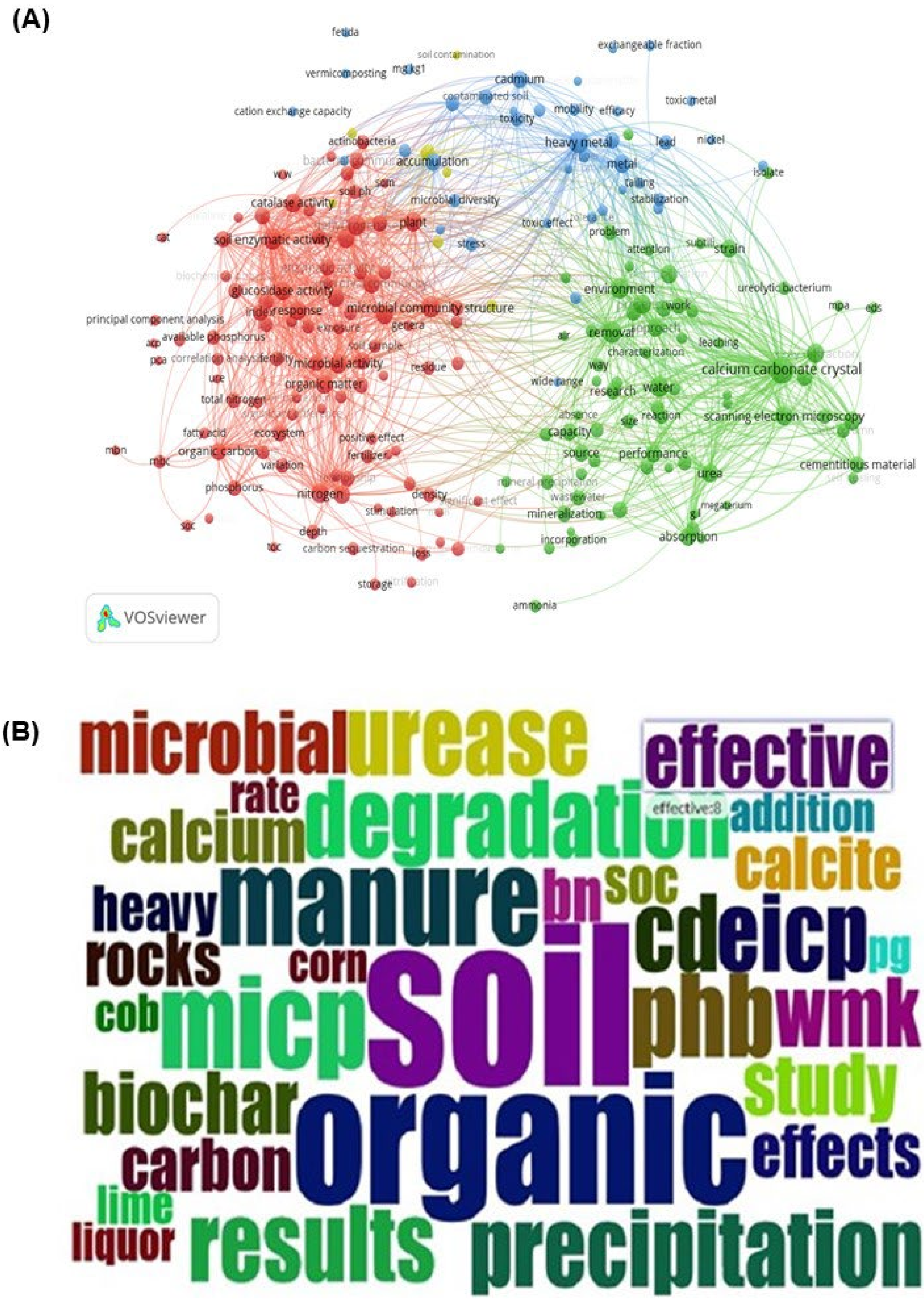

Fig. 9: Research trends or directions of the field. (A) network visualisation map of the co-occurrence of text data (title and abstract) using the VOSviewer program; (B) word cloud analysis of abstract using the R-Studio package.

