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7 Cite Information for this article:

8 Omoregie, A.I., Muda, K., Ojuri, O.O. *et al.* The global research trend on microbially induced carbonate
9 precipitation during 2001–2021: a bibliometric review. *Environ Sci Pollut Res* (2022).

10 <https://doi.org/10.1007/s11356-022-24046-w>

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

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48 **ABSTRACT**

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

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

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78 **1. Introduction**

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

94

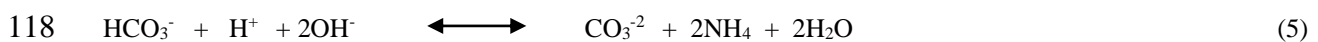
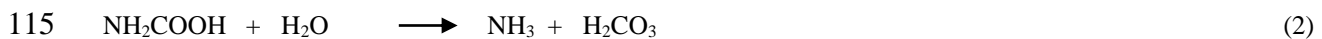
95 MICP is a biomineralization mechanism that relies on microbial metabolic activity to precipitate carbonate
96 crystals (Meng et al. 2021a; Moradi et al. 2021). The MICP process presently has five modes: denitrification,
97 ammonification, ferric reduction, sulphate reduction, and urea hydrolysis (ureolysis)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

103

104 It is critical to understand that the urease enzyme (EC 3.5.1.5) hydrolyzes/breaks down urea into one mole
105 of ammonia and carbamate ions (Eqn. 1). This leads to the creation of ammonium and hydroxide ions (Eqn. 2-3)
106 (Stocks-Fischer et al. 1999). However, after carbamate acid is spontaneously transformed into ammonia and
107 carbonic acid, it is carbonic anhydrase (EC 4.2.1.1) rather than the urease enzyme that causes carbonic acid to be

108 turned into bicarbonate ion (Eqn. 4-5) (Castro-Alonso et al. 2019). As indicated in Eqn. 6, the subsequent synthesis
 109 of ammonium and hydroxide ions raises the pH of the solution, which favours/allows carbonate precipitation in
 110 the presence of calcium ions (i.e., calcium chloride) (Medina Ferrer et al. 2020). The reactions create a shift in
 111 bicarbonate equilibrium, resulting in carbonate ions formation, which reacts with CaCl₂ in the microenvironment
 112 to produce 1 mol of CaCO₃ (Omoriegic et al. 2022).

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

130

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

138 stand-alone stabilising technology with MICP cement-stabilized road base materials (Gowthaman et al. 2022a;
139 Yang et al. 2022).

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

154

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

165

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

168 This is accomplished by reviewing the extant literature on a specific issue to discover possible study topics for
169 future efforts. There is an increasing number of MICP review papers that cover a wide range of topics (for
170 example, historical background, CaCO₃ mechanisms, microbial species, metabolic processes, testing
171 methodologies, kinetic parameters, problems impacting the MICP, and interesting applications). These reviews
172 of the literature are frequently utilised as a subjective way to evaluate the contents and topic areas published in
173 the field. However, detailed assessments of global research trends based on bibliometric analysis have been rare
174 in this subject (Ahenkorah et al. 2021; Pacheco et al. 2021).

175
176 Currently, bibliometric analysis enables the formation of networks based on the relationships between
177 countries, institutions, authors, journals, and keywords important to the research topic (Irfan et al. 2021). To the
178 best of our knowledge, no bibliometric studies on MICP from 2001 to 2021 have been conducted utilising the
179 Scopus database and VOSviewer. As a result, employing Scopus as a source of data mining on MICP-related
180 articles would aid in determining the global research trend in the specific topic of interest. To address the
181 knowledge gaps identified in past studies, the objectives of this bibliometric review were: (1) to analyze the annual
182 article publications and citations trend of MICP from 2001 to 2021; (2) to discuss the leading countries, journals,
183 authors, institutions, funding sponsors in the field of MICP; (3) to identify collaborations/network among authors
184 and countries through VOSviewer analysis; and (4) to highlight the most popular author keywords and research
185 terms used in each journal. Nonetheless, this bibliometric review study will provide many academics with
186 quantitative and qualitative scientific insights into the current research trend and future direction of the MICP
187 process.

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191 **2. Methodology**

192 2.1. Data mining and search strategy

193 The search strategy was used to retrieve documents from the Scopus database on 09 October 2021. Twelves
194 keywords (microbially induced carbonate precipitation, microbially induce calcite precipitation, microbiological
195 precipitation of CaCO₃, biocalcifying bacteria, biocalcification, calcifying microorganism, biomediated calcite
196 precipitation, bioprecipitation of calcium carbonate, microbial carbonate precipitation, microbially induce
197 calcium carbonate precipitation, bacterially induced carbonate mineralization,

198 microorganisms induce calcium carbonate precipitation) were used to search from the title, abstract and keyword
199 sections of the Scopus database. The data collection period covered publications between 2001 and 2021. Article
200 documents, ~~publishing~~, written in English language, published in journals, and at the final stage of publication
201 were selected ~~the only document formats allowed~~.

202 2.2. Data extraction and analysis

203 The retrieved documents (2,942) from the Scopus database based on the selected keywords were classified into
204 11 different document types. **Fig. 1** illustrates the strategy used in selecting the query strings from the Scopus
205 database for this bibliometric review, while **Supplementary information, Table 01** lists the corresponding query
206 strings utilized in each subsequent phase. ~~The~~ Articles had the largest proportion (2,473), accounting for 84.1%
207 of the total document types. This was followed by conference papers (272) and review articles (103). Articles are
208 often the preferred document type by authors due to their high reliability and acceptance in the scientific
209 community (Saravanan et al. 2022). The remaining proportion (3%) were book chapters (40), conference reviews
210 (32), notes (10), erratum (6), editorial (3), book (1), short survey, (1), and retracted (1). The publications extracted
211 from the Scopus database were further grouped into six different source types consisting of Journal (2589),
212 Conference Proceeding (215), Book Series (109), Book (26), Trade Journal (2), and Undefined (1). Of the 14
213 different languages, 2,811 documents (95%) were written in ~~the~~ English language. The remaining 5% of the
214 documents were written in other languages comprising of Chinese (105), Spanish (10), French (4), Hungarian (3),
215 Portuguese (3), Polish (2), Czech (1), Estonian (1), Japanese (1), Persian (1), Russian (1), Turkish (1), and
216 Undefined (1). For this study, only documents (1,058 articles) ~~only~~ written in English were selected and extracted
217 for bibliometric analysis. The exported citations in comma-separated values ~~format~~ files were reviewed when
218 moved to a Microsoft Excel spreadsheet (version 16.54, Microsoft Corporation, Redmond, WA, USA), for data
219 ~~reliability and~~ data analysis. These files were then used to analyze the publication output trend, most prolific
220 authors, countries, journals, institutions, funding sponsors, subject areas, and keywords.

221

222 2.3. Bibliometric mapping

223 The Java-based scientometrics research application is a highly efficient software tool for constructing bibliometric
224 maps (Van Eck and Waltman 2010). The VOSviewer program (version 1.6.18 was adopted since it emphasises
225 the graphical display of bibliometric maps (Afgan and Bing 2021). The number of co-authored documents is used
226 in co-authorship analysis to determine the similarity of items. In contrast, co-occurrence analysis depicts the
227 relationship between objects based on the number of times they are cited together and the number of works

228 completed jointly (Leydesdorff et al. 2013). In network graphs created using the VOSviewer, the size of each
229 node (i.e., circle) represents the weight of the link strength for various parameters (i.e., countries, authors, journals,
230 or keywords). The nodes are assigned depending on several taxonomies or occurrences (Cen et al. 2020). The
231 lines represent the connections between these characteristics, the thickness of the links denotes their
232 relatedness/connection, and the different colours represent the clusters into which they are sorted. The estimated
233 centrality of each parameter determines the node sizes (Cen et al. 2020). As a result, nodes with larger diameters
234 imply higher levels of centrality. As a result, in visualisation maps, the total link strength can be employed to
235 identify or characterise the items in various parameters leading to the groupings. Clusters are produced by
236 VOSviewer analysis to express the collection of nodes that correspond to related subjects.

237

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

258 3.3. Results and discussion

259 3.1. Annual publications and citations

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

278

279 Fig. 3 depicts the total citations and normalised citations per article on MICP research from 2001 to 2021.
280 These publications received a total of 25,996 citations. The chart demonstrated an unstable growth tendency, with
281 numerous increases and dips in annual citations across the year. The year with the most total citations (2,342) was
282 2012, while the year with the fewest citations (215) was 2021. It was expected that articles published a decade
283 ago would be more referenced than those published recently. This is understandable given that articles take longer
284 to be mentioned after they are published. According to Table 1, the entire citations (25,996) were attributed to
285 922 articles. This meant that 87% of all MICP papers have been cited. The total number of citations could be used
286 as a measure of academic accomplishment (Wu et al. 2021a). This is because it provides a measure of the scientific
287 impact, visibility, and readability of a particular study to other scholars in a field (Shuaib et al. 2015). On the other

288 hand, the years with the most normalised citations per article (119) were 2003 and 2006, while the years with the
289 lowest normalised citations per paper (1) was 2021. The findings also revealed that there is no relationship
290 between the total annual number of publications and the total annual number of citations. For example, the year
291 2021 had the most overall publications (170), but only 215 total citations. However, 2012 had the highest number
292 of total citations (2,342) with only 39 total publications. This may have indicated that the work (such as improving
293 sustainable bricks, bio soil consolidation/enhancement for in-situ application, on MICP during these periods was
294 critical in regards to the emerging research interest (Dhami et al. 2012; Filet et al. 2012; Soon 2013). Like total
295 citations, the *h*-index is the dominant metric often used to quantify or evaluate scholarly output (Engqvist and
296 Frommen 2008). According to the Scopus database, the *h*-index of the retrieved articles was 78. This means that
297 out of the 1058 articles that were considered for the *h*-index, 78 have been cited at least 78 times, and this value
298 might increase with time (Sweileh et al. 2016). In addition, 2019 recorded the highest value for the *h*-index (25),
299 while 2001 had the lowest number for the *h*-index (4).

300 3.2. Top contributing countries

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

310

311 The United States, India, the United Kingdom, Australia, Japan, Germany, South Korea, Iran, and Spain
312 had a total of 1000 publications, 23535 citations, and a combined *h*-index of 233. On the other hand, China was
313 the most productive country, with 290 total publications and a single-country publishing proportion of 28%. This
314 suggests that more MICP papers were written by Chinese authors than by authors from any other country. The
315 United States quickly followed with 229 publications. It might be argued that publications from the United States
316 were more accessible/of interest to researchers based on the *h*-index value and total citations because this country
317 obtained the highest *h*-index (45) and total citations (8,180). Furthermore, the publication (DeJong et al. 2006)

318 which originated in the United States was ranked as the most cited article (833 citations) in this field. This was
319 followed by publications (Rodriguez-Navarro et al. 2003; Qabany et al. 2012) originating from Spain (346
320 citations) and the United Kingdom (327 citations). Interestingly, five of the top 10 most productive countries on
321 MICP are among the six largest (China, United States, United Kingdom, India, Japan, and the Russian Federation)
322 emitters of greenhouse gas (GHG) (Olivier and Peters 2019, 2020). While these six largest emitters of GHG
323 account for 62% of the global carbon footprint, China (26%), and the United States (13%) lead the entire world
324 as the largest emitters (Olivier and Peters 2020). The vital urgency to achieve carbon neutrality and reduce carbon
325 intensity has shifted the need for more environmentally friendly manufacturing processes/methods that will result
326 in zero or minimal carbon footprint (Omoregie et al. 2021). This may be the reason MICP has recently gained
327 lots of interest in the scientific community.

328

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

339

340 By analyzing the evolution of article publication over the years from the scientific database it is possible
341 to know the most performing countries that have occupied 1st to 3rd positions (Chang et al. 2020). In general, the
342 magnitude of publications by some countries, such as China and the United States, stands out. However, while
343 looking at country publications by year. It is worth noting that the United Kingdom was not among the top three
344 countries from 2001 to 2008. In 2009, the United Kingdom was only one of the top three most productive
345 countries. During these times, only the United States occupied the top three rankings (except for 2003, 2004, and
346 2007). China was the first country listed in 2005, reappeared in 2010, and will remain on this list (as one of the
347 top three productive countries) until 2021. Only in 2013 and 2017 was the country listed. From 2009 to 2021, the

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

354

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

371

372 Finally, 89.6% of the countries that participated in MICP research had an international collaboration that
373 resulted in publications. This demonstrates that scholars from around the world are exchanging knowledge/ideas
374 and engaging in research/resource engagement to increase scientific output on the use of the MICP process for
375 sustainable environmental applications. The VOSviewer examination of co-authorship for countries revealed that
376 countries had strong international partnerships. Indeed, the requirement for research financing, information
377 exchange, access to facilities, and co-authorship of publications would all have an impact on the research

378 collaboration (Bezak et al. 2021). Because the United States and China were the two major countries in the field
379 of MICP, the co-authorship of articles demonstrated that these two countries have a strong transnational
380 cooperation/connection (52 links). The majority of the 13 separate clusters had four to five countries.

381

382 3.3. Top productive journals

383 The Scopus database data was evaluated to discover the most relevant journals on this topic. **Table 3** summarised
384 the most productive journals on MICP, as well as their total articles, total citations, and other relevant data (such
385 as most-cited articles, publisher names, CiteScore, and quartile ranking). The top ten most productive journals in
386 MICP were credited to five unique academic publishers: Elsevier Ltd, Taylor & Francis Ltd., American Society
387 of Civil Engineers, Springer Nature, and Wiley-Blackwell Publishing Ltd. Elsevier Ltd. had the most journals of
388 any of these publishers (4 journals). Taylor & Francis Ltd. (1 journal), the American Society of Civil Engineers
389 (2 journals), Springer Nature (2 journals), and Wiley-Blackwell Publishing Ltd. published the remaining
390 publications (1 journal). These top ten most prolific journals published 261 papers and garnered 10,056 citations.
391 These publications are from the United Kingdom, the United States, the Netherlands, and Germany. These are
392 developed nations. This proved that one of the G8 countries is leading the scientific world (Jiang and Yanbin
393 2018).

394

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

404

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

408 MICP are all Q1-ranked journals. This means that the main journals in this subject are also top-tier publications
409 with a scientific reputation. These top ten journals frequently attract high-quality manuscripts, which influences
410 the journals' performance (Wu et al. 2021a). Future high-quality MICP publications are anticipated to be published
411 in these top-performing journals. **Table 3** showed the most cited articles on MICP published by the top 10 most
412 productive journals on MICP. The article (Whiffin et al. 2007) which was published in *Geomicrobiology Journal*
413 received the highest number of citations (886). This was followed by articles (DeJong et al. 2006; Harkes et al.
414 2010a) that were published in the *Journal of Geotechnical and Geoenvironmental Engineering* (833), and
415 *Ecological Engineering* (363). It was also observed that Scientific Reports received the lowest number of citations
416 (287), and was the 9th-ranked journal with a total publication (18 articles) among all the top 10 journals. This
417 journal also had the lowest cited article among this group despite having a high CiteScore value (7.1). The data
418 however suggest that most articles on MICP do not receive many citations even though it is an open-access journal.
419

420 3.4. Top prolific authors

421 The Scopus database was used to extract the performance of the authors who were involved in the publication of
422 pertinent MICP research. The top prolific authors in this subject were rated based on the number of publications
423 they had received, as shown in **Table 4**. According to the analysis, the top 10 relevant writers published a total of
424 217 articles, accounting for 14% of the total publications (1,058) on MICP. However, from 2001 to 2021, these
425 top authors each wrote between 13 and 38 publications. The top 10 most notable authors were discovered to be
426 from six different countries. Three of the top ten authors were from China, with the other two from the United
427 States and Japan. One was linked to Singapore, Australia, and India. **Table 4** showed that Satoru Kawasaki has
428 the most publications (38). Jian Chu (31 publications) and Kazunori Nakashima came next (26 publications).
429 Varenayam Achal, on the other hand, had the most citations (1510) and the highest h-index (18). Jian Chu was
430 next, with a total of 1510 citations and an *h*-index of 15. Only three of the top ten most prolific authors (Abhijit
431 Mukherjee, Robin Gerlach, and Mondem Sudhakara Reddy) had all of their works published between 2001 and
432 2021 referenced at least once. Abhijit Mukherjee had the earliest first publication on MICP within this group in
433 2009, while Kazunori Nakashima had the most current first publication in 2017. Among this group, Liang Cheng's
434 publication (Cheng et al. 2013) received the most citations (303). This was followed by Jian Chu's publication
435 (Chu et al. 2012) (215 citations). Varenayam Achal, Abhijit Mukherjee, and Mondem Sudhakara co-wrote the third
436 most referenced article (168) among these highly prolific authors (Achal et al. 2009).

437

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

447

448 Varenym Achal, the researcher with the most total citations and the greatest h-index, is affiliated with the
449 Guangdong Technion-Israel Institute of Technology (China). According to the Scopus database, the author has
450 25 articles of which had already been referenced. This author's most cited paper (168 citations) was published in
451 the Journal of Industrial Microbiology and Biotechnology in 2009. This study showed that an optical density of
452 1.0 for ureolytic bacteria (*Sporosarcina pasteurii*) growing in a low-cost medium (lactose mother liquor) is
453 comparable to that of a laboratory-grade yeast extract media (Achal et al. 2009). The bacterium's urease activity
454 (366 U/mL and 412 U/mL) and calcite concentration (24 to 28% of total treated sand weight) were also equivalent
455 in both mediums, according to the study. Varenym Achal's research is significant in the field of MICP since it
456 demonstrated that alternate cementation reagents (such as lactose mother liquor) might be employed for MICP in-
457 situ applications.

458

459 **Fig. 6** depicts an overlay visualization map of the author network for MICP collaboration from 2001 to
460 2021. From the VOSviewer map, it was revealed that a total of 442 authors were grouped into 29 different clusters,
461 with total links of 1,711 and total link strength of 3,021. The bibliometric map showed that Satoru Kawasaki
462 (identified as Kawasaki, S in the VOSviewer map) recorded the highest number of total link strengths (103),
463 having 33 links with other authors. This was followed by Chu Jian (identified as Chu, J. in the VOSviewer map)
464 (100 total link strength) and Yang Zhao (identified as Zhao, Y. in the VOSviewer map) (88 total link strength)
465 having 38, and 47 links with other authors, respectively. The co-authorship study of authors revealed that, among
466 all the scholars with whom Satoru Kawasaki, was associated, Kazunori Nakashima (identified as Nakashima, K.

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

469 3.5. Top productive institutions and funding sponsors

470 **Table 5** summarises the top ten most prolific institutions in the field of MICP from 2001 to 2021. Six of the top
471 ten institutions were in China or the United States. The four remaining institutions were located in Singapore,
472 Australia, Japan, and Belgium. Nanyang Technological University and Hokkaido University were the leading
473 institutions in terms of overall publications, with each having 39 publications. Southeast University followed suit
474 (37 publications). Furthermore, the University of California, Davis had the most overall citations (2,082), followed
475 by Nanyang Technological University (1,219 citations), and Curtin University (1,219 citations). Nanyang
476 Technological University has the highest *h*-index rating (19), followed by the Chinese Academy of Sciences (17).
477 Only Montana State University had all of its articles mentioned in the top ten most productive institutions. Five
478 of the most prolific MICP researchers are linked with some of the most productive institutions (Nanyang
479 Technological University, Hokkaido University, Montana State University, Curtin University, and Southeast
480 University). Among this group, the highest cited article (DeJong et al. 2006) (833 citations) originated from the
481 University of California, Davis. This was followed by publications (Chu et al. 2012; Cheng et al. 2013) originating
482 from Curtin University (303 citations), and Nanyang Technological University (215 citations), respectively.

483

484 The top 10 most productive funding sponsors when it comes to the MICP scientific community include the
485 National Natural Science Foundation of China (China); the National Science Foundation (United States); Japan
486 Society for the Promotion of Science (Japan); Ministry of Education, Culture, Sports, Science, and Technology
487 (Japan); National Key Research and Development Program of China (China); China Postdoctoral Science
488 Foundation (China); Ministry of Science and Technology of the People's Republic of China (China); European
489 Commission (Luxembourg); National Research Foundation of Korea (Korea); and Engineering and Physical
490 Sciences Research Council (United Kingdom). The ranking shown in **Table 6** is based on the total number of
491 publications. Four out of these top 10 funding sponsors originate from China, two are from Japan, and the
492 remaining four were from the United States, Luxembourg, the Republic of Korea, and the United Kingdom.
493 National Natural Science Foundation of China (China) had the highest total publication (188). This was followed
494 by National Science Foundation (United States) (80), and the Japan Society for the Promotion of Science (Japan)
495 (40). National Natural Science Foundation of China (China) also had the highest total citations (2,940), and *h*-
496 index (30) among this group. This was followed by the National Science Foundation (United States) (total citations

497 of 1,829, and a total h -index of 21). The table further indicated that only Engineering and Physical Sciences
498 Research Council (United Kingdom) had all its publications cited. Among this group, the article (Bachmeier et
499 al. 2002) which was sponsored by National Science Foundation (United States) had the highest total citations
500 (290). This was followed by publications (Li et al. 2013; Kang et al. 2016) that were sponsored by the National
501 Natural Science Foundation of China (China) (177), and the National Research Foundation of Korea (Korea)
502 (118).