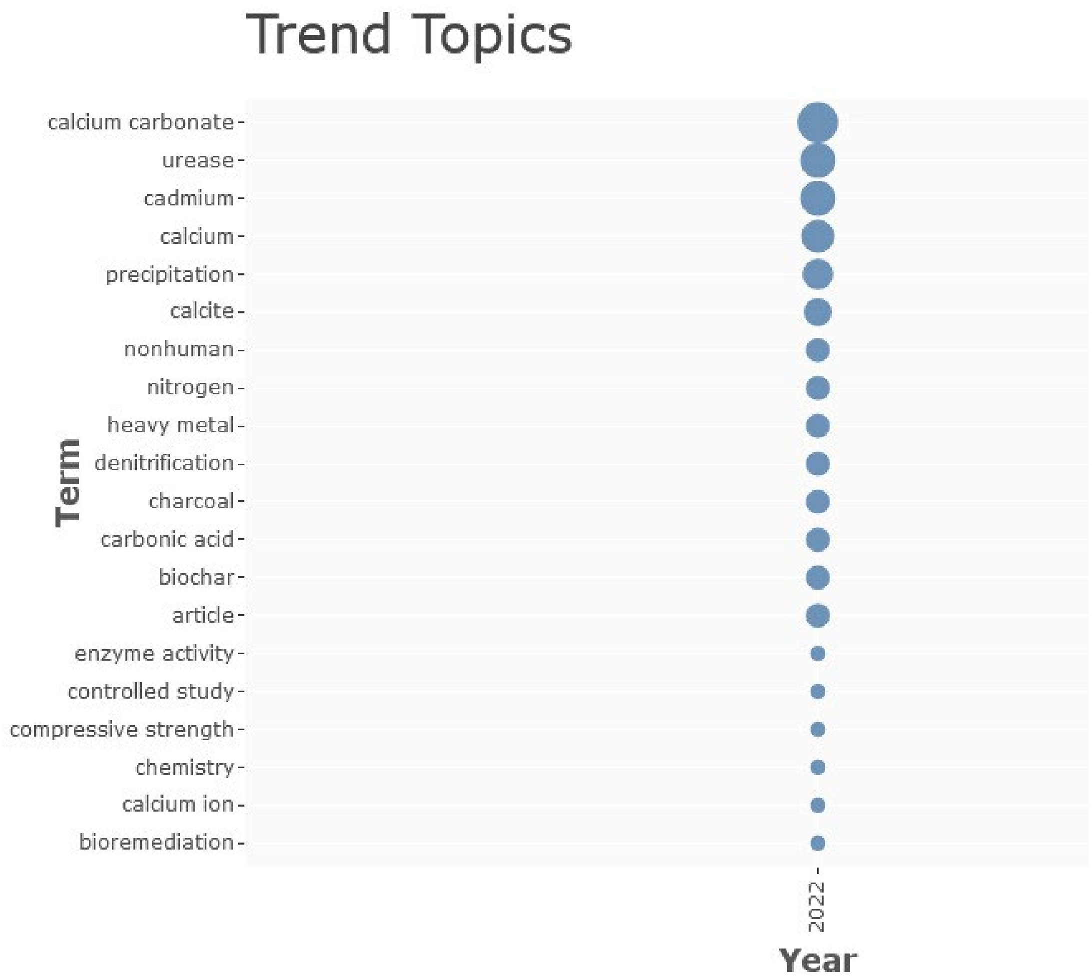

Fig. 10: Research trends or directions of the field follow R-Studio analysis of trend topics based on the latest publication year.

List of tables

Table 1: Summary of several bibliometric articles relating to the field of MICP for heavy metal removal.