503 3.6. Most popular keywords

504 Author keywords have a significant impact on the impact of publishing searches and their accessibility since they
505 provide crucial information that may be linked to published papers in scientific databases. These keywords serve
506 as a vital link that distinguishes information sources from the enormous quantity of available publications
507 (Saravanan et al. 2022). The overlay visualisation mapping of the co-occurrence of author keywords was shown
508 in **Fig. 7**. The VOSviewer algorithm initially recognised a total of 2,456 author keywords. Keyword co-occurrence
509 analysis is a powerful function in the VOSviewer application that can be utilised in knowledge mining (Wang et
510 al. 2021a). After renaming the synonyms and phrases, 546 keywords met the threshold (the minimum number of
511 occurrences is 2) and were grouped into 78 different clusters. The result showed that the term “MICP” was the
512 most used author keyword with 121 occurrences, total link strength of 213, and 152 links to other author keywords.
513 This keyword (MICP) also had an average publication year of 2018.26, and average citations of 30.32. "MICP"
514 has a high association with "biocementation," "unconfined compressive strength," and "*sporosarcina pasteurii*"
515 through 10, 9, and 8 link strength, respectively, among all the author keywords. Furthermore, "calcium carbonate
516 content," "biomineralization," and "calcite precipitation" were among the top trending author keywords, with 84,
517 80, and 79 occurrences, respectively. The MICP technique increases soil strength and durability while decreasing
518 permeability by combining calcium carbonate crystal fillings and extracellular polysaccharide bonding within soil
519 particles. (Wang et al. 2022).

520

521 The VOSviewer analysis also indicated that the remaining top 10 most popular author keywords in this
522 field consisted of “urease enzyme” (68 occurrences), “*sporosarcina pasteurii*” (66 occurrences),
523 “biocementation” (62 occurrences), “calcium carbonate precipitation” (34 occurrences), “bioremediation” (28
524 occurrences), and “self-healing” (27 occurrences). These keywords were more popular than the remaining 536
525 author keywords used in publications. Biocementation is a biological method that uses biomineralization to
526 improve the engineering qualities of granular soil and heal/repair concrete cracks (Xu et al. 2020). Heavy metal

527 ions such as lead and copper can be sequestered through the MICP process to make them stable and less toxic
528 (Kang et al. 2016; Mwandira et al. 2017). MICP has been used in a variety of ways attributable to urease-producing
529 bacteria like *Sporosarcina pasteurii*, which has been extensively explored.

530

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

547

548 3.7. Trending research terms

549 VOSviewer can be used to detect how to research topics related to a field that changes/progresses through time
550 (Jiang and Yanbin 2018). Co-occurrence analysis based on text data from the title and abstract fields was utilised
551 to identify the key research trend. Only 158 terms were chosen (the minimum number of occurrences of a term is
552 20, based on binary count) for the co-occurrence network visualisation map of study subjects shown in **Fig. 9**.
553 The analysis yielded four distinct clusters with a total of 9,661 linkages and a total link strength of 65,466. The
554 first cluster (red colour) had the most research items (75). This was followed by a second cluster (green colour)
555 containing 64 research items in total. The third cluster (blue colour) contained a total of 10 research items, whereas
556 the final cluster (alge colour) contained a total of 9 research items. The red cluster indicated that research trends

557 were focused on "precipitation." This phrase has a total link strength of 8,516, 815 occurrences, and 157
558 connections to other research topics.

559

560 There are 220 publications in which the words "precipitation" and "soil" are linked. 327 studies link
561 "precipitation" to "carbonate," 357 to "MICP," and 151 to "environment." Researchers are interested in the
562 formation/origin of CaCO₃ precipitation, mineral deposition by microorganisms, and mineral deposition in
563 sediment, according to more studies on the items in this cluster. The green-coloured cluster demonstrated that
564 research items were concentrated on "MICP," with a total link strength of 4,749, 411 occurrences, and 153 links
565 to other research items. "MICP" had 175 publications with links to "soil," 127 publications with links to "method,"
566 135 publications with links to "test," and 86 publications with links to "property." Additional analysis of the items
567 in this cluster revealed that researchers are concerned about the utility of MICP technology in improving the
568 engineering properties of soil, developing various techniques to improve the shear strength and stiffness of soil
569 specimens, and how to improve the performance of MICP treatment. The blue-coloured clustered research items
570 were largely about "compressive strength," with a total link strength of 1,129, 107 occurrences, and 139 links with
571 other research items. According to VOSviewer, "compressive strength" had 89 publications linked with
572 "precipitation," 33 publications linked with "specimen," 46 publications linked with "MICP," and 40 publications
573 linked with "carbonate."

574

575 Further analysis of the items in this cluster suggested that researchers focused on concrete crack repair,
576 mortar improvement, the productivity of self-healing concrete, and improving the durability and water absorption
577 performance of the technology. The alge-coloured cluster showed that "Biom mineralization" was the leading item,
578 with a total link strength of 717, 69 occurrences, and 136 links. "Biom mineralization" had 24 links with "formation",
579 26 links with "MICP", 32 links with "carbonate", and 54 links with "precipitation. Further evaluation of the items
580 in this cluster suggests scholars becoming interested in using biominerals from *Sporosarcina* sp for heavy metal
581 remediation. Finally, based on a VOSviewer analysis of titles and abstract fields, it was noticed that the topic
582 (precipitation) was predominantly popular from 2001 to 2018, however, the term "MICP" emerged as the hottest
583 research topic of choice by scholars in 2019 to 2021.

584

585

586 3.8. Environmental impact of MICP technology

587 The literature has numerous reports on the potential of the MICP process through the precipitation of CaCO_3
588 minerals (**Fig. 10**). Unfortunately, MICP technology has a stringent environmental impact which has yet to be
589 fully investigated (Anbu et al. 2016; Rajasekar et al. 2021). MICP pathways such as ureolysis, denitrification, and
590 ammonification results in gaseous by-products. During the ureolysis-driven MICP process, high ammonium
591 contents are produced due to urea hydrolysis. It is estimated that between 850 mg/L to 17,000 mg/L of ammonium
592 is released into waterbodies (Lee et al. 2019; Mohsenzadeh et al. 2021). Other researchers discussed that if 1 m^3
593 of sand is cemented via the MICP process, it is projected to release 11.2 kg of ammonium, and if this is scaled up
594 to a larger amount of soil, the produced ammonium ions may pollute $4.5 \times 10^6 \text{ m}^3$ of drinking water due to the
595 discharge of untreated biocementation effluent. Thus, this will have serious consequences for human health and
596 regrettable environmental impact if not properly managed or prevented. If MICP is to be a sustainable economic
597 construction technology, it must be treated or reused in a way that does not negatively affect other environmental
598 considerations (Porter et al. 2021).

599

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

613

614

615

616 3.9. Limitations of the study

617 This study has some limitations, as have prior bibliometric investigations. Because all the data included in this
618 bibliometric analysis came solely from the Scopus database, many MICP articles that are not indexed in the
619 Scopus database were inevitably excluded. In addition, the selected keywords (microbially induced carbonate
620 precipitation, microbially induce calcite precipitation, microbiological precipitation of CaCO₃, biocalcifying
621 bacteria, biocalcification, calcifying microorganism, biomediated calcite precipitation, bioprecipitation
622 of calcium carbonate, microbial carbonate precipitation, microbially induce calcium carbonate precipitation,
623 bacterially induced carbonate mineralization, microorganisms induce calcium carbonate precipitation) may have
624 not captured all the publications in this field. This is possible if authors mentioned different terminologies in the
625 titles, abstracts, and keyword sections of their papers.

626

627 The data collection period covered publications published between 2001 and 2021. As a result, documents
628 published before 2001 and after 2021 are excluded. Because the data mining and extraction were completed in
629 October 2021, it was not possible to incorporate publications from 2022. As a result, documents published before
630 2001 and after 2022 are excluded. ~~Because the data mining and extraction were completed in October 2021, it
631 was not possible to incorporate publications from 2022. As a result, future bibliometric analyses of MICP research
632 trends should include publications from 2022.~~ Furthermore, the document types were restricted to article
633 publishing, English language, journal publication, and publication at the final stage. This is due to our desire to
634 focus solely on actual research documents. Nonetheless, the findings given in this bibliometric research provide
635 a clear picture of the state and direction of the MICP publication trend. Furthermore, we expect that future
636 researchers will be able to overcome these constraints and use unified scientific databases to further analyse the
637 literature on this topic.

638 4. Conclusion

639 This bibliometric review was able to identify the annual publications and citations output on MICP from 2001 to
640 2021 in the Scopus database. MICP is an active research discipline that has attracted the attention of researchers
641 around the world. Despite a few noticeable fluctuations, the growth in research output is expected to continue
642 increasing with time. The United States and China are the leading contributors in this field. Satoru Kawasaki had
643 the highest number of total publications, while Varenayam Achal had the most citations and h-index. The top 10
644 most prolific authors originated from Japan, Singapore, China, Australia, the United States, and India. Of the most
645 influential academic journals, Construction and Building Materials was the most preferred journal by authors for

646 publications on MICP. The Journal of Geotechnical and Geoenvironmental Engineering received the most
647 citations among all academic journals. Of the 546 author keywords analyzed through VOSviewer, "MICP" was
648 the leading keyword, with 121 occurrences.

649 **Acknowledgements**

650 The authors are thankful to Universiti Teknologi Malaysia for funding this study.; ~~Universiti Malaysia Sarawak,~~
651 ~~and Universiti Kuala Lumpur for providing the experimental facilities and equipment used in this study.~~