Title of article	**Authors**	**Aim of study**	**Scientific database**	**Software tool**	**Selected key terms to search database**	**Years covered in scientific database**	**The main highlight of the study**	**Limitations of the study**
Global scientific research and trends regarding microbial induced calcite precipitation: a bibliometric network analysis	Jarwar et al. (2022)	This paper explores MICP scientific literature through keyword analysis, author productivity, highly cited publications, leading institutions and countries, author, country, and institution collaborations, and trends in journal	Web of Science Core Collection	VOSviewer software	microbial induced calcite precipitation (MICP)	2000 to 2022	The bibliometric analysis of 1580 publications revealed a rapid increase in MICP publications since 2014, with 333 papers published in 2021, and highlighted China as the leading country in terms of publication output, followed by the USA and Australia, indicating growing	The limitations of this study encompass potential issues related to data extraction since collecting data only up to August 2022 might miss recent publications if database updates continue. Additionally, the

		interest over 22 years.					interest in MICP research, especially in the domains of concrete healing, soil geotechnical improvement, and environmentally friendly techniques.	study's reliance on a single keyword, "microbial induced calcite precipitation," for the entire bibliometric analysis may result in a lack of comprehensive coverage and discussion of the field.
The global research trend on microbially induced carbonate precipitation	Omoregie et al. (2022)	The main aim of this bibliometric review is to analyze the trends in annual article publications and citations for	Scopus	VOSviewer software	microbially induced carbonate precipitation, microbially induce calcite precipitation, microbiological	2001 and 2021.	The bibliometric analysis of 1058 articles revealed that China, Construction and Building Materials, Satoru	The main limitation of this study is its reliance on data exclusively from the Scopus database, leading

during 2001–2021: a bibliometric review		MICP from 2001 to 2021, discuss key contributors and collaborations in the field, and identify popular author keywords and research terms in each journal.			precipitation of CaCO3, biocalcifying bacteria, biocalcification, calcifying microorganism, biomediated calcite precipitation, bioprecipitation of calcium carbonate, microbial carbonate precipitation, microbially induce calcium carbonate precipitation, bacterially induced carbonate mineralization, microorganisms		Kawasaki, Nanyang Technological University, and the National Natural Science Foundation of China emerged as leaders in the field. In addition, researchers are primarily focusing on four critical research areas: precipitation, MICP, compressive strength, and biomineralization.	to the exclusion of MICP articles not indexed in Scopus. Additionally, the selected keywords may not have captured all relevant publications if authors used different terminology in their papers. The study's data collection period, covering publications between 2001 and 2021, also

					induce calcium carbonate precipitation			excluded documents published before 2001 and after 2021. Another limitation of this study is its narrow focus on the "Environmental impact of MICP technology," potentially overlooking other important aspects of MICP research.
Artificial neural networks applied for solidified soils	Pacheco et al. (2021)	This article systematically analysed the current state of research,	Scopus and Web of Science	VOSviewer software and R-Studio Program	soil, cement, MICP, UCS, triaxial, ANN and machine learning.	1999 to 2020	The study examined a final portfolio of 64 articles for bibliometric analysis, focusing on	The main limitation of the study is that the selected keywords

data prediction: a bibliometric and systematic review		pinpointing leading research groups and their respective areas of focus. The study examines the fundamental aspects of employing artificial neural networks (ANNs) in cemented soils, assesses its potential applications, and explores the feasibility of extending this approach to various geotechnical, civil,					the primary research area associated with publications on ANN and soils, which is "Geotechnics." This emphasis is attributed to the versatility of ANN approaches and the specific requirements of each research domain. Leading the field are Tinoco J. from the University of Minho in Portugal and researchers in Iran, particularly in the field of Geotechnical and Geological	may not have captured all relevant publications if authors used different terminology in their papers, especially MICP. It is preferable to include the various representations of this acronym (i.e., Microbially Induced Calcium Carbonate Precipitation, microbial induced carbonate

		and environmental engineering domains					Engineering. Notably, an area that remains underexplored in the context of ANN and soil mechanics is biocementation-MICP.	precipitation). Additionally, the state-of-the-art review is not comprehensive enough, as it did not discuss several important areas of the field. The limitations of this study encompass potential issues related to data extraction since collecting data only up to June 2020 might miss recent publications if databases