652 **Ethical Approval**

653 Not applicable.

654 **Consent to Participate**

655 Not applicable.

656 **Consent to Publish**

657 Not applicable.

658 **Authors Contributions**

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

663 **Funding**

664 This study was funded by the Universiti Teknologi Malaysia through research grant number: 05E84.

665 **Competing interests**

666 The authors declare no competing interests.

667 **Availability of data and materials**

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

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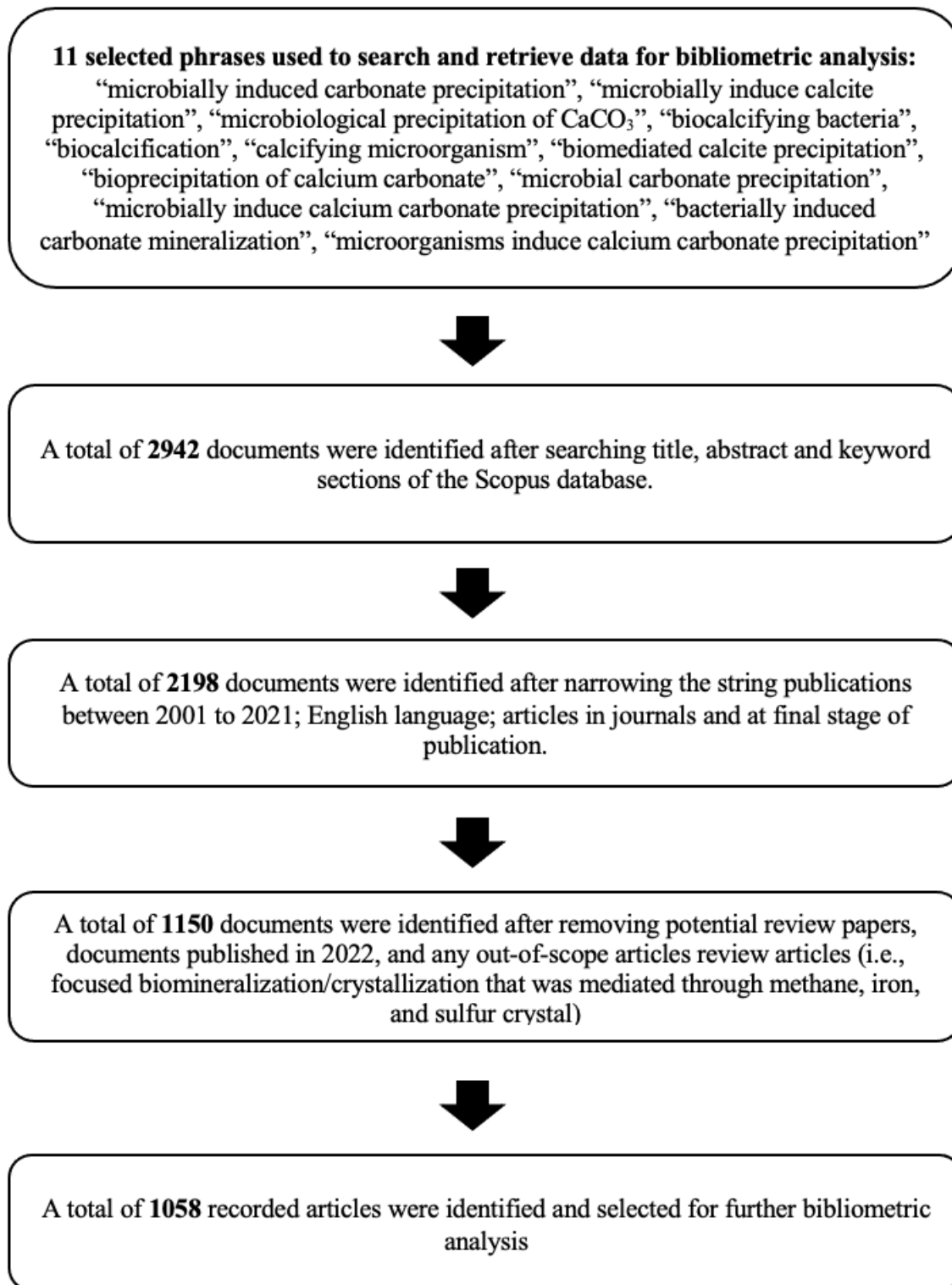
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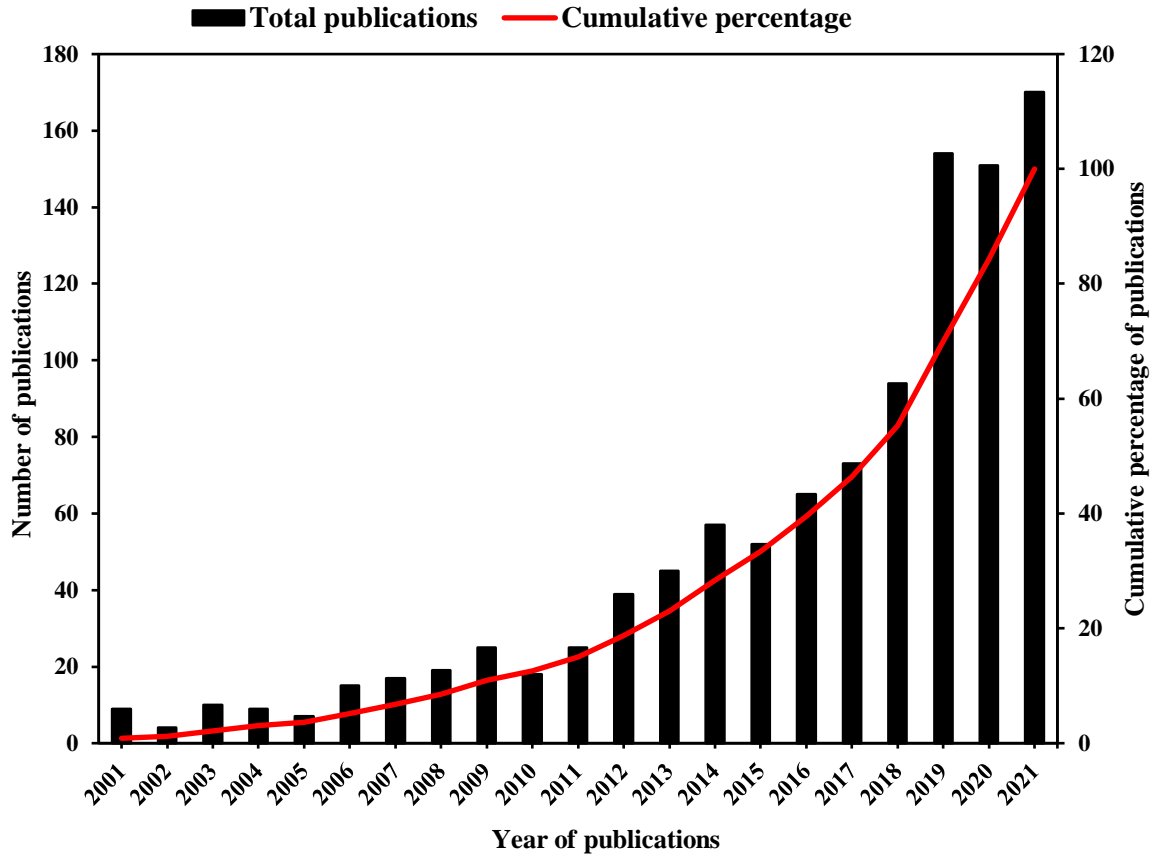


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941 **Fig. 1:** Flow chart of the overall methodology used for data retrieval from the Scopus database.

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

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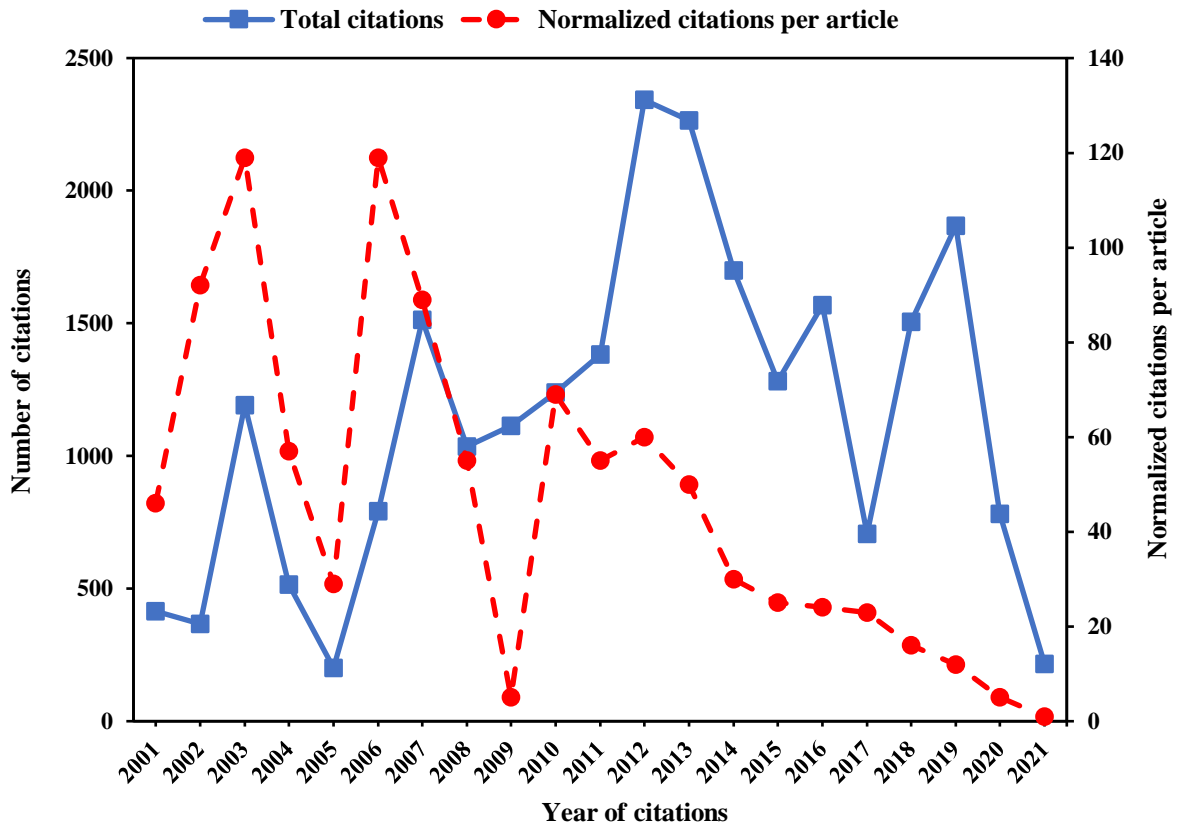
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Fig. 3: Number of citations and normalized citations per article on MICP research from 2001 to 2021.

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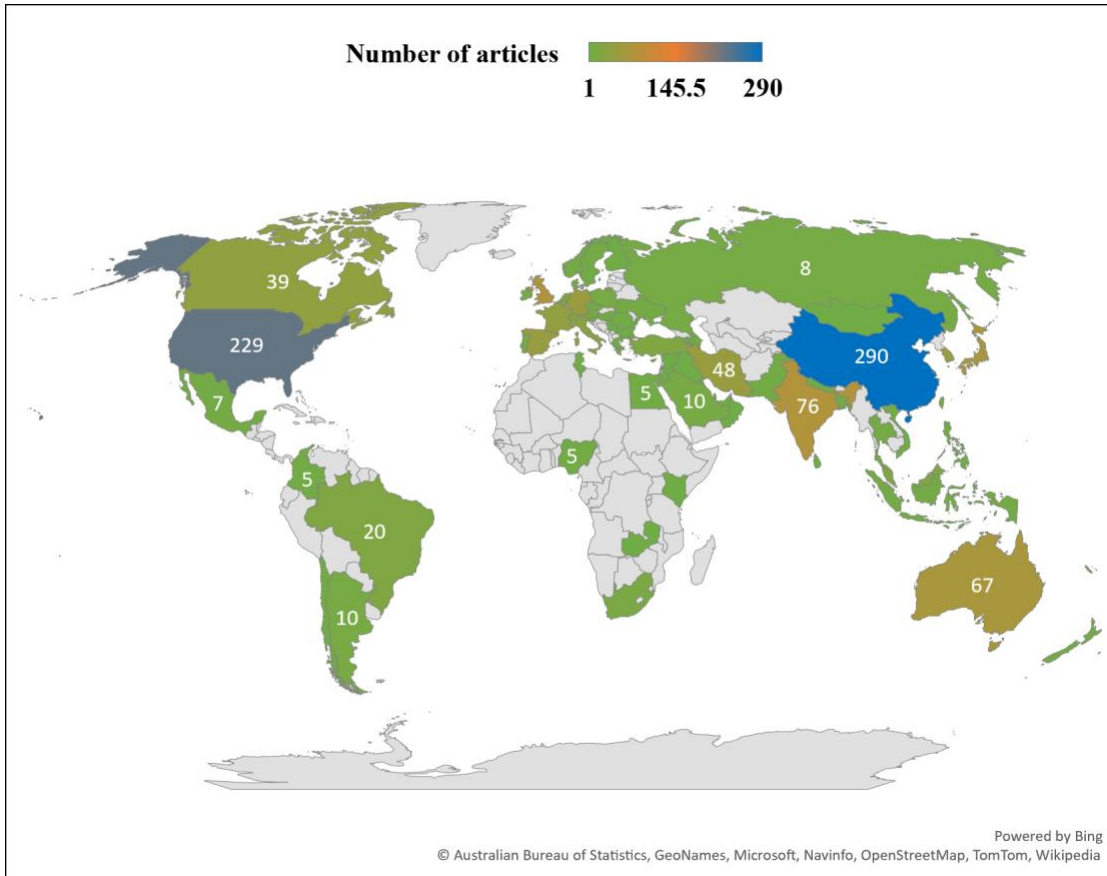
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978 **Fig. 4:** Worldwide distribution by country of publications on MICP between 2001 to 2021 with different colours
 979 on the map signifying the density of total publications by country.

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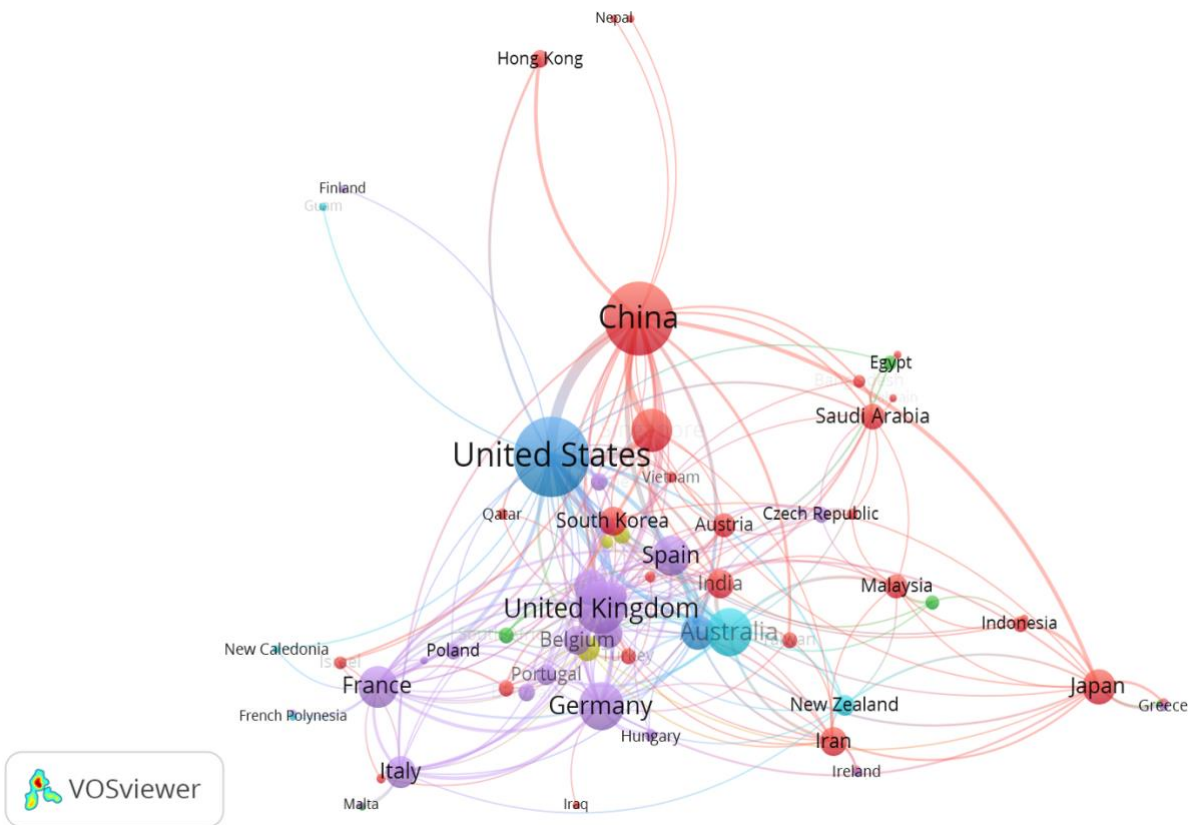
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994 **Fig. 5:** Network visualization of the bibliometric map based on co-authorship analysis of countries. The online
 995 map is available at <https://bit.ly/3o6ZWjv>

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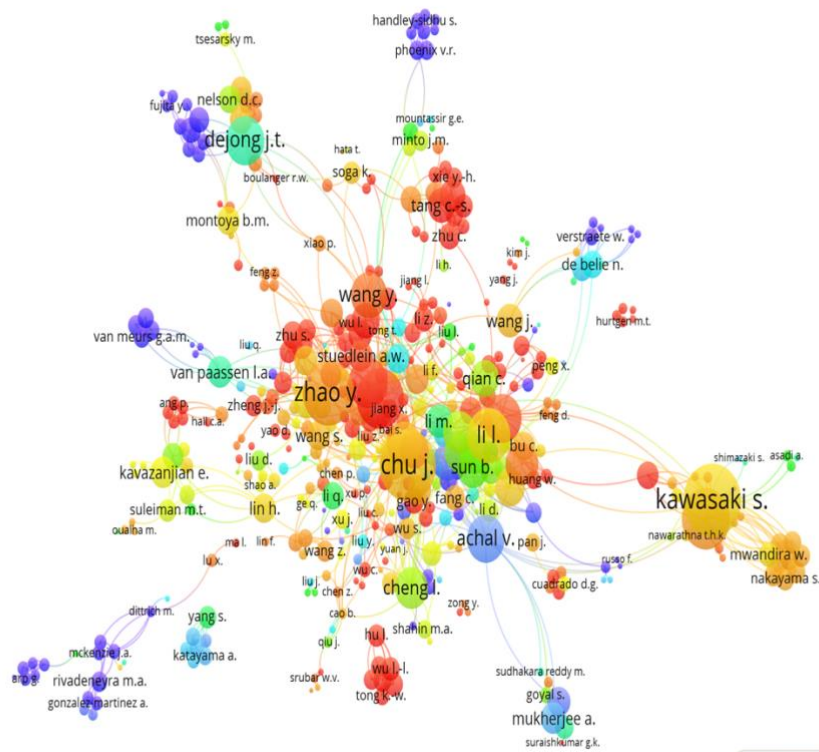
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Fig. 6: Overlay visualization of the bibliometric map based on co-authorship analysis of authors. The online map

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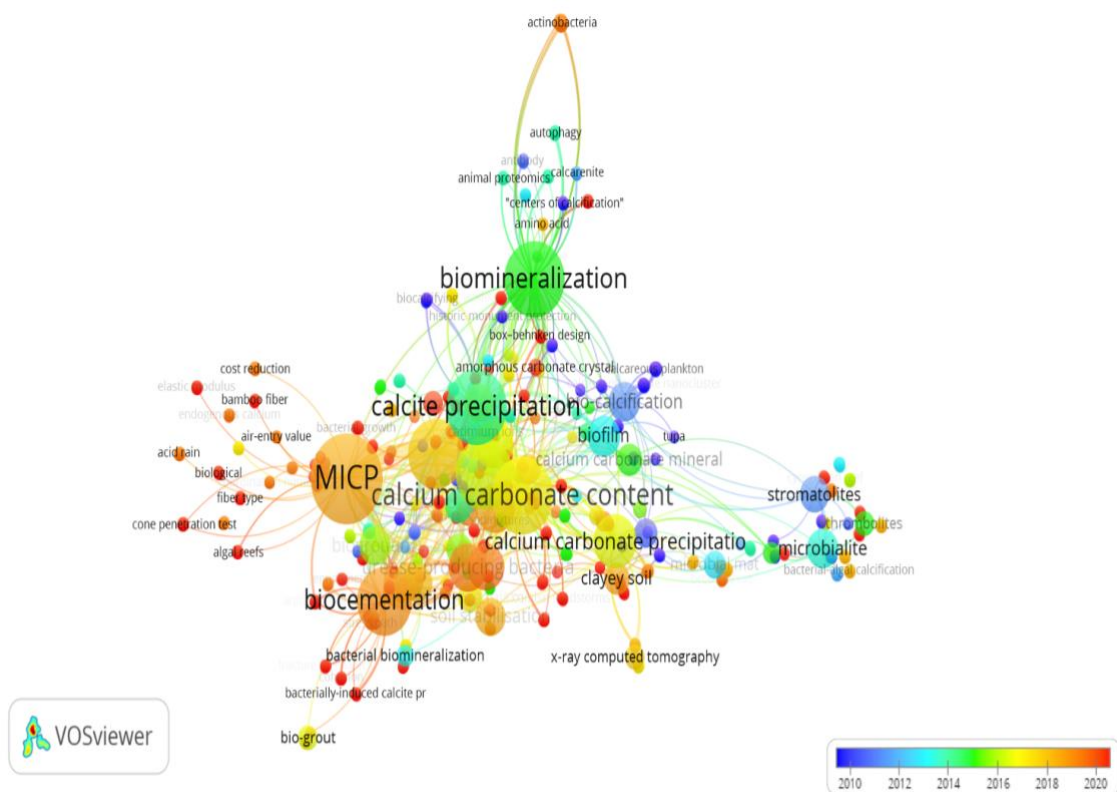
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1027 **Fig. 7:** Overlay visualization of co-occurrence for author keywords. The online map is available at