								(Scopus and Web of Science) updates continue.
The progress and trend of microbially induced carbonate precipitation (MICP) research: a bibliometric analysis	Li et al. (2023)	This study uses bibliometrics to map the development of MICP research, identifying key topics, collaborations, and future directions.	Web of Science (WOS) Core Collection	CiteSpace (version 5.8.R3)	(microbial* NEAR/4 precipitation OR microbial* NEAR/4 carbonate OR microbial* NEAR/4 calcite)	2012-2021	MICP research has boomed in recent years, with China, the US, and leading universities focusing on applications in soil improvement, using novel materials, and exploring the underlying mechanisms.	The study's limitation is that it only analysed data from the WOS Core Collection, potentially excluding relevant publications from other databases, and it provided a quantitative overview without further qualitative analysis for a deeper

								understanding of the research field.
Critical analysis for life cycle assessment of bio-cementitious materials production and sustainable solutions	Al-Gheethi et al. (2022)	To assess the life cycle environmental impact of biocementitious materials compared to traditional cement, focusing on global warming, human health, and ecotoxicity.	Scopus	SimaPro 8, and VOSviewer (version 1.6.15)	"bio-cementitious materials" OR "bio-cementitious", "bacteria" OR fungi", "microbiologically induced calcite precipitation" OR "bioconcrete"	2010-2019	The study provides a comprehensive LCA of bio-cementitious materials compared to traditional cement, highlighting the significant environmental impact of raw materials like cement and Ca(NO3)2.4H2O	The study is limited to data from the WOS Core Collection, potentially excluding relevant publications from other databases, and it provides a quantitative overview without further qualitative analysis for a deeper understanding of the research field.

Perspective of hydrodynamics in microbial-induced carbonate precipitation: a bibliometric analysis and review of research evolution	Omoregie et al. (2024)	To conduct a bibliometric analysis of MICP research related to hydrodynamics and identify trends, gaps, and collaborations, guiding future research in this field.	Scopus	VOSviewer software (version 1.6.17) and RStudio software (version 2021.09.1)	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 AND conductivities) OR (fluid AND injection AND experiments) OR (infiltration) OR (cementation AND	1999 to 2024.	By analysing 1098 MICP research articles, this study reveals a global research effort with China and the US leading the way. It highlights key applications in soil improvement and concrete repair, while uncovering thematic areas like biocementation with potential for environmental solutions.	This study offers a valuable snapshot of MICP research up to February 2024 based on Scopus database. However, it might not capture the very latest trends and focuses primarily on the hydrodynamics aspect, potentially overlooking other dimensions of this field.

					solution) OR (injection AND rates) OR (fracture AND development) OR (matrix AND flow) OR (permeability) OR (hydraulic AND properties) OR (porosity) OR (flow AND processes) OR (fracture AND patterns) OR (pore AND volume AND ratio) OR (injection AND rate) OR (soil-water AND repellency) OR (aquifer AND storage) OR (flow AND rate)			

					OR (syringe AND pump) OR (geo-environmental AND engineering) OR (groundwater AND hydraulics) OR (porous AND media) OR (water AND resources) OR (contaminant AND hydrology) OR (urea AND hydrolysis) OR (pore AND network) OR (crystal AND growth) OR (chemical AND precipitation) OR (adsorption) OR (ion AND exchange) OR (toxic AND			

					metals) OR (groundwater AND hydraulics) OR (breakdown AND pressure) OR (viscous AND fluid) OR (infiltration AND dominance)).			

Table 2: Top 10 most contributing countries in the field of MICP for heavy metal removal from 1999 to 2022.