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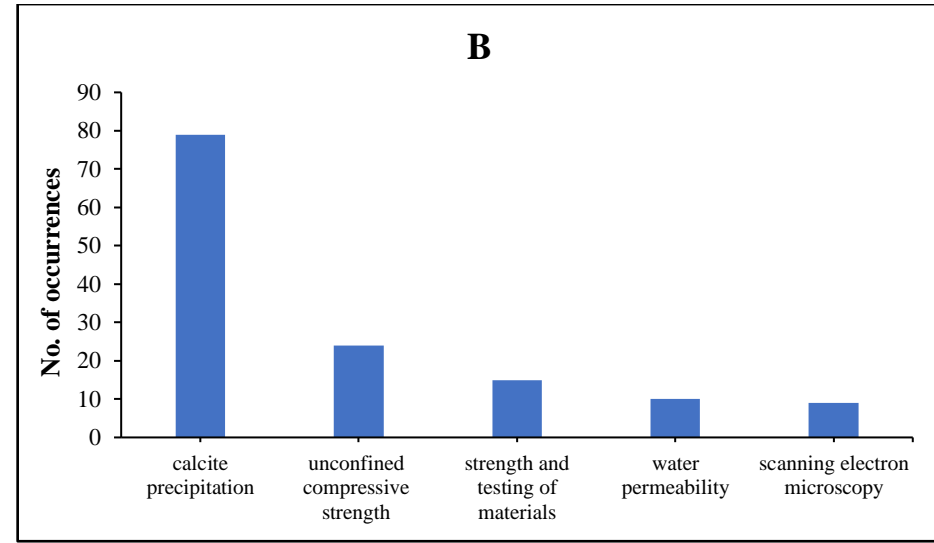
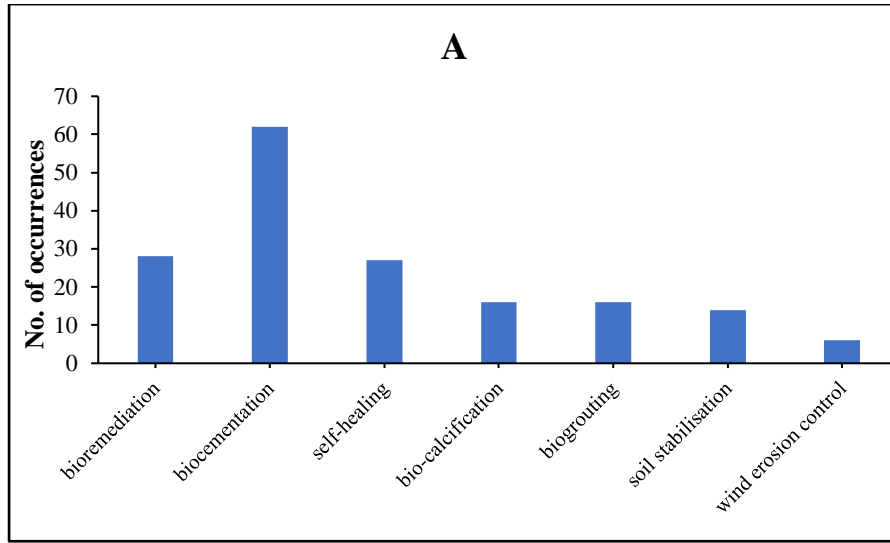
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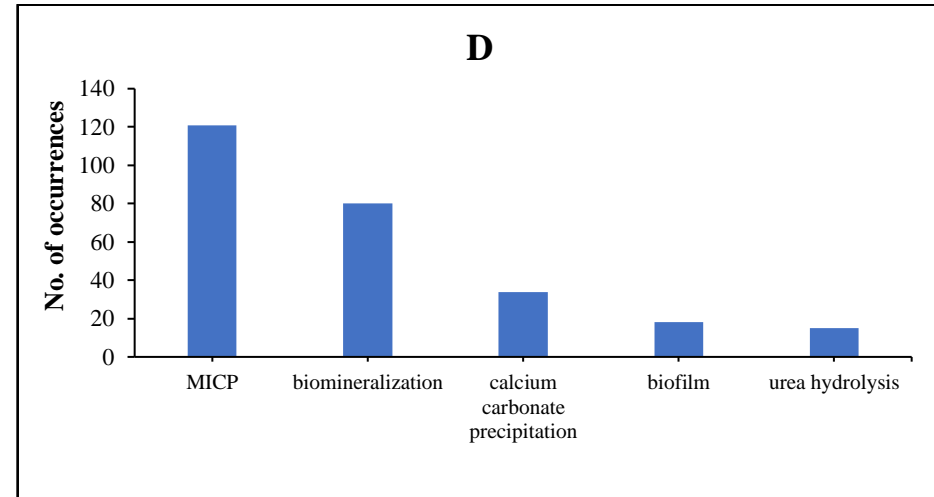
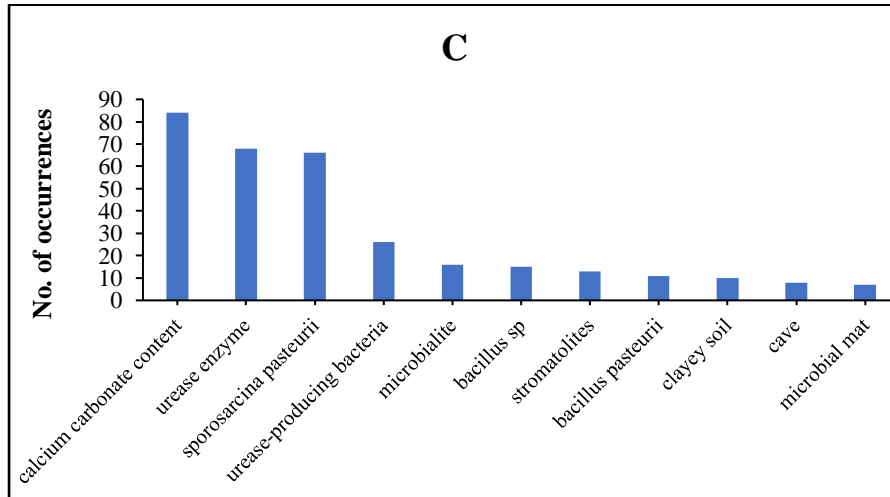
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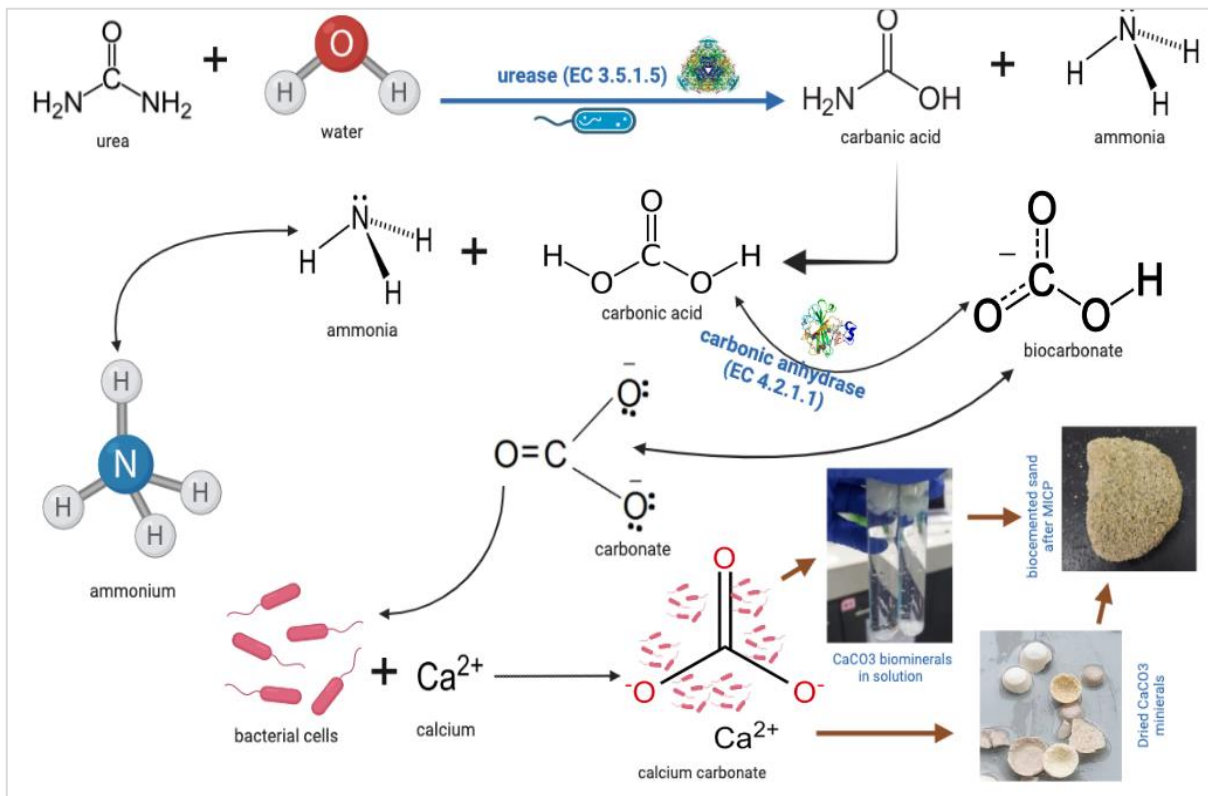
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Fig. 8: The author keywords grouped into various parts: (A) application; (B) performance evaluation methods; (C) materials; and (D) process.

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1060 **Fig. 10:** A illustration of the MICP mechanism that enables CaCO_3 precipitation in solution and soil.

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1077 **List of tables**

1078 **Table 1:** Total publications and citations on MICP research from the Scopus database.

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

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1083 **Table 2:** List of top 10 most contributing countries in the field of MICP from 2001 to 2021

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

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

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

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

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

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1100 *Note: TP = Total publications; TC = Total citations; NCPA = Normalized citations per articles; PCA = Percentage of cited articles; SJR = Scimago journal ranking; SNIP =*

1101 *source normalized impact per paper; HCA = Highest cited article; CHCA = Citation of highest cited article*

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

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

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

6	Chunxiang Qian	18	138	83	7	2010	7202310696	China	Loose sand particles cemented by different bio-phosphate and carbonate composite cement (Yu et al. 2016)	26	<i>Construction and Building Materials</i>
7	Abhijit Mukherjee	17	772	100	14	2009	56863660200	Australia	Lactose mother liquor as an alternative nutrient source for microbial concrete production by <i>Sporosarcina pasteurii</i> (Cheng et al. 2013)	168	<i>Journal of Industrial Microbiology and Biotechnology</i>
8	Robin Gerlach	16	459	100	10	2012	57189020312	United States	Potential CO ₂ leakage reduction through biofilm-induced calcium carbonate precipitation (Phillips et al. 2013)	116	<i>Environmental Science and Technology</i>

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

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1111 *Note: TP = Total publications; TC = Total citations; PCA = Percentage of cited articles; YFP = Year of first publication; HCA = Highest cited article; CHCA = Citation of*
1112 *highest cited article*

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

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

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

							precipitation at various degrees of saturation (Cheng et al. 2013)		
8	Montana State University	Montana, United States of America	21	572	13	100	Potential CO ₂ leakage reduction through biofilm-induced calcium carbonate precipitation (Phillips et al. 2013)	116	<i>Environmental Science and Technology</i>
9	Arizona State University	Arizona, United States of America	19	478	11	89	Mechanical behavior of sands treated by microbially induced carbonate precipitation (Lin et al. 2016)	123	<i>Journal of Geotechnical and Geoenvironmental Engineering</i>
10	Universiteit Gent	Ghent, Belgium	19	810	11	79	Diatomaceous earth as a protective vehicle for bacteria applied for self-healing concrete (Mondal et al. 2020)	201	<i>Journal of Industrial Microbiology and Biotechnology</i>

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1121 *Note: TP = Total publications; TC = Total citations; PCA = Percentage of cited article; HCA = Highest cited article; CHCA = Citation of highest cited article*

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1126 **Table 6:** The top 10 funding sponsors for MICP research from 2001 to 2021

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

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

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

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1128 *Note: TP = Total publications; TC = Total citations; PCA = Percentage of cited articles; HCA = Highest cited article; CHCA = Citation of highest cited article*

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Supplementary information

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

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

	<p>KEY (biocalcification*) OR TITLE-ABS- KEY (bacterially AND induced AND carbonate AND mineralization*) OR TITLE-ABS- KEY (biomediated AND calcite AND precipitation*) OR TITLE-ABS-KEY (calcifying AND microorganism*) OR TITLE- ABS-KEY (biocalcifying AND bacteria*) OR TITLE-ABS- KEY (microorganisms AND induce AND calcium AND carbonate AND precipitation*) OR TITLE-ABS- KEY (microbial AND carbonate AND precipitation) OR TITLE-ABS- KEY (bioprecipitation AND of AND calcium AND carbonate)) AND (EXCLUDE (PUBYEAR , 2000) OR EXCLUDE (PUBYEAR , 1999) OR EXCLUDE (PUBYEAR , 1998) OR EXCLUDE (PUBYEAR , 1997) OR EXCLUDE (PUBYEAR , 1996) OR EXCLUDE (PUBYEAR , 1995) OR EXCLUDE (PUBYEAR , 1994) OR EXCLUDE (PUBYEAR , 1993) OR EXCLUDE (PUBYEAR , 1992) OR EXCLUDE (PUBYEAR , 1991) OR EXCLUDE (PUBYEAR , 1990) OR EXCLUDE (PUBYEAR , 1989) OR EXCLUDE (PUBYEAR , 1988) OR EXCLUDE (PUBYEAR , 1987) OR EXCLUDE (PUBYEAR , 1986) OR EXCLUDE (PUBYEAR , 1985) OR EXCLUDE (PUBYEAR , 1984) OR EXCLUDE (PUBYEAR , 1983) OR EXCLUDE (PUBYEAR , 1979) OR EXCLUDE (PUBYEAR , 1977) OR EXCLUDE (PUBYEAR , 1976) OR EXCLUDE (PUBYEAR , 1975) OR EXCLUDE (PUBYEAR , 1974) OR EXCLUDE (PUBYEAR , 1972)) AND (EXCLUDE (LANGUAGE , "Chinese") OR EXCLUDE (LANGUAGE , "Spanish") OR EXCLUDE (LANGUAGE , "Hungarian") OR EXCLUDE (LANGUAGE , "Portuguese") OR EXCLUDE (LANGUAGE , "French") OR EXCLUDE (LANGUAGE , "Polish") OR EXCLUDE (LANGUAGE , "Czech") OR EXCLUDE (LANGUAGE , "Estonian") OR EXCLUDE (LANGUAGE , "Japanese")) AND (EXCLUDE (LANGUAGE , "Persian") OR EXCLUDE (LANGUAGE , "Russian") OR EXCLUDE (LANGUAGE , "Turkish")) AND (EXCLUDE (DOCTYPE , "cp") OR EXCLUDE (DOCTYPE , "ch")</p>	
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	OR EXCLUDE (DOCTYPE , "cr") OR EXCLUDE (DOCTYPE , "no") OR EXCLUDE (DOCTYPE , "er") OR EXCLUDE (DOCTYPE , "ed") OR EXCLUDE (DOCTYPE , "bk") OR EXCLUDE (DOCTYPE , "sh")) AND (EXCLUDE (DOCTYPE , "tb")) AND (EXCLUDE (PUBSTAGE , "aip")) AND (EXCLUDE (SRCTYPE , "k") OR EXCLUDE (SRCTYPE , "d") OR EXCLUDE (SRCTYPE , "p"))	
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	<p>85088787764) AND NOT EID (2-s2.0-85109012219) AND NOT EID (2-s2.0-85105290941) AND NOT EID (2-s2.0-85111075936) AND NOT EID (2-s2.0-85106248904) AND NOT EID (2-s2.0-85098202097) AND NOT EID (2-s2.0-85098594961) AND NOT EID (2-s2.0-85078097807) AND NOT EID (2-s2.0-29544433319) AND NOT EID (2-s2.0-85115322102) AND NOT EID (2-s2.0-85114614533) AND NOT EID (2-s2.0-85114035314) AND NOT EID (2-s2.0-85109171942) AND NOT EID (2-s2.0-85111298808) AND NOT EID (2-s2.0-85108813421) AND NOT EID (2-s2.0-85108376819) AND NOT EID (2-s2.0-85105335454) AND NOT EID (2-s2.0-85109428396) AND NOT EID (2-s2.0-85100552760) AND NOT EID (2-s2.0-85055906842) AND NOT EID (2-s2.0-30344461328) AND (EXCLUDE (SRCTYPE , "k") OR EXCLUDE (SRCTYPE , "d") OR EXCLUDE (SRCTYPE , "p")) AND (EXCLUDE (PUBSTAGE , "aip")) AND (EXCLUDE (DOCTYPE , "cp") OR EXCLUDE (DOCTYPE , "ch") OR EXCLUDE (DOCTYPE , "cr") OR EXCLUDE (DOCTYPE , "no") OR EXCLUDE (DOCTYPE , "er") OR EXCLUDE (DOCTYPE , "ed") OR EXCLUDE (DOCTYPE , "bk") OR EXCLUDE (DOCTYPE , "sh") OR EXCLUDE (DOCTYPE , "tb")) AND (EXCLUDE (PUBYEAR , 2000) OR EXCLUDE (PUBYEAR , 1999) OR EXCLUDE (PUBYEAR , 1998) OR EXCLUDE (PUBYEAR , 1997) OR EXCLUDE (PUBYEAR , 1996) OR EXCLUDE (PUBYEAR , 1995) OR EXCLUDE (PUBYEAR , 1994) OR EXCLUDE (PUBYEAR , 1993) OR EXCLUDE (PUBYEAR , 1992) OR EXCLUDE (PUBYEAR , 1991) OR EXCLUDE (PUBYEAR , 1990) OR EXCLUDE (PUBYEAR , 1989) OR EXCLUDE (PUBYEAR , 1988) OR EXCLUDE (PUBYEAR , 1987) OR EXCLUDE (PUBYEAR , 1986) OR EXCLUDE (PUBYEAR , 1985) OR EXCLUDE (PUBYEAR , 1984) OR EXCLUDE (PUBYEAR , 1983) OR EXCLUDE (PUBYEAR , 1979) OR EXCLUDE (PUBYEAR , 1977) OR EXCLUDE (PUBYEAR , 1976) OR EXCLUDE (PUBYEAR , 1975) OR EXCLUDE (PUBYEAR , 1974) OR EXCLUDE (PUBYEAR , 1972)) AND (EXCLUDE (LANGUAGE , "Chinese") OR EX</p>	
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	CLUDE (LANGUAGE , "Spanish") OR EXCLUDE (LANGUAGE , "Hungarian") OR EXCLUDE (LANGUAGE , "Portuguese") OR EXCLUDE (LANGUAGE , "French") OR EXCLUDE (LANGUAGE , "Polish") OR EXCLUDE (LANGUAGE , "Czech") OR EXCLUDE (LANGUAGE , "Estonian") OR EXCLUDE (LANGUAGE , "Japanese") OR EXCLUDE (LANGUAGE , "Persian") OR EXCLUDE (LANGUAGE , "Russian") OR EXCLUDE (LANGUAGE , "Turkish")) AND (EXCLUDE (PUBYEAR , 2022))	
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<p>Final (after removing unwanted EID documents)</p>	<p>(TITLE-ABS-KEY (<i>microbially AND induced AND carbonate AND precipitation*</i>) OR TITLE-ABS-KEY (<i>microbially AND induced AND calcite AND precipitation*</i>) OR TITLE-ABS-KEY (<i>microbiological AND precipitation AND of AND caco3*</i>) OR TITLE-ABS-KEY (<i>microbially AND induce AND calcium AND carbonate AND precipitation*</i>) OR TITLE-ABS-KEY (<i>biocalcification*</i>) OR TITLE-ABS-KEY (<i>bacterially AND induced AND carbonate AND mineralization*</i>) OR TITLE-ABS-KEY (<i>biomediated AND calcite AND precipitation*</i>) OR TITLE-ABS-KEY (<i>calcifying AND microorganism*</i>) OR TITLE-ABS-KEY (<i>biocalcifying AND bacteria*</i>) OR TITLE-ABS-KEY (<i>microorganisms AND induce AND calcium AND carbonate AND precipitation*</i>) OR TITLE-ABS-KEY (<i>microbial AND carbonate AND precipitation</i>) OR TITLE-ABS-KEY (<i>bioprecipitation AND of AND calcium AND carbonate</i>)) AND NOT EID (2-s2.0-9344256654) AND NOT EID (2-s2.0-74149091993) AND NOT EID (2-s2.0-23944443706) AND NOT EID (2-s2.0-4444274902) AND NOT EID (2-s2.0-84904874863) AND NOT EID (2-s2.0-10044230606) AND NOT EID (2-s2.0-85036480437) AND NOT EID (2-s2.0-84959264662) AND NOT EID (2-s2.0-84880011137) AND NOT EID (2-s2.0-67649880645) AND NOT EID (2-s2.0-84939955108) AND NOT EID (2-s2.0-79958148413) AND NOT EID (2-s2.0-85019838157) AND NOT EID (2-s2.0-84955593660) AND NOT EID (2-s2.0-33747501039) AND NOT EID (2-s2.0-78650852367) AND NOT EID (2-s2.0-0041663572) AND NOT EID (2-s2.0-84960443515) AND NOT EID (2-s2.0-84960871885) AND NOT EID (2-s2.0-84989767537) AND NOT EID (2-s2.0-85029154829) AND NOT EID (2-s2.0-84929413140) AND NOT EID (2-s2.0-84904876263) AND NOT EID (2-s2.0-84871518046) AND NOT EID (2-s2.0-77954199412) AND</p>	<p>1058</p>