Country	**Publications**	**Citations**	**h-index**	**Highest cited article (reference, journal)**	**Citation of highest cited article**
China	498	11159	54	Heavy metal removal by biomineralization of urease producing bacteria isolated from soil ((Li et al. 2013), *International Biodeterioration and Biodegradation*)	243
United States	105	5968	37	Microbiological precipitation of $CaCO_3$ ((Stocks-Fischer et al. 1999), *Soil Biology and Biochemistry*)	1036

India	68	1734	22	Changes in organic - C, N, P and K and enzyme activities in vermicompost of biodegradable organic wastes under liming and microbial inoculants ((Pramanik et al. 2007), *Bioresource Technology*)	252
Spain	43	3399	24	Different approaches to evaluating soil quality using biochemical properties ((Gil-Sotres et al. 2005), *Soil Biology and Biochemistry*)	533
Australia	40	1552	19	Urease activity in microbiologically-induced calcite precipitation ((Bachmeier et al. 2002), *Journal of Biotechnology*)	335
United Kingdom	40	1429	21	Impact of sugarcane bagasse-derived biochar on heavy metal availability and microbial activity: A field study ((Nie et al. 2018), *Chemosphere*)	176
South Korea	32	1250	16	In situ stabilization of cadmium-, lead-, and zinc-contaminated soil using various amendments ((Lee et al. 2009), *Chemosphere*)	267
Italy	29	1103	18	Influence of red mud, zeolite and lime on heavy metal immobilization, culturable heterotrophic microbial populations and enzyme activities in a contaminated soil ((Garau et al. 2007), *Geoderma*)	300
France	27	934	17	Biocalcification in the Eastern Oyster (Crassostrea virginica) in Relation to Long-term Trends in Chesapeake Bay pH ((Waldbusser et al. 2011), *Estuaries and Coasts*)	181
Iran	25	396	12	Soil specific enzyme activity shows more clearly soil responses to paddy rice cultivation than absolute enzyme activity in primary forests of northwest Iran ((Raiesi and Beheshti 2014), *Applied Soil Ecology*)	86

Table 3: The top 10 most prolific authors in the field of heavy metal removal via MICP from 1999 to 2022.

Authors	Publications	Citations	h-index	Country	Institution	Scopus ID	ORCID	Highest cited article (reference, journal)	Citation of highest cited article
Achal Varenyam	23	1243	16	Israel	Technion - Israel Institute of Technology,	1.5077E+10	0000-0001-5444-7746	Biomineralization based remediation of As(III) contaminated soil by *Sporosarcina ginsengisoli* ((Achal et al. 2012))	206
Ali Amjad Abbas	19	240	8	China	Xi'an University of Architecture and Technology,	5.6992E+10	nil	Isolation of biosynthetic crystals by microbially induced calcium carbonate precipitation and their utilization for fluoride removal from groundwater ((Wang et al. 2021b))	39
Su Junfeng	17	187	7	China	Xi'an University of Architecture and Technology,	14021906000	0000-0001-8434-0851	Isolation of biosynthetic crystals by microbially induced calcium carbonate precipitation and their utilization for fluoride removal from groundwater ((Wang et al. 2021b))	39

Pan Xianglian g	13	741	11	China	Zhejiang University of Technology,	14834194 700	nil	Biomineralization based remediation of As(III) contaminated soil by *Sporosarcina ginsengisoli* ((Achal et al. 2012))	206
Wang Zhao	12	135	5	China	Xi'an University of Architecture and Technology,	5.7208E+ 10	nil	Isolation of biosynthetic crystals by microbially induced calcium carbonate precipitation and their utilization for fluoride removal from groundwater ((Wang et al. 2021b))	39
Xu, Heng	12	269	9	China	Sichuan University,	5.5494E+ 10	0000-0002-7252-284X	Performance of microbial induced carbonate precipitation for immobilizing Cd in water and soil ((Peng et al. 2020))	53
Tejada Manuel	10	1008	9	Spain	Universidad de Sevilla	90438889 00	0000-0003-0944-4946	Use of organic amendment as a strategy for saline soil remediation: Influence on the physical, chemical and biological properties of soil ((Tejada et al. 2006))	407
Gerlach Robin	9	718	8	United States	Montana State University	57189020 312	nil	Microbially enhanced carbon capture and storage by mineral-trapping and solubility-trapping (Mitchell et al. 2010))	180

Cheng Liang	8	192	7	China	Institute of Materials Engineering Nanjing University,	55474102700	0000-0002-1767-2108	Theory of microbial carbonate precipitation and its application in restoration of cement-based materials defects ((Qian et al. 2010))	56
Cunningham Alfred B.	8	694	6	Bozeman, United States	Montana State University	7201846869	nil	Microbially enhanced carbon capture and storage by mineral-trapping and solubility-trapping ((Mitchell et al. 2010))	180

Table 4: The top 10 most productive journals in the field of MICP for heavy metal removal, their performance matric, and most cited articles.