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	<p>NOT EID (2-s2.0-85042596806) AND NOT EID (2-s2.0-84977581036) AND NOT EID (2-s2.0-72449153869) AND NOT EID (2-s2.0-85090914272) AND NOT EID (2-s2.0-84983780708) AND NOT EID (2-s2.0-85026896337) AND NOT EID (2-s2.0-84879868481) AND NOT EID (2-s2.0-85065698556) AND NOT EID (2-s2.0-85069531897) AND NOT EID (2-s2.0-84875273879) AND NOT EID (2-s2.0-85080091873) AND NOT EID (2-s2.0-84945304051) AND NOT EID (2-s2.0-85069695839) AND NOT EID (2-s2.0-85039450097) AND NOT EID (2-s2.0-85057243899) AND NOT EID (2-s2.0-17644374135) AND NOT EID (2-s2.0-84899835461) AND NOT EID (2-s2.0-85061334535) AND NOT EID (2-s2.0-85055906842 AND 2-s2.0-30344461328) AND NOT EID (2-s2.0-85081656917) AND NOT EID (2- s2.0-85065720160) AND NOT EID (2-s2.0-85094979113) AND NOT EID (2-s2.0-85078656192) AND NOT EID (2-s2.0- 85095789457) AND NOT EID (2-s2.0-85083403083) AND NOT EID (2-s2.0-85063369465) AND NOT EID (2-s2.0- 63249121479) AND NOT EID (2-s2.0-85084958099) AND NOT EID (2-s2.0-85053527817) AND NOT EID (2-s2.0- 85010754782) AND NOT EID (2-s2.0-85091107686) AND NOT EID (2-s2.0-85082797698) AND NOT EID (2-s2.0- 85070333302) AND NOT EID (2-s2.0-85093892040) AND NOT EID (2-s2.0-85087684494) AND NOT EID (2-s2.0- 85067872930) AND NOT EID (2-s2.0-85088642851) AND NOT EID (2-s2.0-84939505837) AND NOT EID (2-s2.0- 85088835482) AND NOT EID (2-s2.0-85081282658) AND NOT EID (2-s2.0-85033364992) AND NOT EID (2-s2.0- 85103969970) AND NOT EID (2-s2.0-85107762354) AND NOT EID (2-s2.0-85088787764) AND NOT EID (2-s2.0- 85109012219) AND NOT EID (2-s2.0-85105290941) AND NOT EID (2-s2.0-85111075936) AND NOT EID (2-s2.0- 85106248904) AND NOT EID (2-s2.0-85098202097) AND NOT EID (2-s2.0-85098594961) AND NOT EID (2-s2.0- 85078097807) AND NOT EID (2-s2.0-29544433319) AND NOT EID (2-s2.0-85115322102) AND NOT EID (2-s2.0- 85114614533) AND NOT EID (2-s2.0-85114035314) AND NOT EID (2-s2.0-85109171942) AND NOT EID (2-s2.0-</p>	
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	<p>85111298808) AND NOT EID (2-s2.0-85108813421) AND NOT EID (2-s2.0-85108376819) AND NOT EID (2-s2.0-85105335454) AND NOT EID (2-s2.0-85109428396) AND NOT EID (2-s2.0-85100552760) AND NOT EID (2-s2.0-85055906842) AND NOT EID (2-s2.0-30344461328) AND NOT EID (2-s2.0-85109145028) AND NOT EID (2-s2.0-85108792484) AND NOT EID (2-s2.0-85104286443) AND NOT EID (2-s2.0-85089476071) AND NOT EID (2-s2.0-85079815345) AND NOT EID (2-s2.0-85077710074) AND NOT EID (2-s2.0-85017116349) AND NOT EID (2-s2.0-84991674455) AND NOT EID (2-s2.0-84957541927) AND NOT EID (2-s2.0-85042666061) AND NOT EID (2-s2.0-84907142114) AND NOT EID (2-s2.0-79951826157) AND NOT EID (2-s2.0-79955027044) AND NOT EID (2-s2.0-77952243417) AND NOT EID (2-s2.0-67349158614) AND NOT EID (2-s2.0-46749142616) AND NOT EID (2-s2.0-0344961678) AND NOT EID (2-s2.0-0141460749) AND NOT EID (2-s2.0-0038666002) AND NOT EID (2-s2.0-0034799674) AND NOT EID (2-s2.0-84912567983) AND NOT EID (2-s2.0-77956608553) AND NOT EID (2-s2.0-85027943519) AND NOT EID (2-s2.0-84969814747) AND NOT EID (2-s2.0-84876181933) AND NOT EID (2-s2.0-58149202327) AND NOT EID (2-s2.0-74149092972) AND NOT EID (2-s2.0-74149092972) AND NOT EID (2-s2.0-84907355788) AND NOT EID (2-s2.0-70349307412) AND NOT (methane*) AND NOT (sulfur*) AND NOT (iron*) AND NOT (sulphur*) AND NOT EID (2-s2.0-1542289624) AND NOT EID (2-s2.0-74149091659) AND NOT EID (2-s2.0-58149512789) AND NOT EID (2-s2.0-1342287541) AND NOT EID (2-s2.0-33646571600) AND NOT EID (2-s2.0-0036903708) AND NOT EID (2-s2.0-0034926098) AND NOT EID (2-s2.0-36849065807) AND NOT EID (2-s2.0-33645050414) AND NOT EID (2-s2.0-84894438505) AND NOT EID (2-s2.0-74949100157) AND NOT EID (2-s2.0 60949110770) AND NOT EID (2-s2.0-51149109798) AND NOT EID (2-s2.0-84957831081) AND NOT EID (2-s2.0-19944414704) AND NOT EID (2-s2.0-38949188610) AND NOT EID (2-s2.0-84856966005) AND</p>	
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NOT EID (2-s2.0-70350125582) AND	NOT EID (2-s2.0-84982208063) AND	NOT EID (2-s2.0-74549224540) AND
NOT EID (2-s2.0-84920381694) AND	NOT EID (2-s2.0-52249097030) AND	NOT EID (2-s2.0-0037438930) AND
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NOT EID (2-s2.0-80053937530) AND	NOT EID (2-s2.0-84455171980) AND	NOT EID (2-s2.0-80051581245) AND
NOT EID (2-s2.0-15944373209) AND	NOT EID (2-s2.0-72749116689) AND	NOT EID (2-s2.0-33745621641) AND
NOT EID (2-s2.0-15744380435) AND	NOT EID (2-s2.0-84921480787) AND	NOT EID (2-s2.0-84906235889) AND
NOT EID (2-s2.0-84902437077) AND	NOT EID (2-s2.0-43649101280) AND	NOT EID (2-s2.0-55949094852) AND
NOT EID (2-s2.0-33748886007) AND	NOT EID (2-s2.0-79952440924) AND	NOT EID (2-s2.0-85018485098) AND
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NOT EID (2-s2.0-77954014929) AND	NOT EID (2-s2.0-84934880038) AND	NOT EID (2-s2.0-84871118664) AND
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NOT EID (2-s2.0-4544239539) AND	NOT EID (2-s2.0-84872672407) AND	NOT EID (2-s2.0-84979834020) AND
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NOT EID (2-s2.0-84951193642) AND	NOT EID (2-s2.0-84926431933) AND	NOT EID (2-s2.0-84876497085) AND
NOT EID (2-s2.0-84876497085) AND	NOT EID (2-s2.0-84924239362) AND	NOT EID (2-s2.0-61349195135) AND
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NOT EID (2-s2.0-70349987110) AND	NOT EID (2-s2.0-41149172498) AND	NOT EID (2-s2.0-81555199303) AND
NOT EID (2-s2.0-36349021848) AND	NOT EID (2-s2.0-0036800835) AND	NOT EID (2-s2.0-85072013477) AND
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	<p>NOT EID (2-s2.0-84913549625) AND NOT EID (2-s2.0-84938542221) AND NOT EID (2-s2.0-84891521507) AND NOT EID (2-s2.0-84870388290) AND NOT EID (2-s2.0-70849120192) AND NOT EID (2-s2.0-33744471377) AND NOT EID (2-s2.0-85064408658) AND NOT EID (2-s2.0-0035246242) AND NOT EID (2-s2.0-0041418444) AND NOT EID (2-s2.0-85111481609) AND NOT EID (2-s2.0-85077943903) AND NOT EID (2-s2.0-85105629411) AND NOT EID (2-s2.0-85075916537) AND NOT EID (2-s2.0-85065388870) AND NOT EID (2-s2.0-0000960909) AND NOT EID (2-s2.0-0036319901) AND NOT EID (2-s2.0-34247561338) AND NOT EID (2-s2.0-85095948097) AND NOT EID (2-s2.0-85088836419) AND NOT EID (2-s2.0-84858009912) AND NOT EID (2-s2.0-84857030312) AND NOT EID (2-s2.0-84856321942) AND NOT EID (2-s2.0-84874517907) AND NOT EID (2-s2.0-84874517907) AND NOT EID (2-s2.0-84919644173) AND NOT EID (2-s2.0-77956892577) AND NOT EID (2-s2.0-85074007715) AND NOT EID (2-s2.0-84896547597) AND (EXCLUDE (SRCTYPE , "k") OR EXCLUDE (SRCTYPE , "d") OR EXCLUDE (SRCTYPE , "p")) AND (EXCLUDE (PUBSTAGE , "aip")) AND (EXCLUDE (DOCTYPE , "cp") OR EXCLUDE (DOCTYPE , "ch") OR EXCLUDE (DOCTYPE , "cr") OR EXCLUDE (DOCTYPE , "no") OR EXCLUDE (DOCTYPE , "er") OR EXCLUDE (DOCTYPE , "ed") OR EXCLUDE (DOCTYPE , "bk") OR EXCLUDE (DOCTYPE , "sh") OR EXCLUDE (DOCTYPE , "tb")) AND (EXCLUDE (PUBYEAR , 2000) OR EXCLUDE (PUBYEAR , 1999) OR EXCLUDE (PUBYEAR , 1998) OR EXCLUDE (PUBYEAR , 1997) OR EXCLUDE (PUBYEAR , 1996) OR EXCLUDE (PUBYEAR , 1995) OR EXCLUDE (PUBYEAR , 1994) OR EXCLUDE (PUBYEAR , 1993) OR EXCLUDE (PUBYEAR , 1992) OR EXCLUDE (PUBYEAR , 1991) OR EXCLUDE (PUBYEAR , 1990) OR EXCLUDE (PUBYEAR , 1989) OR EXCLUDE (PUBYEAR , 1988) OR EXCLUDE (PUBYEAR , 1987) OR EXCLUDE (PUBYEAR , 1986) OR EXCLUDE (PUBYEAR</p>	
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	<p>, 1985) OR EXCLUDE (PUBYEAR, 1984) OR EXCLUDE (PUBYEAR, 1983) OR EXCLUDE (PUBYEAR, 1979) OR EXCLUDE (PUBYEAR, 1977) OR EXCLUDE (PUBYEAR, 1976) OR EXCLUDE (PUBYEAR, 1975) OR EXCLUDE (PUBYEAR, 1974) OR EXCLUDE (PUBYEAR, 1972) OR EXCLUDE (PUBYEAR, 2022)) AND (EXCLUDE (LANGUAGE, "Chinese") OR EXCLUDE (LANGUAGE, "Spanish") OR EXCLUDE (LANGUAGE, "Hungarian") OR EXCLUDE (LANGUAGE, "Portuguese") OR EXCLUDE (LANGUAGE, "French") OR EXCLUDE (LANGUAGE, "Polish") OR EXCLUDE (LANGUAGE, "Czech") OR EXCLUDE (LANGUAGE, "Estonian") OR EXCLUDE (LANGUAGE, "Japanese") OR EXCLUDE (LANGUAGE, "Persian") OR EXCLUDE (LANGUAGE, "Russian") OR EXCLUDE (LANGUAGE, "Turkish"))</p>	
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