Journals	**Publications**	**Citations**	**h-index**	**Highest cited article (reference)**	**Citation of highest cited article**	**Publisher**	**CiteScore (2022)**	**SJR (2022)**	**SNIP (2022)**	**Quartile**
Chemosphere	66	2478	24	Monitoring of bioremediation by soil biological activities ((Margesin et al. 2000))	374	Elsevier	13.3	1.727	1.624	Q1

Science of the Total Environment	52	1573	24	Response of soil enzyme activities and bacterial communities to the accumulation of microplastics in an acid cropped soil ((Fei et al. 2020))	187	Elsevier	16.8	1.946	2.026	Q1
Journal of Hazardous Materials	46	1307	21	Biomineralization based remediation of As(III) contaminated soil by *Sporosarcina ginsengisoli* ((Achal et al. 2012))	206	Elsevier	20.2	2.570	2.136	Q1
Environmental Science and Pollution Research	30	558	14	Bioremediation of Cd by strain GZ-22 isolated from mine soil based on biosorption and microbially induced carbonate precipitation ((Zhao et al. 2017)	63	Springer Nature	7.9	0.944	1.214	Q1
Ecotoxicology and Environmental Safety	26	515	13	Optimization of combined phytoremediation for heavy metal contaminated mine tailings by a field-	53	Elsevier	11.7	1.348	1.389	Q1

				scale orthogonal experiment ((Li et al. 2019))						
Journal of Environmental Management	25	644	13	Evaluation of the effectiveness of sepiolite, bentonite, and phosphate amendments on the stabilization remediation of cadmium-contaminated soils ((Sun et al. 2016))	318	Elsevier	13.4	1678	1.849	Q1
Construction and Building Materials	24	908	14	Modification of recycled concrete aggregate by calcium carbonate biodeposition ((Pan et al. 2015))	189	Elsevier	12.4	1.888	2.214	Q1
Bioresource Technology	23	1141	14	Changes in organic - C, N, P and K and enzyme activities in vermicompost of biodegradable organic wastes under liming and microbial inoculants ((Pramanik et al. 2007))	252	Elsevier	19.0	2.473	2.016	Q1
Environmental Pollution	22	671	12	LDPE microplastic films alter microbial community composition and enzymatic activities in soil ((Huang et al. 2019))	207	Elsevier	14.9	1.954	2.110	Q1

Ecological Engineering	19	1144	16	Influence of urea and calcium dosage on the effectiveness of bacterially induced carbonate precipitation on limestone ((De Muynck et al. 2010))	173	Elsevier	7.6	0.946	1.141	Q1

Table 5: The highest cited articles in the field of MICP for heavy metal removal published from 1999 to 2022

Year of publication	Publication	Highest cited article (reference, journal)	Citation of highest cited article
1999	3	Microbiological precipitation of $CaCO_3$ ((Stocks-Fischer et al. 1999), *Soil Biology and Biochemistry*)	1036
2000	6	Monitoring of bioremediation by soil biological activities ((Margesin et al. 2000), *Chemosphere*)	374
2001	3	Microbially mediated calcium carbonate precipitation: Implications for interpreting calcite precipitation and for solid-phase capture of inorganic contaminants ((Warren et al. 2001), *Geomicrobiology Journal*)	243
2002	4	Urease activity in microbiologically-induced calcite precipitation ((Bachmeier et al. 2002), *Journal of Biotechnology*)	335
2003	9	Conservation of ornamental stone by *Myxococcus xanthus*-induced carbonate biomineralization	387

		((Rodriguez-Navarro et al. 2003), *Applied and Environmental Microbiology*)	
2004	6	Strontium incorporation into calcite generated by bacterial ureolysis ((Fujita et al. 2004), *Geochimica et Cosmochimica Acta*)	188
2005	10	Different approaches to evaluating soil quality using biochemical properties ((Gil-Sotres et al. 2005), *Soil Biology and Biochemistry*)	533
2006	9	Use of organic amendment as a strategy for saline soil remediation: Influence on the physical, chemical and biological properties of soil ((Tejada et al. 2006), *Soil Biology and Biochemistry*)	407
2007	10	Influence of red mud, zeolite and lime on heavy metal immobilization, culturable heterotrophic microbial populations and enzyme activities in a contaminated soil ((Garau et al. 2007), *Geoderma*)	300
2008	6	Stimulation of microbial urea hydrolysis in groundwater to enhance calcite precipitation ((Fujita et al. 2008), *Environmental Science and Technology*)	205
2009	16	In situ stabilization of cadmium-, lead-, and zinc-contaminated soil using various amendments ((Lee et al. 2009), *Chemosphere*)	267
2010	11	Microbially enhanced carbon capture and storage by mineral-trapping and solubility-trapping ((Mitchell et al. 2010), *Environmental Science and Technology*)	180
2011	27	Biocalcification in the Eastern Oyster (*Crassostrea virginica*) in Relation to Long-term Trends in Chesapeake Bay pH ((Waldbusser et al. 2011), *Estuaries and Coasts)*	181
2012	27	Biomineralization based remediation of As(III) contaminated soil by *Sporosarcina ginsengisoli*	206

		((Achal et al. 2012), *Journal of Hazardous Materials*)	
2013	36	Heavy metal removal by biomineralization of urease producing bacteria isolated from soil ((Li et al. 2013), *International Biodeterioration and Biodegradation*)	243
2014	44	Effect of biochar on carbon fractions and enzyme activity of red soil ((Demisie et al. 2014), *Catena*)	157
2015	45	In situ stabilization remediation of cadmium (Cd) and lead (Pb) co-contaminated paddy soil using bentonite ((Sun et al. 2015), *Applied Clay Science*)	139
2016	49	Immobilization of Cd in river sediments by sodium alginate modified nanoscale zero-valent iron: Impact on enzyme activities and microbial community diversity ((Huang et al. 2016), *Water Research)*	216
2017	50	The effects of rice straw biochar on indigenous microbial community and enzymes activity in heavy metal-contaminated sediment ((Huang et al. 2017), *Chemosphere*)	219
2018	52	Impact of sugarcane bagasse-derived biochar on heavy metal availability and microbial activity: A field study ((Nie et al. 2018), *Chemosphere*)	176
2019	82	LDPE microplastic films alter microbial community composition and enzymatic activities in soil (Huang et al. 2019), *Environmental Pollution*)	207
2020	117	Response of soil enzyme activities and bacterial communities to the accumulation of microplastics in an acid cropped soil ((Fei et al. 2020), *Science of the Total Environment)*	187

2021	138	Microbial induced calcium carbonate precipitation study using *Bacillus subtilis* with application to self-healing concrete preparation and characterization ((Feng et al. 2021), *Construction and Building Materials*)	46
2022	170	Microplastics change soil properties, heavy metal availability and bacterial community in a Pb-Zn-contaminated soil ((Feng et al. 2022), *Journal of Hazardous Materials*)	47

Table 6: Recent directions of MICP and related techniques in environmental remediation.

Application	**Key Findings**
Soil Remediation (As, Pb, Cd)	Effective stabilization of As, Pb, and Cd contaminants in soil using amendment materials and microorganisms.
Cr Contaminated Groundwater	Promising potential of Cr(VI) remediation by *Sporosarcina saromensis* and MICP.
Heavy Metal Stability (Pb) in Soil	Enhanced stability of Pb through a combination of biochar and MICP technology.
Zinc (Zn) Contaminated Soil	Successful reduction of Zn mobility and concentration in the soil through MICP.
Gypsum Plaster Enhancement	Improved gypsum plaster strength, durability, and microstructure with bacterial species and porous conch shell powder.
Heavy Metal Stability (Cd, Pb, Cu, Zn) in Soil	Biochar effectively passivated heavy metals and increased soil microbial activity in heavy metal-contaminated soil.
Heavy Metal Stabilization (Pb) in Water Bodies	Effective use of self-healing MICP materials to prevent Pb migration in contaminated water bodies.

Cadmium (Cd) Immobilization in Soil	Significant reduction in soil Cd mobility, improved soil fertility, and enhanced bacterial diversity through a biochar-bacteria partnership.
Biochar for Heavy Metal Remediation in Soil	Biochar effectively immobilized heavy metals, enhanced soil microbial activity, and modified heavy metal forms.
Microbial Calcium Precipitation with *Staphylococcus* sp	Demonstrated the capability of *Staphylococcus* sp. H6 in consolidating sand particles through microbial calcium precipitation.
Biological Soil Crusts for As Immobilization	Co-inoculation of *Leptolyngbya* sp. XZMQ and *Bacillus* sp. XZM forming biological soil crusts for enhanced As immobilization.
Fly Ash-Based Inoculum for Concrete Repair	Application of fly ash-based bacterial inoculum to promote MICP for concrete structure repair.
Cd Immobilization in Soil	Evaluation of various microbial agents for enhancing Cd remediation in *Solanum nigrum* with insights into optimized strategies.
Carbonate Precipitation for Cd Removal	Isolation of urease-positive bacteria with potential for efficient Cd removal from solution, contributing to bioremediation.
Stone Material Consolidation	Utilization of MICP to consolidate stone materials, enhancing strength and durability.
Long-Term Stability of Cd Immobilization in Soil	Investigation of Cd immobilization stability influenced by phosphate levels and nitrogen fertilizer input in agricultural areas.
Pb and Cu Remediation Using MICP and EICP	A comparative study evaluating the performance of Pb and Cu remediation using MICP and EICP.

Cd Immobilization in Soil	Ureolytic bacteria (*Ochrobactrum* sp. POC9) metabolites containing carbonates significantly reduce Cd bioavailability and uptake by plants, enhancing soil properties.
Groundwater Contaminant Removal (NO3--N, Ca2+, F-, Phenol)	Microencapsulated immobilization reactor with *Aquabacterium* sp. CZ3 efficiently removed NO3--N, Ca2+, F-, and phenol from complex groundwater.
Microbial Consortia in Bio-Concrete	Incorporation of microbial consortia with high alkali resistance and endospore formation into bio-concrete for improved strength and reduced toxicity.
Immobilization of Cd2+ and Pb2+ in Soil and Water	Stabilization of Cd2+ and Pb2+ by a microbial consortium, *Sporosarcina* sp, providing a novel resource for biomineralization in soil and water.
Cu Immobilization in Contaminated Sites	MICP technology demonstrated effective Cu immobilization under near-neutral pH conditions, offering promise for Cu-contaminated site remediation.
Sewage Sludge Heavy Metal Stabilization	Integration of MICP treatment in sewage sludge anaerobic digestion-land application effectively stabilized ionic-state Cd, reducing exchangeable fractions of Pb and Cd.
Lead-Zinc Tailings Remediation	MICP technology solidified and reduced heavy metal pollution in lead-zinc tailings, with maximum efficiency at a 2 cm thickness.
Strontium (^{90}Sr) Removal Using MICP	MICP-induced calcite and strontianite formation, with higher Sr/Ca ratios promoting strontium incorporation into minerals, aiding in strontium removal.
Phytoremediation of Cd-Contaminated Soil	*Bacillus cereus* BL4 enhanced plant growth and Cd accumulation in plant tissues, reducing Cd bioavailability in soil, offering a phytoremediation solution.